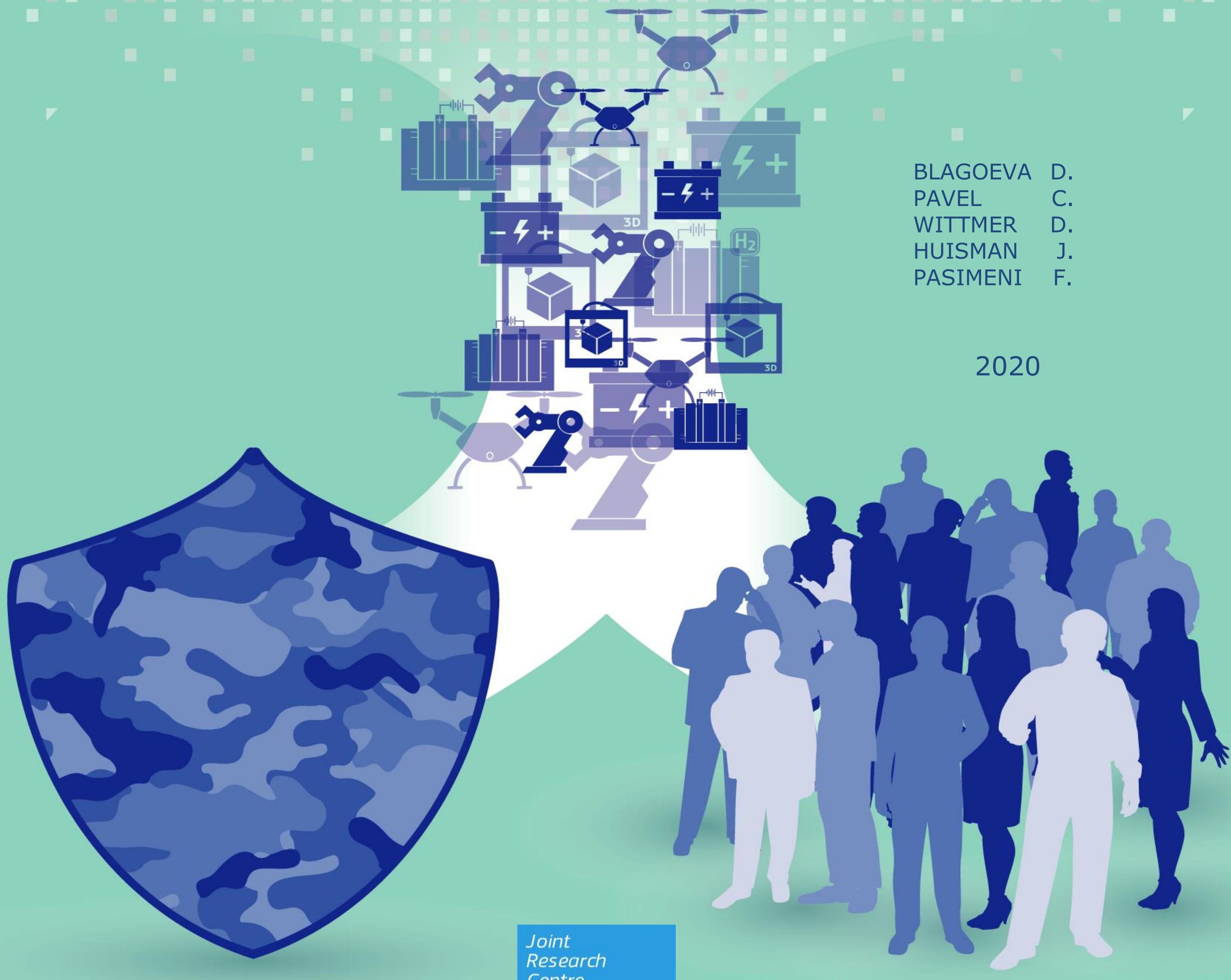
European Commission

JRC TECHNICAL REPORTS

MATERIALS DEPENDENCIES FOR DUAL-USE TECHNOLOGIES RELEVANT TO EUROPE'S DEFENCE SECTOR

Background Report



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2020

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JRC Science Hub
https://ec.europa.eu/jrc

JRC118394

EUR 29889 EN

PDF ISBN 978-92-76-16658-0 ISSN 1831-9424 doi:10.2760/977597

Luxembourg: Publications Office of the European Union, 2020

How to cite: Blagoeva, D., Pavel C., Wittmer, D., Huisman, J. and Pasimeni, F., *Materials dependencies for dual-use technologies relevant to Europe's defence sector*, EUR 29889 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-16658-0, doi:10.2760/977597, JRC118394.

This is a re-edition of: Blagoeva, D., Pavel C., Wittmer, D., Huisman, J. and Pasimeni, F., *Materials dependencies for dual-use technologies relevant to Europe's defence sector*, EUR 29889 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-12194-7, doi:10.2760/253871, JRC118394.

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Acknowledgements

The authors would like to gratefully thank the contributing experts: Christophe-Alexandre Paillard (Ecole Militaire Strategic Research Institute, Ministry of Defence, France), Neil Adams (Innovation Bridge Consulting, United Kingdom), Karsten Pinkwart (University of Applied Science Karlsruhe, Germany), Alexander Andriotis (AVQ GmbH, Germany), Antidio Viguria (Advanced Aerospace Technologies (FADA-CATEC), Spain), Geert De Cubber (Royal Military Academy of Belgium — Unmanned Ground Vehicles Centre) and Alessandro Busachi (The Boston Consulting Group (BCG), Italy) for their comprehensive and useful contributions, feedback and critical review throughout the development of this report.

The support and the contribution of many Joint Research Centre colleagues are also gratefully acknowledged. We are thankful to Beatriz Acosta Iborra, Patricia Alves Dias, Marek Bielewski, Jonathan Davies, Francesco Dolci, Colette Lambeau, Natalia Lebedeva, Fabrice Mathieux, Pietro Moretto, Rafael Ortiz Cebolla, David Pennington, Alberto Pilenga and Eveline Weidner for the insights, comments, data and information they have shared with us.

We are also thankful to Ernest Cutuk (DG Research and Innovation), Milan Grohol (DG Internal Market, Industry, Entrepreneurship and SMEs), Miguel Aguado Monsonet (DG Internal Market, Industry, Entrepreneurship and SMEs) and Thierry Buttin (DG Internal Market, Industry, Entrepreneurship and SMEs) for the review and comments provided.

Last but not least, the authors are very grateful to Paul Anciaux (DG Internal Market, Industry, Entrepreneurship and SMEs) and Mathieu Moreau (DG Internal Market, Industry, Entrepreneurship and SMEs) for their reviews, continuous support and guidance throughout the preparation of this document.

Abstract

In order to support the European Commission in the preparation of future initiatives fostering the sustainability of strategic supply chains, this study was commissioned to assess bottlenecks in the supply of materials needed for the development of technologies important to Europe's defence and civil industries. The study focuses on five dual-use technology areas, namely advanced batteries, fuel cells, robotics, unmanned vehicles and additive manufacturing (3D printing). The technologies are preselected on the basis of a previous study (EASME, 2017) that explored the dual-use potential of key enabling technologies in which Europe should strategically invest. In addition, this report examines how these technologies could address specific military needs and their differences in relation to civil needs and identified opportunities for future defence research areas that could potentially serve as a basis for the design of research initiatives to be funded under the future European Defence Fund. Moreover, potential opportunities for common policy actions are also identified, notably: to strengthen Europe's position in the selected technologies' supply chains; to facilitate collaboration between stakeholders; to increase industry involvement with special emphasis on small and medium-sized enterprises; to improve existent legislation; and increase synergies between civil and defence sectors in order to speed up progress in promising research areas.

This JRC Technical Background report provides a comprehensive overview of all data and information sources used to prepare the Summary JRC Science for Policy report: EUR 29850 EN.

Executive summary

There has been growing concern throughout the EU in recent years about the security of supply of strategic raw and advanced materials that are critical for both civil and defence applications. The European defence action plan was launched to tackle such issues and to make the defence and security sectors more competitive and efficient via the European Defence Fund and other actions to support Member States with more efficient spending on joint defence.

In order to support the European Commission in the preparation of future initiatives to foster the sustainability of strategic supply chains, a study was commissioned to assess bottlenecks in the supply of materials needed for the development of technologies that are important to Europe's defence and civil industries. The report also identifies common dual-use research needs that would benefit from support from the European Defence Fund.

This report focuses on five dual-use technology areas: advanced batteries, fuel cells, robotics, unmanned vehicles (UVs) and additive manufacturing (3D printing — 3DP). The technologies were preselected on the basis of a study (EASME, 2017) that explored the dual-use potential of key enabling technologies in which Europe should strategically invest. These technology areas were selected for their high relevance to the European defence technological and industrial base and their contribution to:

- the strategic independence of the civilian and defence supply chains;
- the economic impact on EU growth and job creation;
- the EU's knowledge base (impact on R & D capital stock).

The five selected technology areas were thoroughly analysed with regard to their geopolitical supply chain dependencies, accompanied by a comprehensive overview of the corresponding key players (countries and companies). Other bottlenecks were also examined, such as the availability of a skilled work force, cost, quality issues, regulation, certification and legislation. Standardisation matters and intellectual property rights (IPR) issues have also been identified.

The report also examined how these technologies could address specific military needs and how these differ from civil needs. In light of the above, the study identified opportunities for future defence research areas that could potentially serve as a basis for the design of research initiatives to be funded under the European Defence Fund. Potential opportunities for common policy actions were also identified, notably: to strengthen Europe's position in the selected technologies' supply chains; to facilitate collaboration between stakeholders; to increase industry involvement, with special emphasis on small and medium-sized enterprises (SMEs); to improve current legislation; and to increase synergies between civil and defence sectors to speed up progress in promising research areas.

A dedicated methodology, relying on several key parameters, was developed to identify forthcoming bottlenecks (supply risks) in the supply chains of the selected five technologies, from raw materials to final assemblies (e.g. lithium-ion (Li-ion) cells, fuel cells, robots, drones, 3D printers). Such parameters reflect the concentration of supply, the availability of domestic production in Europe, import reliance on specific raw materials, the use of critical raw materials (CRMs) in the technologies in question and the substitution and recycling potential of the raw materials required for these technologies. Potential bottlenecks are then visualised using a traffic-light colour matrix, in which red, yellow and green mean respectively supply issues of high, medium and low risk.

Key findings

The technologies

Advanced batteries: Li-ion

Li-ion battery technology has improved recently, and has now become a real emerging technology across a wide range of civil and defence applications. Li-ion batteries offer improved power and energy performance compared to the currently used lead-acid batteries. Li-ion batteries are now used for portable applications such as tactical radios, thermal imagers and portable computing. In the next 5 years Li-ion batteries will further expand to heavy-duty platforms, such as military vehicles, boats, shelter applications, aircraft and missiles. Military land applications represent the largest fraction of the military battery market, followed by military naval ships and electric drone applications. While Li-ion batteries are crucial for defence applications, their development and future uptake are primarily driven by the civilian demand for portable electronic devices and, most recently, electric vehicles.

Fuel cells

Fuel cells are providing operational advantages to different mobile, stationary and portable defence applications as a power solution. Fuel cells require less maintenance and zero lubricants, increase endurance and ensure a high specific energy and power density beyond that which can be achieved using conventional battery power. In addition they have the potential to reduce sound and thermal signatures, which is an essential advantage for defence applications. The defence sector could gain noticeably from the unique features of fuel cells, which can provide tactical benefits to and increase the efficiency of the army. There is strong military interest in fuel cells as a means of reducing the logistics burden: fuel cells allow military forces to generate power in the operational theatre using local fuels or other sources, reducing the need to transport fuel with the associated high logistics costs and levels of risk.

Robotics and exoskeletons

Robotics is an emerging field of technology offering enormous potential for many civil and defence applications. Robots can perform military operations considered too risky, too complex or even impossible for humans. Military robots are autonomous or remote-controlled mobile robots designed for military applications, from transport, to search and rescue, to attack. Robots are used in the military on all three fronts — ground, water and sky — for rescue operations, disaster management, surveillance and security. Major tasks performed by robots include bomb disarmament, mine clearance, surveillance and help in search and rescue operations. Wearable robotics for the military is the most dynamic subset of the exoskeleton industry. Exoskeletons can be used by the army to support strength and endurance and protect soldiers from strain injury.

Unmanned vehicles

UVs are an evolving technology with enormous growth potential. The defence industry has recently witnessed growing application in unmanned aerial vehicles (UAVs), as well as in unmanned ground vehicles (UGVs) and unmanned underwater vehicles (UUVs). The potential for market discontinuity is particularly evident for UAVs, as this branch is further developed in terms of market volumes than the UGV and UUV subsectors.

UVs are expected to make significant changes to army, navy and air force operations in the 2021-2040 time frame up to the global scale. They will be crucial for mixed manned and unmanned arms operations. Increased load capabilities, in particular of UGVs and UAVs, will enable the soldier load to be reduced and will thus extend the soldier's active area. UAVs in particular show the potential to provide key support in military operations such as remote sensing; reconnaissance; surveillance; target and decoy; the delivery of military cargo to and near combat zones, including lethal and non-lethal payloads; and armed attacks. Eventually, the application of UVs has the potential to reduce human exposure to hazards, reduce costs, extend application ranges and generally give commanders more options for action.

3D printing

3DP is a new technology, which will disrupt the aerospace supply chain significantly by eliminating multiple manufacturing stages. It allows for reduction, substitution, recycling and mitigation in the use of CRMs and traditionally manufactured components. This is particularly relevant to defence in resource-constraint situations and/or remote locations in order to keep aerospace platforms operational. Currently, the use of 3DP in the defence sector is both very promising and merely anecdotal. The sector is not yet thoroughly incorporating 3DP, and thus is not yet exploiting the full technical potential offered by reducing weight and creating stronger and more efficient components.

Raw materials supply risks

Access to raw materials, and in particular to CRMs, is of great importance for the successful and smooth deployment of established and emerging technologies in Europe. This applies in particular to the five investigated technologies, which show massive growth potential. Several factors play a role when defining the risk of supply disruptions for Europe. One factor is the limited production of raw materials in Europe. Another factor is the high geographic concentration of the supply for some materials. The supply of certain strategic materials is dominated by only a few countries, several of which have politically instable governments. These factors, coupled with a rapid increase in demand, are risk factors for a potential supply shortage.

The study confirmed the supposition that Europe currently produces only a small proportion of the raw materials required overall for Li-ion batteries, fuel cells, robotics, drones and 3DP technologies. The study has revealed Europe's extremely high dependence on the supply of raw materials for all five technologies, supplying between 2 % of the raw materials (for Li-ion) and 5 % (for fuel cells). China dominates global production of the raw materials required for these five technologies, supplying between 22 % and 32 % across the five technologies. Other key suppliers of raw materials are South Africa, Russia and Brazil for all five technologies except Li-ion batteries, for which Australia and Chile are the major suppliers after China.

Critical raw materials supply risks

As regards the supply of CRMs for the five technologies, drones require the most at 23 CRMs, followed by robotics (19 CRMs), fuel cells (11 CRMs), 3DP (8 CRMs) and Li-ion batteries (5 CRMs). Europe provides only 1 % of the CRMs required for its research and industrial needs. The major supplier of CRMs is China, with a share of almost 40 %, followed by South Africa, Russia, the Democratic Republic of the DRC and Brazil. China is the major supplier of 13 of the 23 CRMs, namely Sb, Bi, F, Ga, In, Mg, C, P, rare earth elements (REEs), Sc, Si, W and V. Around 40 % of the CRMs are provided by many small suppliers, with a < 1 % production share. Altogether, Li-ion batteries, fuel cells, robotics, UVs and additive manufacturing rely on 23 CRMs [1]. The most used critical material in all five selected technologies is cobalt. The demand for cobalt is expected to rise sharply, especially with the market launch of electromobility, which may create supply shortages. Another bottleneck or supply risk is linked to the geopolitical stability of the main producing country. Currently, 54 % of cobalt mine production comes from the Democratic Republic of the Congo, a country experiencing situations of violence and political instability. An additional bottleneck for cobalt is the refining stage: the majority is refined in China. China is also the major producer of magnesium, natural graphite, silicon metal and vanadium (CRMs used in four of the five technologies). Most of the other critical materials are used in three of the five technologies.

The CRMs used in the selected technologies are listed below.

- Li-ion batteries. Cobalt, fluorspar, natural graphite, phosphorus and silicon metal.
- Fuel cells and hydrogen-related technologies. Boron, cobalt, magnesium, natural graphite, palladium, platinum, REEs, rhodium, ruthenium, silicon metal, vanadium.
- Robotics. Antimony, bismuth, gallium, indium, tantalum and tungsten, in addition to the CRMs required in Li-ion batteries and fuel cells.
- Unmanned (aerial) vehicles. Beryllium, niobium, hafnium and scandium, in addition to the CRMs needed in robotics.
- 3DP. Cobalt, hafnium, magnesium, niobium, scandium, silicon metal, tungsten and vanadium. Of the non-critical materials, titanium is particularly relevant to metal-based 3DP for aerospace.

Processed materials supply risks

By the term ‘processed materials’ we mean manufactured materials such as composites, ceramics, steels and special alloys, along with advanced materials such as nanomaterials, graphene and carbon nanotubes. With the exception of Li-ion batteries, Europe is a strong supplier, globally, of the processed materials required for the five selected technologies. In general, Europe produces around 30 % of the processed materials required for Li-ion batteries, fuel cells, robotics, drones and 3DP technologies.

Although a strong player in the field of processed materials production, Europe is highly dependent on the supply of some specific materials such as aramid fibre, semiconductors (main supplier the Unites States), ferroniobium (main supplier Brazil) and processed materials for Li-ion batteries (main supplier China). Such dependencies apply to both the civil and the defence sectors. To a lesser degree, Europe also relies on the supply of nanomaterials, specific Al alloys and speciality steels.

The key suppliers of processed materials resulting from the analysis are:

- China, Japan and South Korea for Li-ion batteries;
- United States, China and Japan for fuel cells;
- United States, China and India for robotics and drones;
- United States, Canada and Japan for 3DP.

The United States is a major supplier of the processed materials used in fuel cells, robotics and drones such as fibres (carbon and Kevlar), semiconductors, polymers, yttria-stabilised zirconia, nanomaterials and carbon nanotubes. Japan is among the key suppliers of processed materials for Li-ion batteries (nickel cobalt aluminium (NCA)

[1] Platinum group metals (PGMs) are considered to be separate materials, while REEs were considered as a single material in the assessment.

cathode material) and is an important supplier of carbon fibre composites (CFCs), used in robotics and drones. China is a key supplier of processed materials for Li-ion batteries and is an important supplier of Mg and Ni-Ti alloys, along with magnetic alloys/powders for robotics and drones. South Korea is an important supplier of semiconductors and cathode and anode materials for Li-ion batteries. India is an important supplier of the steels and special alloys (Al, Ni, Ni-Ti) required in robotics and drones, while Canada is an important supplier of processed materials for fuel cells.

Europe is relatively strong in processing capacities of materials for 3DP, with 40 % to 60 % of the suppliers of Ti alloys, Al/Mg alloys, Ni alloys, stainless steel alloys and special alloys being located in Europe. With only a small number of metal (aluminium and titanium) powder suppliers identified globally so far, the supply risk for metal-based 3DP for aerospace is still evaluated as high. Europe also appears to have a gap in the supply chain of all metal wire products. The analysis identified only two main suppliers with headquarters located in Europe. Most of the suppliers (at least 10) are located in China, and two suppliers in the United States. This may cause a significant lack of customisation capabilities between processed materials and the specific 3DP technologies that have been developed.

Specific processed materials for military applications are those used in low-signature (low observable) applications. However, country production shares for such materials could not be assessed due to a lack of data.

Components supply risks

By the term 'components' [2] we mean finished parts ready to be used in certain applications, such as cathodes for batteries or fuel cells, motors and gears for robots and sensors for drones. With the exception of fuel cell technology, Europe is home to a relatively low rate of domestic production of components. A key issue for batteries is the lack of EU capacity in Li-ion cell component manufacturing (cathodes, anodes, electrolytes and separators) and in cell manufacturing itself, for each of which there is a high level of dependence on China. Although the European share of the production of Li-ion cells is expected to increase — following the European strategic action plan on batteries adopted in 2018 — Li-ion batteries for common military applications are still assembled from commercial cells manufactured in Asia. China is also a major supplier (80 %) of the REE magnets used in robots and drones for both civil and defence applications.

A high level of dependency is also observed in robotics and UAVs: one of the main concerns of the EU industry is the lack of EU component manufacturers, with the United States leading the supply of actuators, controllers (processors), graphics processing units (GPUs) and inertial measurement units (IMUs), while Japan dominates the supply of high-precision gears. The key suppliers of components shown in the analysis are:

- China, Japan and South Korea for Li-ion batteries;
- North America, Japan and Europe for fuel cells;
- United States, China and Japan for robotics and drones.

Overall, Europe produces around 12 % of the components required for Li-ion batteries, fuel cells, robotics, drones and 3DP technologies. More specifically, Europe produces around 8 % of the components for Li-ion batteries, 25 % for fuel cells, 4 % for robotics and 13 % for drones. It can be assumed that such dependencies are basically valid for both civil and defence applications.

[2] Components step for 3DP was not considered (explanation given in the 3DP chapter).

Assembly supply risks

By the term 'assembly' we mean finished products such as Li-ion cells, fuel cells, robots, drones and 3DP systems. Overall, Europe produces around 0.2 % of Li-ion batteries, 1 % of fuel cells, 41 % of robots, 9 % of UAVs and 34 % of 3D metal systems globally.

Europe is still a strong player in the production of robots (mainly service but also industrial) and 3D metal systems. Europe provides around 40 % of robots and supplies 34 % of additive manufacturing metal systems globally. However such leadership is being strongly challenged by China for both technologies; the picture may change drastically in the coming years — by 2025 — reflecting the ambitious 'Made in China 2025' initiative. Europe has some production of drones, though certainly not enough to satisfy its needs. Europe is very weak in the supply of Li-batteries and fuel cells, which are predominantly provided by Asia (China, Japan and South Korea) and North America (United States and Canada).

Japanese manufacturers dominate industrial robotics, while USA manufacturers dominate non-industrial robotics (e.g. surgical, defence and rescue), UVs and artificial intelligence. China dominates the manufacture of UAVs for civil purposes. The United States is the key player in military drones, along with military UGVs and UUVs, of which Europe is the second-biggest producer. Europe leads the exoskeleton market (based on the number of companies producing exoskeletons), followed by the United States, Japan, Canada and several other countries. The main use of exoskeletons is currently in the medical sector for rehabilitation purposes. Defence represents only 8 % of the exoskeleton market, in which USA companies are the key players. Requirements for military exoskeletons are more stringent than for their civil counterparts: they need more strength and less weight, in addition to smaller, optimised power units allowing troops to be more independent. As the use of fibres (Kevlar and carbon) is critical for military exoskeletons, Europe faces a high level of dependence on the United States for the supply of such materials.

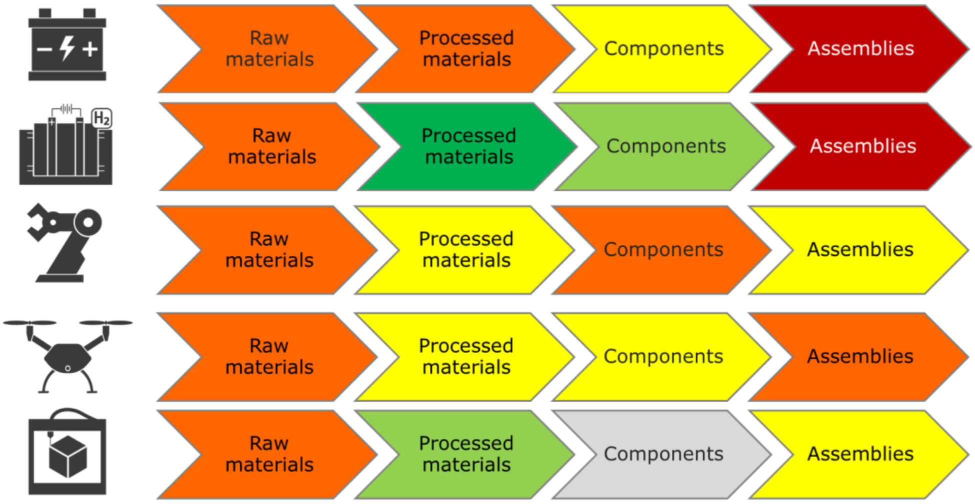
Regarding 3D printers for industrial use, the United States leads in polymer-based technologies, with Europe strongly present in metal additive manufacturing (AM), which is more relevant to aerospace. On the basis of total units sold, Europe has about 20 % of the market share and the United States and Israel represent over 71 % of supply. Europe's share in the number of suppliers is 25 % and 21 % respectively for the two key sub-technologies: powder bed fusion (PBF) and directed energy deposition (DED). China has a high and fast-growing number of individual suppliers, albeit with a relatively low number of unit shipments so far. For aerospace applications, the United States and the EU are equally present in the top 15 system integrators such as Airbus and Boeing, driving the development of 3DP on a large scale in their own way, in their respective supply chains.

Policy recommendations

This report stresses the importance of utilising the synergies between the civil and defence sectors in order to increase interest in common, dual-use research and investment opportunities. For some technologies, such as Li-ion batteries and fuel cells, supporting such synergies is even more crucial where volumes for defence are small and Europe has a weak position globally.

The analysis has shown that the weakest step in the supply chain, for the five technologies under the spotlight, is the supply of raw materials. Furthermore, the supply of assemblies appears to be very critical for three of the technologies, namely Li-ion batteries, fuel cells and drones. The supply of processed materials is shown to be critical for Li-ion batteries, though some supply risks are also detected for robotics and drones. At the components level, though some supply risks are detected for Li-ion batteries and drones, robotics seems to be the most vulnerable of the technologies (Figure 1).

Figure 1 Identified supply risks for Europe in the supply chains of Li-ion batteries, fuel cells, robotics, drones and 3D printing



Source: JRC

Europe should therefore introduce mitigation strategies throughout the whole supply chain as soon as possible. At the level of raw materials, such strategies could include **supply diversification, increased recycling volumes and the substitution of critical materials**, for example the substitution of cobalt and PGMs, needed in Li-ion batteries and fuel cells and relevant also for robotics and UVs. Cobalt is also one of the CRMs for 3DP technology. Recycling is of particular importance for Li-ion batteries as a feasible way to secure access to raw materials. The role of China as a key supplier in the supply chains examined here is noteworthy. China has acquired, and continues to expand its dominant position in the Li-ion battery and drone supply chains, and has ambitious plans in the fields of robotics, fuel cells and 3DP.

In addition, stockpiling could be considered to secure access to raw materials in the event of a crisis. A dedicated study needs to be commissioned to evaluate and analyse in more depth the potential of stockpiling materials essential to the development of certain technologies, looking at the environmental and economic impact and taking into account the expected technological developments in the future.

Tailored, competitive awards-based programmes could be initiated to encourage European companies, in particular small businesses, to engage in European defence R & D with the potential for commercialisation, i.e. high technology readiness level. The European Defence Fund could notably fund cross-border defence R&D to increase its attractiveness and to encourage SMEs to get involved. Such programmes, with a primary focus on defence, would lead to the procurement and development of new industrial capabilities addressing raw and processed materials criticalities with additional civil potential.

The report also calls for support to **increase manufacturing opportunities in Europe** by creating an attractive investment environment for European companies.

Further key policy actions identified in the report include fostering international collaboration (e.g. for fuel cells); supporting standardisation activities (e.g. 3DP, fuel cells, robotics and drones); and promoting the cyber physical security of robotics systems (including UVs).

Research needs relevant to defence applications

Besides the dual-use research needs identified in this study, important defence-related research areas should also be explored as potential topics for future research.

Li-ion batteries

- **Research on system management to address specific military requirements** such as thermal management, electromagnetic compatibility and battery safety.
- **Research on Li-ion batteries** with lithium iron phosphate as a cathode material and lithium titanate replacing the graphite in the anode to improve the specific energy [3] and reduce discharging and costs. Such battery types are of interest to the naval and land defence sectors, especially for military vehicle applications in relation to providing 'silent-watch' conditions.
- **Research on emerging advanced batteries such as lithium-sulfur (Li-S) and lithium-air (Li-air)**, with high potential for military applications, as they are both characterised by a very high specific energy density. Li-air batteries represent an emerging and promising chemistry for soldier-portable batteries and aviation. Li-S batteries also show great potential, especially for high-energy military applications, as they can offer a theoretical energy density more than five times that of Li-ion batteries. They have the advantage of not containing any environmentally harmful fluorine, but research on new manufacturing processes is needed to make this technology commercially viable and usable for the defence sector.

Fuel cells

For military purposes, operating fuel cell systems independently from a hydrogen infrastructure is an essential point. The hydrogen needs to be produced on-site. This aspect is especially important for mobile fuel cell applications, including defence applications. The most feasible way to produce hydrogen for military purposes is reforming of diesel fuel or kerosene, as both fuels are readily available in the armed forces and logistics are available for these types of fuel. However, logistic fuels contain some amount of sulfur, which is detrimental for fuel cells — it poisons the noble metal catalysts. Desulfurisation is therefore considered to be a very important step in fuel-processing technologies for military purposes. Consequently, the following research areas should be explored.

- Development of **systems that can operate on logistic fuels as well as fuel cell systems, capable of operating in harsh environmental conditions** (e.g. Arctic or desert) and giving an advantage to the army. Fuel cells tolerating sulfur could greatly facilitate military operations.
- Research on **portable on-site fuel reformers and desulfurisation methods applicable directly to logistic fuels**. This includes innovative materials for on-site hydrogen purification — for example, materials based on noble metals such as silver, gold and palladium seem to be a promising solution for the desulfurisation of logistic fuels.
- Development of **reliable stack-sealing concepts** [4], which could be more challenging for defence applications, especially mobile ones, due to more stringent requirements regarding vibrations and shock.

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[3] The specific energy of a battery is defined as the battery capacity in weight (Wh/kg), or the energy that can be stored in 1 kg of active material.

[4] Each individual fuel cell needs to be securely sealed in order to be protected from the environment and neighbouring cells. Stack sealing is therefore decisive for the cell's lifespan. Sealing materials should be reliable (resist thermal and mechanical shocks and vibrations), should

- Fuel cells such as direct-methanol fuel cells (DMFCs) can save energy and reduce the operating costs associated with dependence on foreign oil. These fuel cells are relevant to defence applications when used in remote locations to ensure electric power for battery charging, auxiliary power for surveillance and regular power for communication equipment. Research actions aiming at **replacing methanol with ethanol in DMFCs** could be relevant due to the toxicity of methanol.

Robotics and unmanned vehicles

- Development of **advanced, lightweight, high-strength, structural materials** (e.g. based on Al, Mg, Ti-alloys, composites) for robotics (including exoskeletons) and large UAVs.
- Development of **innovative smart** [5] and **multifunctional materials** [6] for special applications such as: multifunctional actuators[7] and artificial muscles (e.g. vanadium-based materials); **electronic skin** [8] (e.g. composites of soft materials with conductive fillers, polymer-based materials, which could also incorporate metallic (e.g. Ni) microparticles into a polymer network, flexible and porous graphene foams); **materials, paints and textiles to mitigate and reduce signatures** (e.g. foams, plastics, elastomers, low-emissivity paints, multispectral patterned textile netting); and **materials for soft robotics** (e.g. printed liquid metals, metallic glass, liquid silicone rubber).
- Development of **smaller, more powerful, high-speed and precision electronics for military applications**: complex military systems require efficient power electronics. High-density power electronics with high efficiencies (> 90 %) are becoming a requirement for high-end mission-critical military platforms, including UAVs, for which size, weight and power are limited. Gallium nitride-based radio-frequency components are beginning to populate military radio-frequency applications.
- Energy storage is a major bottleneck for mobile robotics. The development of **smaller and more efficient power/energy sources** (batteries, fuel cells or other alternative sources) and electric motors specifically important for exoskeletons and UAVs is another challenge to be faced by robotics and UAVs.
- Development of **armour with high ballistic performance** and increased blast and shrapnel protection (e.g. complex composite materials, steel-alloys, Ti-alloys etc.).
- **Cyber physical security of electronics systems** (such as controllers) for military robotics applications, including UAVs: methods to protect military systems (and critical civil infrastructure) against cyber supply-chain attacks.
- Technology advancements to develop **more autonomous, smaller, more economical and more efficient military UAVs**.
- Research on counter drone systems will secure the data link and support shielding for emissions security (e.g. silver plating).

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not react with the other fuel cell components and also should not be expensive.

[5] Smart materials are materials that can change their stiffness and shape, for example.

[6] Multifunctional materials, integrating processes like sensing, movement, energy harvesting or energy storage (e.g. materials that can change over time to adapt or heal). Smart materials can be considered to be multifunctional materials that have the ability to react upon an external stimulus, thus simulating the behaviour of nature's materials.

[7] Actuators can be considered to be a robot's muscles.

[8] Electronic skin refers to flexible, stretchable and self-healing electronics that are able to mimic the functionalities of human or animal skin.

3D printing

Targeted investment in 3DP R & D for defence will enhance capabilities related to mobility, sustainability, repair and maintenance. More investment is needed to keep up with the pace of development in the United States and China. The potential of 3DP for defence capabilities is crucial for the smooth operation of combat and peacekeeping missions. It is recommended that R & D focus specifically on the following.

- The **development of new sustainable materials and processes**, and related characterisation in the field of multifunctional materials, multi-materials and materials with highly improved functionality for aerospace applications, special alloys used for defence and space purposes and incorporating such elements as niobium, hafnium/zirconium and scandium.
- **REACH** (registration, evaluation, authorisation and restriction of chemicals) related issues to be further investigated to ensure safe handling and proper removal and recycling from powder beds (9).
- The **standardisation and certification of metal powders and wire recipes for AM**, which would aid EU companies in particular, considering that EU companies, and SMEs in particular, are relatively well positioned to produce high-quality components. The preference of the aerospace industry itself is to have a stable and international standardisation process involving European and international bodies (AM-motion, 2018; DefenceIQ, 2016). With regard to the Chinese research and development pace, which is seemingly much faster than that of the EU, it is recommended that targeted research and innovation actions be funded in this technical domain.
- An improved **strategic assessment of the resilience of the military supply chains**. The (future) supply chain of the critical sectors of aerospace and defence will inevitably rely more and more on 3DP in the near future. This warrants a careful reconsideration of specific strategies to mitigate supply risk. As a supporting strategy, **creating strategic stockpiles for the manufacturing** of the main 3DP powders can be reconsidered (RPA, 2012). Here, the most relevant 3DP powders identified in the background report include titanium grade 2, grade 5 and grade 23, Al-10Si-Mg, Al07Si-0.6Mg, nickel alloys 316L and 625, stainless steel alloy 718; CoCr and possibly specific zirconium and niobium alloys.
- The use of **3DP for the repair and maintenance of equipment used in operations at remote locations.**
- Address the current **lack of customisation capabilities between the processed materials and the specific 3DP technology**, as well as the availability of high-quality, environmentally friendly and cost-effective materials.
- The comprehensive assessment of aspects related to **sustainability, responsible sourcing, skills and workforce, IPR protection and digital security.**

Cross-cutting research topics identified in this study include **the maintenance of a knowledge base and skilled workforce in Europe**, including **software development skills** — a key enabler for the development of robotic and autonomous systems for both European military forces and civil applications. **Sensors are another cross-cutting element**, becoming ever more important; their development and the processing of their data should receive close attention.

[9] Nickel is restricted for certain uses related to skin contact. Cobalt, magnesium, niobium and tungsten are registered as well. In this case, their specific properties will likely lead to more demand rather than restricted use in the future.

Policy context

Raw materials are crucial for the trade and competitiveness of EU industry, as highlighted in various policies such as the renewed industry policy strategy (COM(2017) 479 final), the raw material initiative (COM(2008) 699) and the circular economy action plan (COM(2015) 614). Secure and sustainable access to raw materials is vital for strategic value chains such as batteries, e-mobility, renewable energy and defence. Following communication COM(2013) 542 and the European defence action plan (COM(2016) 950), this report analyses raw materials supply risks for the value chains of five dual-use technologies considered both strategically important for resilience in the defence sectors and fundamental for competitiveness in relation to their civil use.

Main findings

This study identifies bottlenecks and supply risks linked to raw materials and processed materials needed for the development of key defence capabilities by Europe's defence industry. **The dependence of Europe on the supply of raw materials for the five analysed technologies is extremely high.** Europe produces on average around 3 % of the overall raw materials required in Li-ion batteries, fuel cells, robotics, drones and 3DP technology. China dominates global production, supplying around one third of the raw materials. Other key suppliers are South Africa (7 %) and Russia (4 %). **With regard to the supply of CRMs required in these five technologies, Europe provides only 1 % of them.** The major supplier is China, with a share of almost 40 %, followed by South Africa (9 %) and Russia (6 %).

With the exception of Li-ion batteries, in general Europe is an important supplier of processed materials for these technologies, providing on average about one third of the materials. Other key suppliers are United States (20 %), China (19 %) and Japan (8 %). Canada, India and South Korea are also key suppliers for 3DP, robotics and Li ion batteries.

With regard to the supply of components, with the exception of fuel cell technology **Europe has a relatively low level of domestic production of components**. On average Europe produces around 12 % of the components required in Li-ion batteries, fuel cells, robotics and drones. Most of the components are supplied by Asia (46 %) and North America (31 %).

Europe is very weak with regard to the supply of Li-ion, LiPo batteries and fuel cells, which is predominantly covered by Asia (China, Japan and South Korea) and North America (United States and Canada).

Europe is a major player in the production of robots. Japanese manufacturers dominate industrial robotics, while USA manufacturers dominate non-industrial robotics, robotics for the military, UVs and artificial intelligence. Europe is the leader in the production of exoskeletons for medical and industrial purposes. Other key manufacturers are the United States and Japan. Manufacturers in the United States are also the key players for military exoskeletons.

Europe has some drone production capability, though not enough to satisfy its needs. The United States and China dominate UAV assembly and manufacturing for civil applications. The United States is the leader in the production of UGVs and UMVs. Europe is the second-biggest manufacturer of UGVs and UMVs.

Regarding 3D printers for industrial use, the United States leads in polymer-based technologies, with Europe strongly present in metal additive manufacturing. However, more R & D investment is needed to keep pace with the speed of development observed in the United States and China.

Key conclusions

It is important for Europe to secure the supply throughout the whole supply chain for important emerging dual-use technologies such as Li-ion batteries, fuel cells, robotics/exoskeletons, unmanned systems and 3DP technology. The analysis has shown that **the weakest step in the supply chain for the five investigated technologies is the supply of raw materials.** Furthermore, the supply of assemblies appears to be very critical for three of the technologies, namely Li-ion batteries, fuel cells and drones. The supply of processed materials is critical for Li-ion batteries, though some supply risks are detected for robotics and drones. At the components level, though some supply risks are detected for Li-ion batteries and drones, robotics seems to be the most vulnerable technology.

The extremely high dependency of Europe on the supply of raw materials required for these technologies should be mitigated via various measures. China has the dominant position in the supply of raw materials, including CRMs used in the five technologies. The other two major suppliers are South Africa and Russia. Yet a large amount of the materials are provided by numerous small suppliers, which gives good perspectives for **supply diversification**. The same is also true for the supply of processed materials and components required in those dual-use technologies for which Europe has no or insufficient production. In addition, **stockpiling** could be another way to secure access to raw or processed materials and components in the event of a crisis. A comprehensive analysis is needed to evaluate the potential and the feasibility of stockpiling for each of the technologies in question. Securing sustainable access to the right quantity and quality of raw materials is also a key element for future responsible developments in EU industry.

Tailored, **competitive awards-based programmes** could be initiated to encourage domestic small businesses to engage in European defence research with the potential for commercialisation, i.e. a high technology-readiness level. The European Defence Fund could fund collaborative cross-border defence R&D to encourage the involvement of SMEs. Such programmes, with a primary focus on defence, would lead to the procurement and development of new industrial capabilities with additional civil potential.

The report also calls for the provision of support to **increase manufacturing opportunities in Europe** by creating an attractive investment environment for European companies.

Further key policy actions identified in the report include **fostering international collaboration** (e.g. for fuel cells); **supporting standardisation activities** (e.g. 3DP, fuel cells, robotics and drones); and **promoting the cyber physical security of robotics systems** (including UVs).

Cross-cutting research topics identified in this study include the maintenance of a knowledge base and a skilled workforce in Europe, including software development skills — a key enabler for the development of robotic and autonomous systems for both European military forces and civil applications. Sensors are another cross-cutting element that is becoming ever more important; their development and the processing of their data should receive close attention.

Lastly, it is recommended that **more outreaching, strategic and comprehensive discussions on the role and future competitiveness of these emerging technologies be organised**, in particular on the aspects of material availability, sustainability, IPR protection, software development and digital security for key military and civil supply chains.

Related and future JRC work

This study is a part of the JRC raw materials project, which aims at supporting various EU policies by building the knowledge base (e.g. data, indicators, analysis, models and methodologies) required to ensure a secure and sustainable supply of primary and secondary raw materials across a wide range of value chains and sectors. The study is a follow-up to the 2016 study Raw Materials in the European Defence Industry, which identified a list of raw materials that are important for European defence. The present study analyses in more detail the specific supply risks in the entire value chain for five key technologies, with a focus on the early stage of extraction and refining of raw materials, and processed materials available for manufacturing.

The outcomes of this report support the further development of the EU's knowledge base on raw materials and the JRC Raw Materials Information System. It also provides valuable insights into individual materials to update the list of CRMs to be published in 2020. Finally, the results feed into ongoing research on the supply of primary and secondary raw materials, supporting in particular the implementation of the strategic action plan on batteries (COM(2018) 293).

The content of this report has been summarised in a JRC Science for Policy report "Materials dependencies for dual-use technologies relevant to Europe's defence sector", Summary Report, EUR 29850 EN.

1 Introduction

Materials are important assets that contribute to the prosperity and power of nations. They are seen as powerful weapons in economic warfare. Ensuring a sustainable supply of materials is, therefore, of crucial importance for Europe. And when they are needed for defence applications, materials assume strategic importance. The supply of raw materials is, however, just one side of the coin. The processing of raw materials and their transformation into advanced industrial products, in the context of growing scarcity and an increasing world population, is equally important. The need to obtain more with less is even greater, considering the relatively low or even non-existent potential for recycling of some of the materials used in many modern products. The potential for material substitution is often weak and is limited in many fields, amplifying yet further the need to secure our supplies. The processing of raw materials must therefore become smarter and more effective, producing high quality products with as little of the raw material as possible. Using advanced manufacturing methods such as additive manufacturing is just one way to deal with such a challenge. Applying innovative methods to achieve higher recovery rates during the recycling of products is another. Reuse and remanufacturing approaches, part of a circular economic policy, are mitigating measures that can further reduce the demand for primary materials.

Various measures can be introduced to mitigate the supply risk, but they will not be sufficient to cope with rapidly increasing demand. The supply of primary raw materials will continue to be a key factor in the vulnerability of Europe and its deployment of emerging technologies. Europe is highly dependent on the supply of raw materials. Ensuring sustainable access to them is crucial for the processing and manufacturing industries, in both the civil sector and the defence sector. The present study aims to identify bottlenecks in the supply of materials needed for the development of several dual-use emerging technologies important to Europe's defence and civil industries. The ultimate goals of the study are to: (1) identify possible opportunities for targeted policy actions to support the sustainable supply of such materials; (2) support DG Internal Market, Industry, Entrepreneurship and SMEs in the preparation of future research programmes at EU level; and (3) raise awareness among companies, in particular SMEs, about possible supply chain issues related to materials.

Five emerging dual-use technologies have been selected for this study, namely: (1) batteries; (2) fuel cells and hydrogen storage; (3) robotics; (4) UVs; and (5) additive manufacturing (3DP). All five technologies are part of a wider list of technologies of high relevance to the European Defence Technological and Industrial Base in terms of strategic independence, economic impact and knowledge and innovation. The list was established by a recent study (KET4Dual[10]), where 38 technology areas were identified as innovation areas of common interest for both the civil and the military sector in which Europe should invest strategically.

The five selected technologies are thoroughly examined with regard to pertinence to specific civil and defence applications, future demand trends, material requirements, supply of materials and key players in the supply chain, along with specific bottlenecks beyond material supply issues, including the necessity of a skilled workforce, know-how, regulation and legislation matters and the involvement of industry. There is a special focus on technology supply-chain issues, from raw materials to assembly, identifying key players at specific levels of the supply chain. Four supply-chain levels were chosen for the analysis, namely: level 1 - raw materials; level 2 - processed materials; level 3 - components; and Level 4 - assemblies. The specificities of these five technologies to defence applications are analysed, as military requirements are often more challenging than civil ones.

[10] KET4Dual, STUDY ON THE DUAL-USE POTENTIAL OF KEY ENABLING TECHNOLOGIES (KETs), Contract nr. EASME/COSME/2014/019, Final Report, January 2017.

A dedicated methodology, relying on several key parameters, has been developed to identify forthcoming bottlenecks in the supply chains of the selected five technologies, from raw materials to final assemblies (e.g. Li-ion cells, fuel cells, robots). Such parameters reflect the concentration of supply, the availability of domestic production in Europe, the import reliance on specific raw materials, the use of CRMs in the analysed technologies, and the substitution and recycling potential of raw materials required in these technologies. The expected demand trends for each technology are also taken into consideration as a factor that could challenge the adequate, continued and sustainable supply of materials, components and assemblies. Potential bottlenecks are then visualised using a traffic light colour matrix in which red, yellow and green respectively mean a high, medium and low risk of supply issues.

This study also provides an overview of ongoing research in Europe in relation to the selected five technologies. A dedicated patent analysis covering worldwide patent activities has also been carried out, following a methodology developed specifically for this analysis. A comparison between Europe and other leading countries has been made, and the top patenting companies listed for each technology.

Finally, opportunities for research activities and policy actions were proposed, based on the analysis described above.

2 Advanced (Li-ion) battery technology

2.1 Description of battery technology and relevance to civil and defence sectors

Electrical energy plays an important role in our daily life, but the challenges of storing it pose a problem. In batteries, the energy of chemical compounds acts as a storage medium, and during discharge, a chemical process occurs that generates energy (e.g. chemical compounds with a higher energy content are converted by a chemical reaction into compounds with a lower energy content). This energy can be drawn from the battery in the form of an electric current at a certain voltage. For a number of battery systems, the chemical composition can be restored during recharging, therefore re-establishing the original structure within the battery. As a consequence, there are two main battery systems.

- Primary batteries are designed to convert their chemical energy into electrical energy only once. Many applications using single use batteries have moved to rechargeable, for instance to reduce the cost of ownership.
- Secondary batteries are reversible energy converters designed for repeated discharges and charges. However, the recharge ability is not unlimited. They are also known as electrochemical storage systems.

The cell is the basic working element of a battery and each cell consists of a negative and a positive electrode. When operating during discharge, electrons flow from the negative electrode (anode), through an external circuit, to the positive electrode (cathode). An electrolyte and/or separator (e.g. a liquid or semi-porous solid through which ions can move between the two electrodes) separates the anode and cathode within the cell.

There is a wide range of battery types available, both primary and secondary (Table 1).

Table 1. Main primary and secondary types of batteries

Battery chemistry types

Primary batteries	Primary and secondary batteries	Secondary batteries
Carbon-zinc	Alkaline manganese	Lead-acid
Carbon-zinc chloride	Silver-zinc	Nickel types (metal hydride, cadmium, iron, zinc, hydrogen)
Mercury-zinc and other mercury types	Silver-cadmium	Zinc-chloride
Manganese dioxide-magnesium perchlorate	Zinc-air	Sodium-sulphur
Magnesium organic	Cadmium-air	Li-ion battery
Lithium types		Li-metal polymer battery
Thermally activated and seawater		

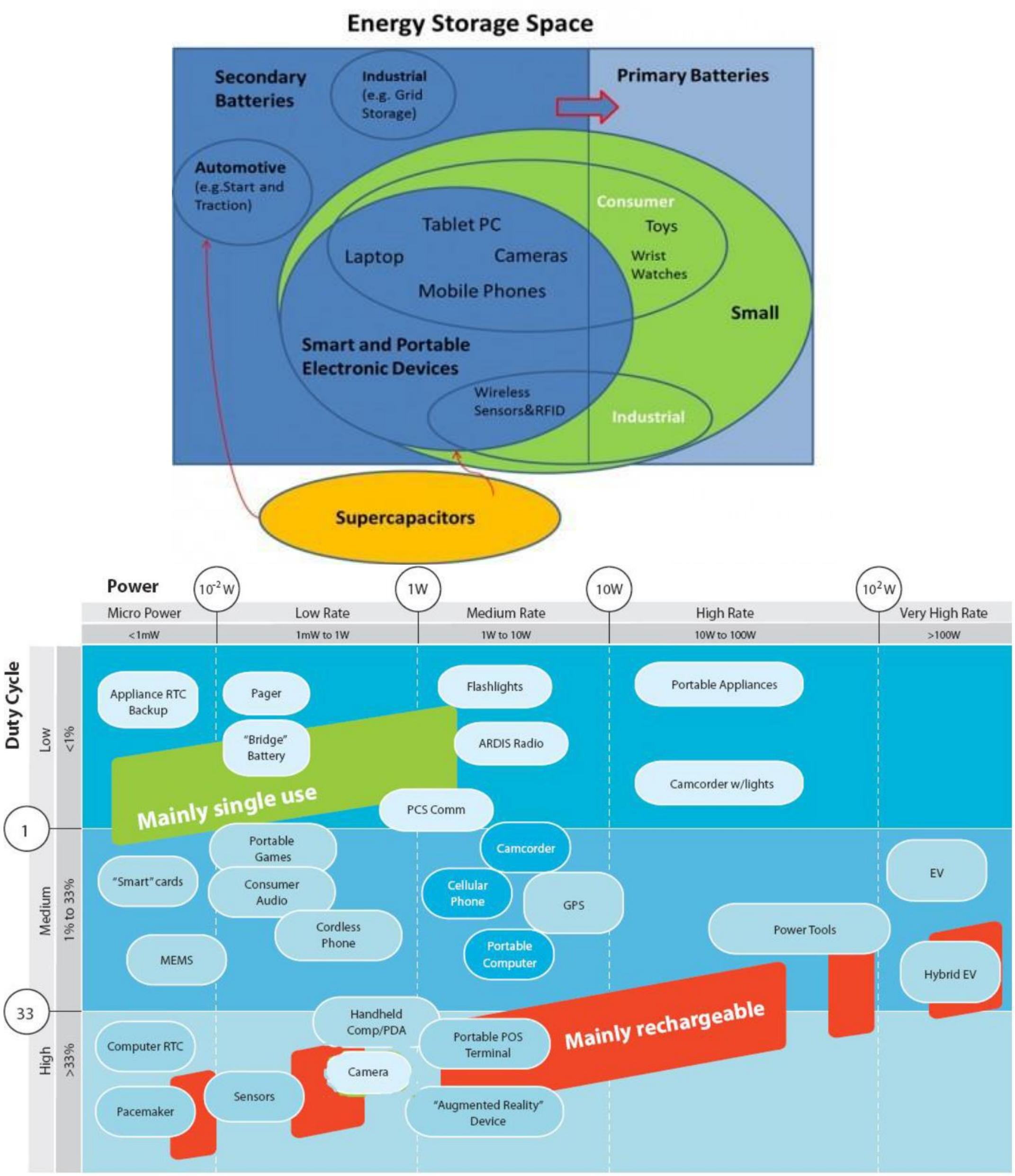
Source: JRC compilation with data from Crompton[11]

The manufacturing industry of both primary (non-rechargeable) and secondary (rechargeable) batteries has undergone tremendous growth and development in recent decades to meet the requirements of various applications. For example, batteries of larger capacities are employed as standby in stationary applications, to provide energy in vehicles like forklift trucks, as traction power in electric vehicles/buses and to stabilise

[11] T.R. Crompton, Battery reference book, third edition, 2000

electrical networks. Rechargeable batteries are usually the first choice in such stationary applications, since primary batteries are too expensive for the high capacity required. In portable applications like toys, portable radios, mobile phones and laptop computers, both primary and secondary batteries of smaller capacities are employed. The overall applications of batteries for smart and portable electronic devices are shown in Figure 2.

Figure 2 Applications of primary and secondary batteries



Source: IDTechEx[12]

A set of battery applications together with the typical battery capacities required by these applications is presented in Table 2.

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[12] IDTechEx report, Li-ion batteries 2018-2028. From raw materials to new materials, through gigafactories and emerging markets. 2018

Table 2 Overview of battery types and applications

Battery type	Battery chemistry	Energy range	Application
Miniature batteries	Mostly primary cells in small button cell packages	100 mWh-2 Wh	Electric watches, calculators, implanted medical devices
Batteries for portable equipment	Mostly secondary cells such as lithium-ion, besides nickel-cadmium (NiCd) and nickel-metal hydride (NiMH) as well as some alkaline primary cells	2 Wh-100 Wh	Flashlights, toys, power tools, portable radio and TV, mobile phones, camcorders, laptop computers, memory refreshing, instruments, cordless devices, wireless peripherals, emergency beacons
SLI batteries (starting lighting & ignition)	Mostly lead acid batteries and Li-ion batteries in the future	100-600 Wh	Cars, trucks, buses, lawnmowers, wheelchairs, robots
Vehicle traction batteries	Li-ion besides some NiMH	20 -630 kWh	Electric and hybrid vehicles, forklift trucks, milk floats, locomotives
Stationary batteries	Li-ion, lead-acid and other chemistries such as redox flow batteries	250 Wh-5 MWh	Emergency power, local energy storage, remote relay stations, communication base stations, uninterruptible power supplies (UPS)
Military & aerospace	**Nickel hydrogen, water-activated batteries, silver oxide, silver-zinc, lithium-ion and other**	**Wide range**	**Satellites, munitions, robots, emergency power, communications**
Special purpose	Mostly lead acid batteries	3 MWh	Submarines
Load levelling batteries	Various lead acid and lithium plus others	5-100 MWh	Spinning reserve, peak shaving, load levelling

Source: MpowerUK[13]

The batteries cover a wide range of civil applications such as:

- domestic equipment: battery-operated household appliances, power tools, TVs, radios, computers, toys, lighting equipment, communications, warning beacons, live-saving equipment;
- medical equipment including pacemakers, battery-operated implant devices and other portable medical and non-medical recording and logging equipment;
- transport applications in conventional vehicles, aircraft, the newer electric vehicles, forklift trucks, etc.;
- IT equipment including computers and electronics.

In the defence and aerospace sectors, batteries power many types of equipment, ranging from torpedoes to ground-to-air and air-to-air missiles as well as space vehicles

[13] https://www.mpoweruk.com/applications.htm

and satellites. More specifically, batteries are employed in land, air and sea vehicles as well as single-use military applications. In the future, other emerging dual-use applications, such as unmanned aerial systems (UAS), are expected to increase their usage of battery power (e.g. small UASs will make exclusive use of battery power to run the motor, control, data link, and imaging equipment for missions lasting nearly two hours, and larger UASs will continue migration towards hybrid energy, with batteries becoming the primary power propulsion). [14] The main battery characteristics required by military applications are typically as follows: high levels of reliability in extreme environments of temperature, dust, humidity, shocks and vibrations; safety (in a military environment); high energy density; high power density (able to draw off high power where needed) and reduced recharge cycle times.

Batteries in single-use military applications

Single-use military/aerospace systems are an emerging defence technology which is expected to become more sophisticated and miniaturised. Such applications are designed to be used only once and could vary from ordinance guidance systems to torpedoes, smart ammunition, mines, sonobuoys, unattended ground sensors, UAVs, artillery fuses, active decoy systems, trajectory correction add-on kits, proximity fuses for bombs, and dispersed munitions sensors. Although the battery technologies used to power these devices have remained essentially unchanged for decades, more intelligent battery-powered solutions need to be developed in the future. Different battery technologies in terms of performance, quality, and safety criteria are required to ensure optimised results. The most common battery technologies that power single-use military applications are listed below.[15]

- Reserve and thermal batteries, encompassing a range of different technologies and chemistries, including thermal, lead-acid, silver-zinc and lithium thionyl chloride chemistries.
- Silver-zinc batteries, whose drawbacks include the high cost, long production lead times and performance limitations due to their low energy density. Once activated, they have a low shelf-life.
- Spin-activated batteries (lead acid and lithium thionyl chloride), especially for military fuses, certain marine applications, minelets or communication jammers.
- High-power lithium metal batteries, commercially available and able to deliver high current pulses, high rate energy and long-term commercial reliability (10-15-year storage life due to a very low annual self-discharge rate).

Batteries in military land vehicles

The electrical energy demand for military land vehicles is increasing as they are fitted with more electronic equipment such as radios, surveillance equipment, battle management systems, remote weapons stations and electronic warfare counter measures. Batteries for military land vehicles need to be highly reliable and safe. They need to deliver high energy, as requested for silent watch, must be capable of delivering high power for engine starting and load levelling, and withstanding the harsh conditions of military environments. They need to be able to charge fast, to minimise engine-on time during silent watch operations, reducing the noise and heat signature, thus lowering the risk of detection, as well as conserving fuel and reducing emissions.

[14] D. Moore, sales manager for defense/aerospace, Avnet, in Brainstorm: design inspiration for military battery technology, December 2017, ECN Magazine. Available at: https://www.ecnmag.com/article/2017/12/brainstorm-design-inspiration-military-battery-technology

[15] Product design & development, Choosing battery-power options for single-use military applications, 2018. Available at: https://www.pddnet.com/article/2018/01/choosing-battery-powered-options-single-use-military-applications

Insufficient electrical energy storage can inhibit the performance of military land vehicles.

The majority of military land vehicles currently use lead-acid batteries. Although this type of battery is reliable and low cost, its low energy density capability, combined with the long charging time, leads to low silent watch performance on military land vehicles. On the other hand, lead-acid batteries offer high safety in the application as well as for the user. They are available all over the world and do not require a sophisticated management system.

In general, lithium ion batteries offer improved power and energy performance compared with lead-acid batteries. The most promising battery technology that can meet these requirements today is the lithium metal oxide type, using various metals including nickel, cobalt, aluminium, manganese and a mixture of these.[16] It has high specific energy and power. However, there is a trade-off in safety. There are two variants of lithium ion batteries with increased safety: lithium iron phosphate and lithium titanate batteries, the latter being very safe, with potential for use inside military vehicles. However, lithium-iron phosphate batteries have lower specific energy than lithium metal oxide; lithium titanate batteries lower still. By using these types of lithium ion battery, it is expected that the silent watch endurance on military land vehicles will improve over lead-acid. Lithium ion batteries using ionic liquid electrolytes and lithium-sulphur batteries (a subset of lithium-metal batteries) are also of interest for defence applications. Although the development of a viable ionic liquid electrolyte remains a big challenge today, this type shows high potential to improve battery safety, and in the case of the lithium sulphur type, increase the energy capability, at low cost.

Box 1. On the battery procurement timescales

Military procurement timescales are typically quite long, with equipment often used for decades. However, battery technology advances are relatively straightforward to accommodate in military systems for in-service upgrades where the benefits are strong and defence ministries are prepared to invest in development to enable their integration. For example, the USA Defence Logistics Agency (DLA) recently helped the USA Army to procure a new lithium-ion power system for the BGM-71 TOW (tube-launched, optically-tracked, wire-guided) 2 anti-tank guided missile system that has been in-service since 1970, to replace a nickel-cadmium battery system (including a detached charging system). Two lithium-ion batteries that are already qualified will fit within an existing battery box and be used to power the missile guidance system and night vision sight. Production is underway as of 2018 and is expected to result in battery procurement savings of USD 8 million per year and weight savings of 55 kg for each system. The lithium-ion power system will allow over 90 missile firings before the system needs to be recharged; far more than the current nickel-cadmium system, which will give military users a clear operational advantage. The USA Defence Logistics Agency is also investing in manufacturing capability for new lead-acid batteries for armoured vehicles (such as the Bradley Fighting Vehicle) that use absorbent glass-like materials, such as fine fibreglass, that do not require users to open cells and refill them with acid. These materials will be safer, lengthen the life of the battery, charge more quickly, hold the charge longer and create fewer disposal issues.

Soldier-portable batteries

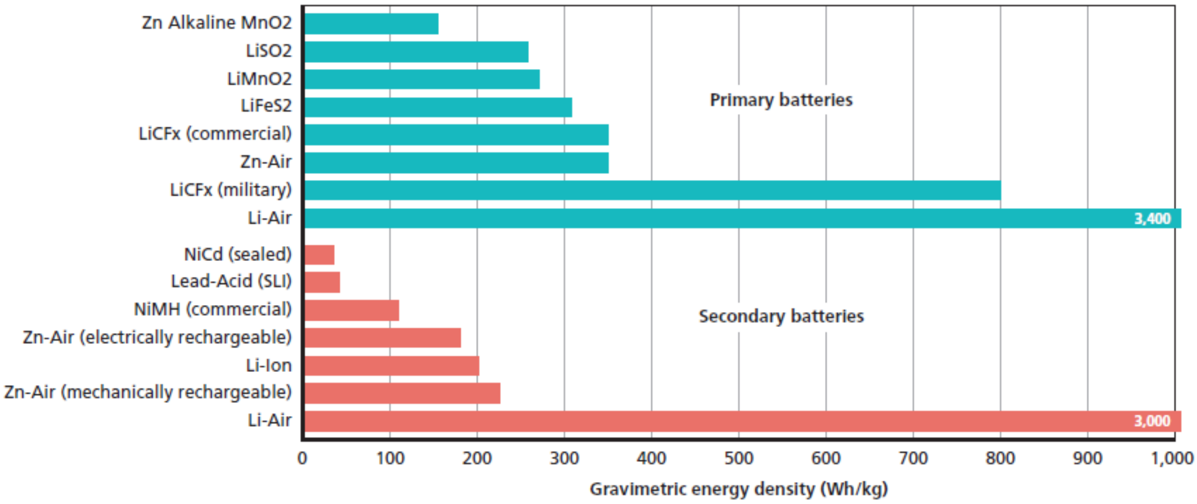
Modern warfare requires growing use of battery-powered equipment by soldiers (e.g. radios and weapons and their sighting systems) for overall effectiveness in the battlefield. For example, while a typical NATO dismounted soldier in 2004 consumed about 500 Wh during a 72-hour mission, today he needs twice as much to power his

[16] B. Sims and S. Crase, Review of battery technologies for military land vehicles, Department of Defence, Science and Technology, Australian government, 2017.

high-tech electronic equipment.[17] The performance request for soldier-portable batteries will increase even more in the future as digital technology advances, forced by the need for more efficient communication, the monitoring of military equipment and instant access to strategic information, e.g. through remote wireless devices. According to the USA Army, a platoon typically carries 700 pounds (318 kg) of batteries for a three-day mission, which is a battery weight per soldier of approximately 16 pounds (7 kg)[18,19], but a soldier may carry 10-30 pounds of batteries (4–13 kg) depending on their role in the platoon.[20]

Both primary and secondary batteries are currently used in soldier-portable applications. Primary batteries have several advantages over secondary ones, with similar chemistries in terms of lower unit costs and higher specific energy (Figure 3).

Figure 3 Comparison of gravimetric energy density for current and emerging battery cells



Source: Rand[21]

A higher gravimetric/volumetric energy density is highly desirable in batteries as the military makes great efforts to reduce the weight and volume that soldiers are required to carry. Safer battery chemistry is also needed for military systems, among other stringent specifications such as battery capacity, storability and stability.

Currently, many primary batteries used in soldier-portable applications are based on various lithium and nickel-based chemistries as well as air-breathing batteries. Lithium primary cells are lithium iron disulphide ($LiFeS_2$) and lithium sulphur dioxide ($LiSO_2$).

Lithium-ion rechargeable batteries have also been introduced into soldier-portable applications. They have several advantages such as higher specific energy and lower self-discharge rate in comparison with nickel-based chemistries (e.g. nickel-metal-hydride (NiMH) and nickel-cadmium (NiCd)). However, the NiMH batteries remain competitive with Li-ion technology in some applications.

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[17] Epsilor, Battery technology transforms the defence industry, August 2017. Available at: https://www.epsilor.com/sections/blog/Blog24082017/
[18] International Defence, Security and Technology, 'Powering the Future Global Soldiers with Wearable, Wireless, Energy Harvesting and Smart Energy Solutions', May 8, 2017.
[19] Institute for Defence Analyses, 'IDA Contributions to the Soldier and Small Unit Operational Energy Program', April 2018.
[20] Army Technology Interview with Head of Electrochemistry Branch of US Army Research Laboratory, 'Super cells: developing the next generation of soldier batteries', June 2014.
[21] Rand, Soldier-portable battery supply, 2014.

Lithium carbon monofluoride (LiCFx) and lithium-air (Li-air) represent two emerging chemistries for batteries, as they are both characterised by a very high specific energy density. While a primary LiCFx technology is already available, the Li-air one is still far from ready for commercial application, as scientists must first solve a series of problems relating to the battery chemistry.

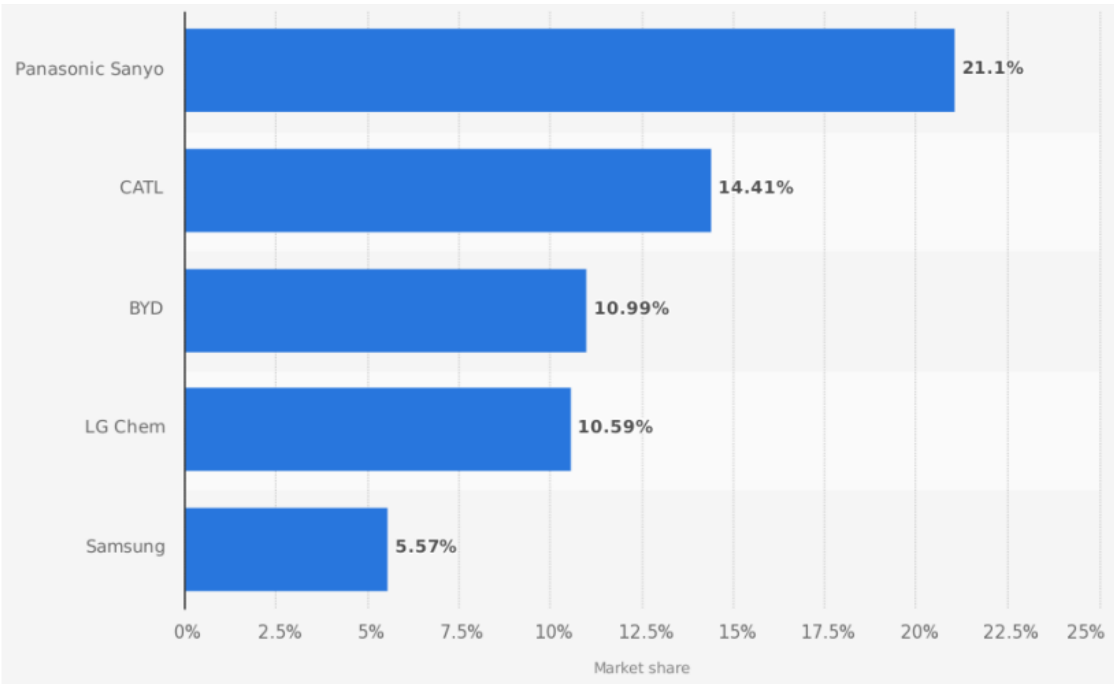
2.2 Battery technology development stage

Traditional lead-acid batteries have been in use by mechanised military forces since WWI, going through a major modernisation phase in the 1970s with the introduction of sealed lead-acid batteries. Today, there is a huge need for energy to power modern defence applications, such as: wearable computers, night-vision systems, video surveillance, software defined radios, mobile phones, satellite communication, lasers, acoustics, magnetic and seismic sensors, drones, land missiles and other types of electronic equipment.

Over the past 10 to 15 years, Li-ion battery technology has grown to become one of the major secondary battery technologies across a wide range of civil and defence applications. This is due to improvements in many aspects, including electrode materials and cell design. Li-ion batteries now dominate the consumer electronics market due to their ability to store large amounts of energy per unit weight and unit volume, and they will gain an increased use in both civil and defence sectors. We can therefore consider the lithium-ion battery as an emerging technology for dual-use applications.

In the first quarter of 2018, the top five lithium-ion battery manufacturing companies were dominated by five Asian players: Panasonic Sanyo (Japan), CATL (China), BYD (China), LG Chem (South Korea) and Samsung (South Korea) (Figure 4).

Figure 4 Global market share of lithium-ion battery makers, Q1 2018



Source: Statista[22]

There is a continuous drive to improve battery systems performance in civil and military electronics, allowing them to become more lightweight and reliable, while meeting safety

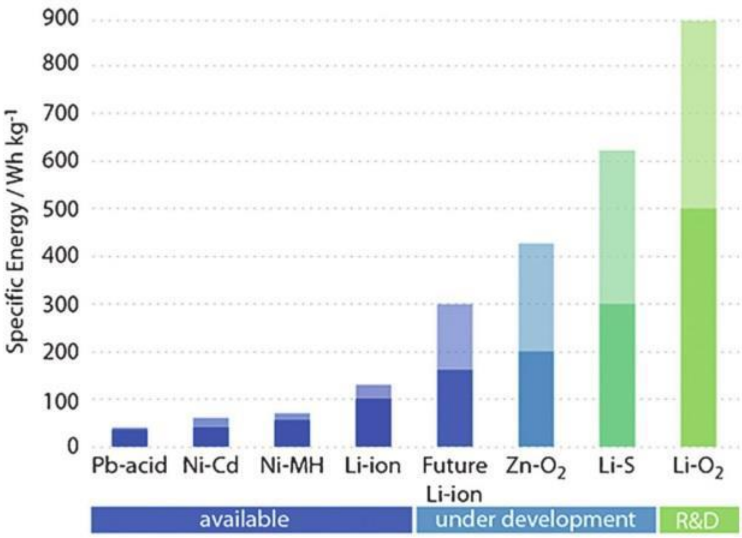
[22] https://www.statista.com/statistics/235323/lithium-batteries-top-manufacturers/

requirements. For example, supercapacitors could be used in parallel with a battery to increase its lifespan.

Incremental improvements have been made in recent years to lithium-ion batteries, in terms of gravimetric and volumetric energy density. Future research on batteries will focus on new anodes (lithium metal, silicon), new cathodes (with high voltage and high capacity) and closer packing (less electrolyte, thinner separators and thinner current collectors) in order to increase the specific energy while maintaining the high specific power capability. At the same time, safety becomes increasingly important: here, research focuses on fire-retarding electrolyte additives, ionic liquid electrolytes, the use of ceramic separators, ceramic coating of electrodes and solid-state batteries. Increasing safety however means trading off against specific energy and power. Such research also needs to address potential issues linked to materials supply, in particular for lithium and cobalt, used in some types of cathode. For example, by changing the cathode chemistry mix, using substitute materials such as nickel and/or aluminium, the overall proportion of cobalt in Li-ion batteries can be decreased.

Post-lithium-ion technologies, some lithium-metal types such as lithium-sulphur and lithium-air are expected to be the next generation batteries; today these technologies are still at research phase (Figure 5).

Figure 5 Current developments in lithium-ion batteries



Source: IDTechEx[12]

In the case of the lithium-sulphur battery, recent investigations have shown that a limited amount of change/discharge is possible. Although interest among manufacturers in this type of battery has diminished over recent years, it promises advantages for military applications such as a reduced weight burden on soldiers. Lithium-air technology may not reach the market until 2040, due to chemical problems yet to be resolved.

2.3 Materials used in Li-ion batteries

A lithium-ion battery is a complex chemical system made of scores of different materials that can potentially interact with each other to form new compounds. The most relevant materials used in a lithium-ion battery are presented in Table 3.

Table 3 Representative materials used in lithium-ion batteries

Material	Battery components			
	Anode	Electrolyte	Cathode	Other
Lithium		√	√	
Carbon (organic)		√		√
Carbon (graphite)	√			
Fluorine		√		
Aluminium			√	√
Silicon	√			
Phosphorus		√	√	
Titanium	√			
Manganese			√	
Cobalt			√	
Iron			√	
Nickel			√	
Copper				√
Tin	√			

2.4 Trends in Li-ion batteries

There is a continuous shift in civil and defence preferences towards secondary (rechargeable) batteries. While lithium-ion batteries are crucial for defence applications, their development and future uptake is primarily driven by civilian demand for portable electronic devices and most recently, electric vehicles.

In the defence sector, lithium-ion batteries have been widely used for over a decade in portable applications like tactical radios, thermal imagers and computing, and they will expand in the next five years to heavy-duty platforms such as military vehicles, boats, shelter applications, aircraft and missiles.

Table 4 shows the use of different types of battery in various applications, as well as future market trends: whether it is expected to grow, remain the same or decrease.

According to IDTechEx[12] estimations, the global lithium-ion battery market will increase about twelvefold in the next 10 years from 145 GWh in 2018 to 1700 GWh in 2028, or more than 30 % CAGR for this period.

Table 4 Battery technology adoption per market share

Segments	Sub-segments		Lead acid (PbA)	Nickel-cadmium (NiCd)	Nickel-Metal Hybrid (NiMH)	Lithium-ion (Li-ion)
Civil Electronics	Consumer electronics				Low →	High ↗
	Medical devices		High ↘			Low ↗
	Other				Low →	High ↗
Road transportation & Marine	Starters		High ↘			Low ↗
	Electric car				Low ↘	High ↗
	Electric bus		Medium ↘			High ↗
	Electric truck					High ↗
	Marine					High ↗
Railway & Aviation	Railway			High ↘		Low ↗
	Aviation			High ↘		Low ↗
Industrial stationary	Energy Storage Systems (ESS)	Utilities	High ↘	Low →		Medium ↗
		Industrial & Commercial	High ↘	Low →		Medium ↗
		Residential	High ↘			Medium ↗
	Stationary back-up power	Uninterruptible power supply (UPS)	High ↘			Low ↗
		Power continuity	High ↘	Low →		Low ↗
Motive industrial	Industrial vehicles		High ↘			Low ↗
Space & Defense	Space			Low ↘		High ↗
	Defense			Low ↘		High ↗

Relative technology adoption: High, Medium, Low, Marginal/Null. Trend: ↗ Growing → Stable ↘ Declining

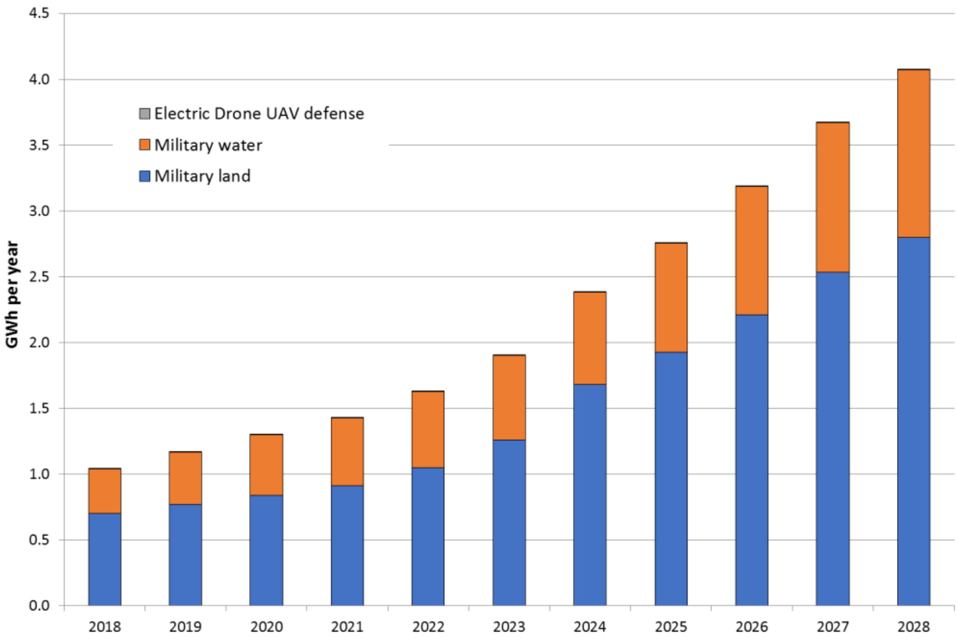
Source: Avicenne Energy[23]

In terms of markets to watch, passenger cars and electric buses will remain the largest. The battery market for consumer electronics will stagnate and/or decrease for a short while, before sales will pick up again due to new gadgets enabled by lower battery costs. The share of lithium-ion batteries on the stationary storage market will also increase by 2028, but this technology will compete with other chemistries like redox flow batteries. Safer, non-flammable battery alternatives will be the winners in this struggle for the future battery market.

Although defence applications today represent less than 1 % of total battery demand, this is expected to quadruple between 2018 and 2028. According to IDTechEx, the battery market for military land applications represents the largest fraction, followed by military water and electric drones applications (Figure 6).

[23] Avicenne Energy, The world rechargeable battery market 2016 – 2025, September 2017.

Figure 6 Global market size forecast for lithium-ion batteries in selected defence applications



Source: IDTechEx[12]

Future developments in lithium battery technology will mainly be driven by the civil sector. Particular military requirements like high reliability, and especially high safety, could require special development programmes.

2.5 Materials supply chain in batteries

The main challenges and bottlenecks of securing the raw materials for batteries in the EU were recently presented in a Commission report on raw materials for battery application.[24] By analysing the conditions needed to create a competitive and sustainable battery manufacturing industry in Europe, **the report identifies the need to strengthen all the steps along the battery value chain, starting from ensuring a sustainable supply of battery raw materials. In view of the large quantities of raw materials needed in the future – in particular, cobalt, lithium and graphite as a result of the exponential growth in battery demand – the supply chain of these materials is found to be vulnerable to disruption.** In this chapter, other segments of the battery value chain are analysed in response to concerns about security of supply for the civil, and where possible, defence industries.

2.5.1 Main steps of the battery supply chain

Although more complex, the materials supply chain for lithium-ion battery can be divided into five principal segments (Figure 7), starting with mining and processing of raw materials, through cell components and cell manufacturing, to assembly of the battery pack.

Figure 7 Overall Lithium-ion battery supply chain

Raw materials	Processed materials	Cell components	Cells	Battery pack
Basic input materials such as metal ores (e.g. nickel, lithium, graphite, cobalt, copper, manganese, aluminium). Mined and typically refined close to source of raw material.	Purified input materials and processed into powders ready for transformation into cell components. Purity of processed materials greatly influences cell performance and production yields (are considered Critical to Quality). Materials readily shipped.	Coated electrodes (cathode and anode), separators, electrolyte, packaging. Critical to Quality especially cathode which contributes to cell capacity and overall performance. Can be shipped but shelf life, contamination and environmental constrains apply.	Self-contained unit case comprising four main components: cathode, anode, separator and electrolyte. Highly automated packaging process, but format standard is an issue. Shipped as hazardous goods with shelf life and environmental constraints (cost).	Comprises multiple cells (assembled to modules), controls, thermal management and physical protection. Manufacturing in proximity to end-use application is highly desirable due to high shipping costs and hazardous goods requirements.

Source: JRC

However, due to difficulties obtaining separate data on cell and battery pack producers, a simplified supply chain for Li-ion cells is used for the analysis.

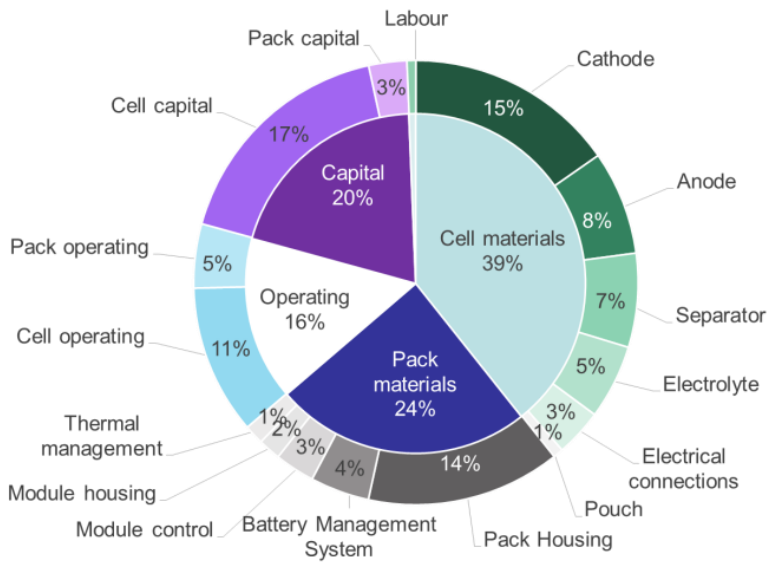
[24] European Commission, Staff Working Document, Report on raw materials for battery applications, SWD(2018) 245 final, Brussels, 17.5.2018.

Step 1: Raw materials in Li-ion cells

There are many minerals and raw materials needed for the manufacture of lithium-ion batteries. The most relevant are listed in Figure 7. In total, 13 raw materials are considered for this analysis. Five of these materials, namely Co, natural graphite, Si, F (fluorspar) and P are deemed critical in the 2017 CRM list.

Cost and access to raw materials are two important factors to be considered by a battery plant. Materials can account for 50 % to 70 % of the final cost of a cell, depending on its end-use application, making a significant impact on the battery company's profit.[25] An illustrative breakdown of a battery pack system as used in an electric vehicle is represented in Figure 8. In this case, the cell materials-related cost comprises four main categories: cathode active materials (15 %), anode (8 %), separator (7 %) and electrolyte (5 %). Another materials category is pack assembly, accounting for 14 % of the total battery cost.

Figure 8 Lithium-ion EV battery pack breakdown



Source: Bloomberg, 2018[26]

For defence applications, it can be assumed that special military requirements will result in a different pie chart. Pack materials and operating segments in particular will have higher values.

The four materials of concern in the production of Li-ion batteries are cobalt, lithium, graphite and, lately, nickel. Further details about the supply of these four materials are given below.

Cobalt

The first supply risk for cobalt is due to the fact that over 94 % of its production is generated as a by-product of copper and nickel extraction, making its supply dependent on copper and nickel demand. Its price and availability therefore fluctuate based on those of copper and nickel. In today's lithium-ion battery cells, cobalt is the most expensive raw material, and its price doubled in 2017.

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[25] C. Pillot, Avicenne Energy, The rechargeable battery market and main trends 2017-2025, June 2018.

[26] Bloomberg New Energy Finance, Long-term electric vehicle outlook 2018, May 2018.

Demand for cobalt is expected to rise sharply, especially with the market launch of electromobility, using lithium-ion batteries. It is therefore even more important to ensure a reliable supply. Military applications and prices will follow these developments. The most important future cobalt-containing technologies with high growth potential are lithium-ion cells and superalloys. Reduction of material costs and resources need to occur in parallel with the technology development. On the other hand it will also lead to enhancement of material performance, as the electrical conductivity and Li^+ diffusivity increase with more Ni content.[27]

The second risk to supply is linked to the geopolitical stability of the producing countries. Currently, 54 % of cobalt mine production happens in the Democratic Republic of Congo (DRC), which is associated with unstable political conditions and business challenges. Looking at the distribution of today's known world reserves for cobalt and lithium, it is clear that Australia could play a more significant role in future supply. Some manufacturers try to secure access to cobalt years ahead. In the long term, availability and sustainability will become increasingly important, as will the substitution of raw materials and the availability of alternative technologies.

At the moment, cobalt recycling does not appear to be feasible for balancing demand due to the 10-year battery life and other complicating factors. To avoid the danger of demand surpassing supply, additional capacity must be brought online.

Cobalt refineries are rarely located near source mine sites. Instead, major refiners purchase cobalt concentrate from various mines, ship to their own locations and refine it to a usable form for cathode production. With huge investment in this sector, the majority of cobalt refining now takes place in China.

Lithium

In 2016, almost 90 % of lithium was produced in Australia (43 %), Chile (33 %) and Argentina (13 %) combined, mostly from brine and spodumene sources. China is fourth on the list with 7 % of global production, requiring large imports of lithium to satisfy domestic demand for cathode production. According to the literature, lithium supply has the potential to expand with wide enough geographical distribution and new lithium sources to meet growing demand for the next 10 years. [28] The location of brine mining does not appear to drive manufacturing investments, and based on current lithium reserves, exploration projects and potential new refining capacity, lithium supply is not expected to be an issue for the battery supply chain in the short or medium term. However, shortages and price spikes are possible, as lithium production from brines (mainly Chile and Argentina) has a several year lead-time for ramp-up and is vulnerable to any rain in these generally dry, desert areas. Nevertheless, as car manufacturers ramp up plans for EVs, and products powered by rechargeable batteries gain popularity, lithium demand is expected to hit new highs. This means that manufacturers need to secure strong supplier relationships with lithium producers in the short term or brace for major price fluctuations.

Graphite

China currently supplies 86 % of natural graphite globally, with the iron and steel industry the main driver for its demand. About 10 % of natural graphite is used for anodes in battery applications. There is potential for increased production in Brazil, Africa and the USA as natural graphite is fairly easy to mine. [31] Although more expensive, synthetic graphite is a viable substitute. The supply of natural graphite is therefore not a cause for concern. There are also significant drivers for its substitution. Increasing energy densities on the cathode side require new active materials on the

[27] Fraunhofer ISI, Energiespeicher – Roadmap, update 2017. Available at: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/lib/Energiespeicher-Roadmap-Dezember-2017.pdf

[28] S. Jaffe, Vulnerable links in the lithium-ion battery supply chain, Joule, 1 (2017) 225-228.

anode side to allow for meaningful electrode balancing. **Its substitution is also likely to be driven by the demand for quick-charging capabilities, a property of particular military interest.**

Nickel

The global nickel market has traditionally been driven by stainless steel production, but the fast-growing rechargeable battery market is expected to boost the demand for nickel – high purity class 1 nickel in particular, because only this class is suitable for battery manufacture. As a result, the global nickel industry may enter a period of change due to the shift in end-use demand towards rechargeable batteries as the adoption of electric vehicles accelerates. A shortfall in class 1 nickel production is likely as current low nickel prices do not support class 1 nickel capacity expansions, and alternative strategies seem unlikely to provide long-term solutions. [29] **The future direction of cathode technology, for example shifting from cobalt- to more nickel-intensive lithium-ion batteries, alongside companies' willingness to restart class 1 production and the potential for increased class 1 nickel recycling, will greatly influence the potential shortfall in class 1 nickel supply.**

Other raw materials

According to Dougher and Johnson[30], there is little supply concern or impact to battery production from other raw materials such as copper (current collector), aluminium (current collector) and manganese (cathode), as well as other compounds such as polypropylene/polyethylene (separators) and fluorine, used for the production of lithium hexafluorophosphate – $LiPF_6$ (electrolyte), etc. They are common commodities with a relative low share in the battery end-market, making little impact on manufacturing decisions. If supply shortages of these materials were to occur, or their price were to increase, existing suppliers would be able to ramp up production and new suppliers could enter the market.

The introduction of alternative cathode materials (beyond cobalt) is also based on the premise that appropriate electrolytes will be available to meet life cycle challenges. Graphite will continue to be used in the foreseeable future as an anode material. The structural thickness will continue to be adapted to the maximum possible optimum. Composite materials made of silicon and graphite will become increasingly important and the proportion of silicon will increase continuously. The main advantage of silicon/graphite composites is the increase in both gravimetric and volumetric energy densities.

Step 2: Processed materials in Li-ion cells

The following processed materials are taken into account here: anode materials (processed natural graphite and artificial graphite) and cathode materials (NCA, NMC, LCO). Data on manufacturing companies are taken from Avicenne Energy. [25]

One of the big challenges regarding the second stage of the battery value chain – processed materials – is securing high quality products to be refined into battery-grade material. This condition is noted as critical to quality (CTQ) and it represents an area where intellectual property and trade confidences may confer competitive advantage beyond price. The CTQ elements are generally transferable across various end-use applications.

Processed materials are used to manufacture electrodes, which are key components of battery cells. Electrodes and cells are typically produced in the same facility due to the risk of contamination during transportation. However, drying processes for electrode materials have also been developed, allowing these products to be shipped effectively,

[29] McKinsey & Company, The future of nickel. A class act., November 2017.
[30] C. Dougher and T. L. Johnson, Breaking down the lithium-ion cell manufacturing supply chain in the US to identify key barriers to growth, April 2018.

serving global markets. Cathodes, anodes and separators can take the form of sheets, and are either wound or stacked to form alternating layers of cathode-separator-anode, with ions flowing between the cathode and anode sheets through an electrolyte solution.

Step 3: Components in Li-ion cells

Four main components are considered here, namely cathodes, anodes, electrolytes and separators. Data on the relevant manufacturing companies are taken from Bloomberg New Energy Finance database (data extracted in March 2019).

Step 4: Li-ion cells

In the next step, cathodes, anodes, separators and electrolytes are inserted into various container types (e.g. cylindrical, prismatic, pouch, etc.), forming battery cells. Cell production is responsible for integrating the majority of the processed materials and components upstream, and is a critical step in the supply chain as it requires a relevant workforce, high capital to build and operate and technical manufacturing knowledge. Generally, battery cells are customised specific to end-use applications. For example, since the battery cells for automotive applications are not yet standardised, they are specifically produced for the particular electric vehicles in which they will be installed. This approach mainly applies to buyers of large numbers of cells. Otherwise, the user either has to pay special prices or be satisfied with standard cell formats. **Since the cell characteristics for military applications are mostly different from those in civilian products, much higher price margins are to be expected.**

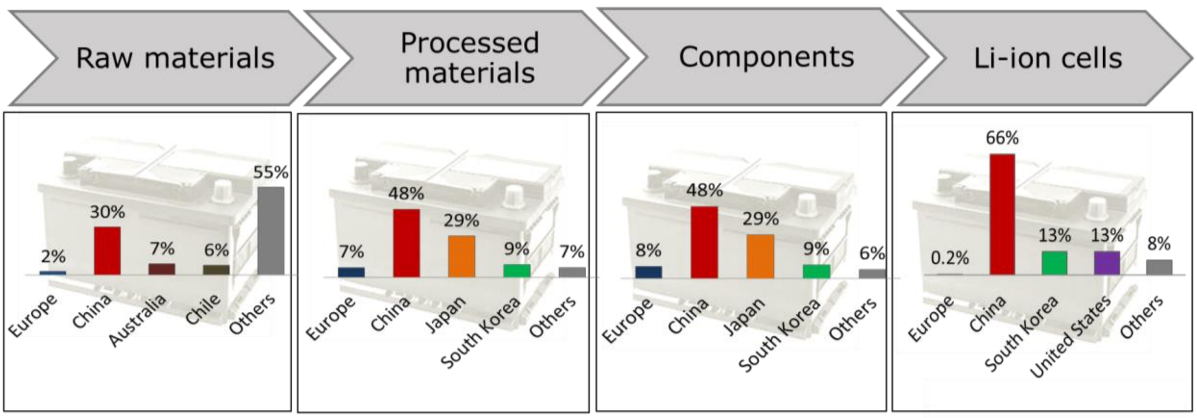
Battery cells, along with other components such as controlling systems, thermal management and physical protection, are finally assembled into a complete battery pack. Because battery packs are not cost-effective to ship, their manufacture is concentrated in the regions where they are employed.

Data on manufacturing companies for Li-ion cells are taken from the Bloomberg New Energy Finance database (data extracted in March 2019).

2.5.2 Key players and market share along the battery value chain

The key players along the Li-ion cells supply chain are shown in Figure 9.

Figure 9 Li-ion batteries: key players in the supply chain



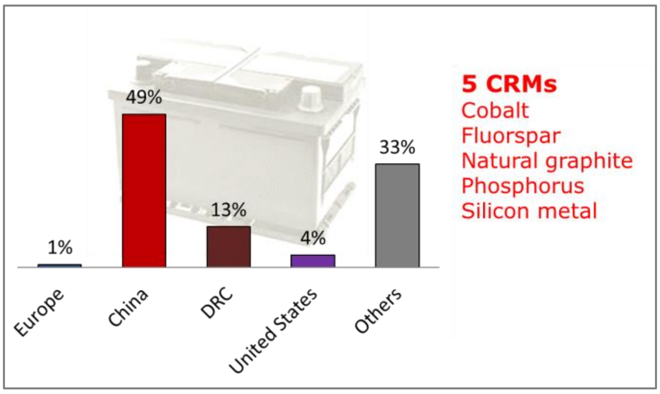
Source: JRC

China is the major supplier along the whole Li-ion cells supply chain – from raw materials to battery cells. The majority of production of processed materials and cell components – cathodes, anodes, electrolytes and separators – takes place in China, Japan and South Korea. This concentration of supply started in Asia in the 1990s, driven by the consumer electronics market. Supported by local governments, over time, these countries created a vertically integrated supply, from processed materials to pack production, leading to the regional supply chain advantages and cost benefits of today (e.g. by eliminating the cost of transportation). Japan and South Korea are other key suppliers of processed materials and components for Li-ion batteries. South Korea and USA are other key suppliers for the Li-ion batteries themselves.

The current European contribution to the global manufacture of cell components in lithium-ion battery is tiny (<1 %). There are no European companies producing anode materials. Around 9 % of global cathode materials (NCA, NMC, LCO) is produced by European companies. At component level, while European companies produce around 30 % of cathodes and 4 % of electrolyte, no production is known for anodes and separators.

With regard to the supply of critical raw materials, China is the major supplier of around half of CRMs for Li-ion batteries (Figure 10).

Figure 10 Supply of CRMs for Li-ion batteries: key players



Source: European Commission, 2017, Study on the review of the list of critical raw materials

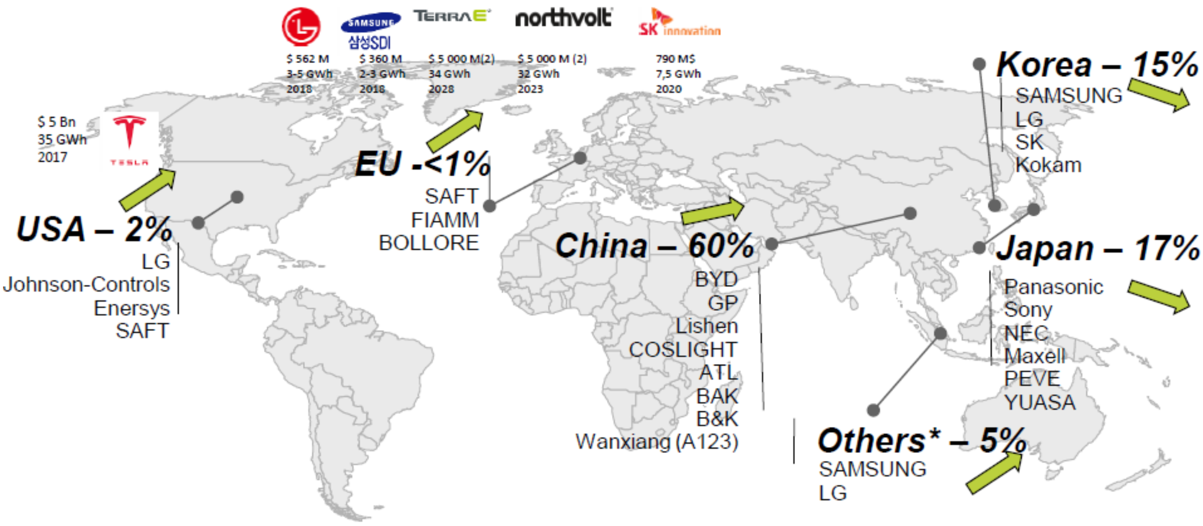
Raw and processed materials are currently produced and shipped to all international makers, while cell components and manufacturing are more regionally placed. Overall, Asia dominates lithium-ion battery cell production, with a robust upstream supply chain ranging from processed materials to complete cell manufacture.

Considering the fast adoption of electric vehicles and their need for lithium-ion batteries, the key question is whether or not there will be sufficient and timely supply of materials at reasonable prices to meet the anticipated increase in materials demand for such batteries. Among the raw materials required in lithium-ion battery manufacturing and based on expected material demand developments, some challenges in supply are associated with cobalt, lithium, graphite and nickel. [31,32]

Today, battery cells manufacturing serving all end-market applications is primarily located in Asia, with China and South Korea accounting for around 80 % of global production capacity (Figure 11). These countries also play host to a significant quantity of key battery-specific upstream components supply (e.g. electrodes, separators, electrolytes, etc.), constituting supply chain 'clusters' focused on lithium-ion battery production. The current know-how of lithium-ion battery production was developed primarily by companies serving the consumer electronics markets, creating robust supply chains and production experience over time.

[31] E.A. Olivetti, G. Ceder, G. G. Gaustad and X. Fu, Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical materials, Joule, 1 (2017) 229-243.
[32] McKinsey Energy Insights, Metal mining constraints on the electric mobility horizon, April 2018.

Figure 11 Key players in Lithium-ion battery cell production



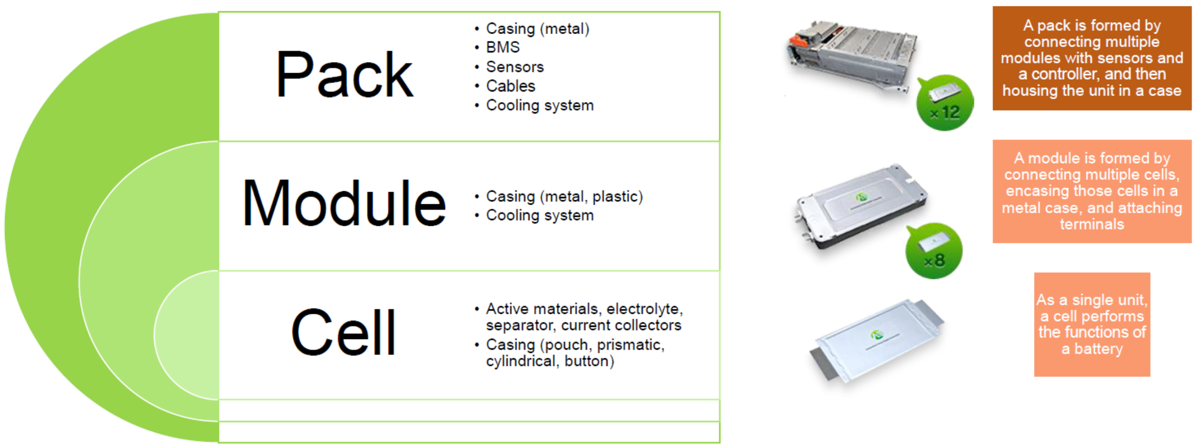
Source: Avicenne, 2018 [25]

While it is possible for new entrants to succeed, they are likely to face challenges in establishing cost-competitive, high-volume production due to the relatively high performance, safety and reliability requirements of end-use customers. The EU currently accounts for up to 0.2 % of global lithium-ion battery cell manufacturing. This production share is likely to increase, driven by the European strategic action plan [33] for batteries adopted in 2018, and other policy and industrial initiatives. Moreover, battery cell manufacturing faces additional changes, with Korean companies starting to move their production to Malaysia.

Battery pack

The final step in the battery value chain is the assembly of the battery pack, which is composed of modules and various control/protection systems, including a battery management system (BMS) and cooling system. A comparison between the battery cell, module and pack is represented in Figure 12.

Figure 12 Main differences between a battery cell, module and pack



Source: IDTech, 2018 [12]

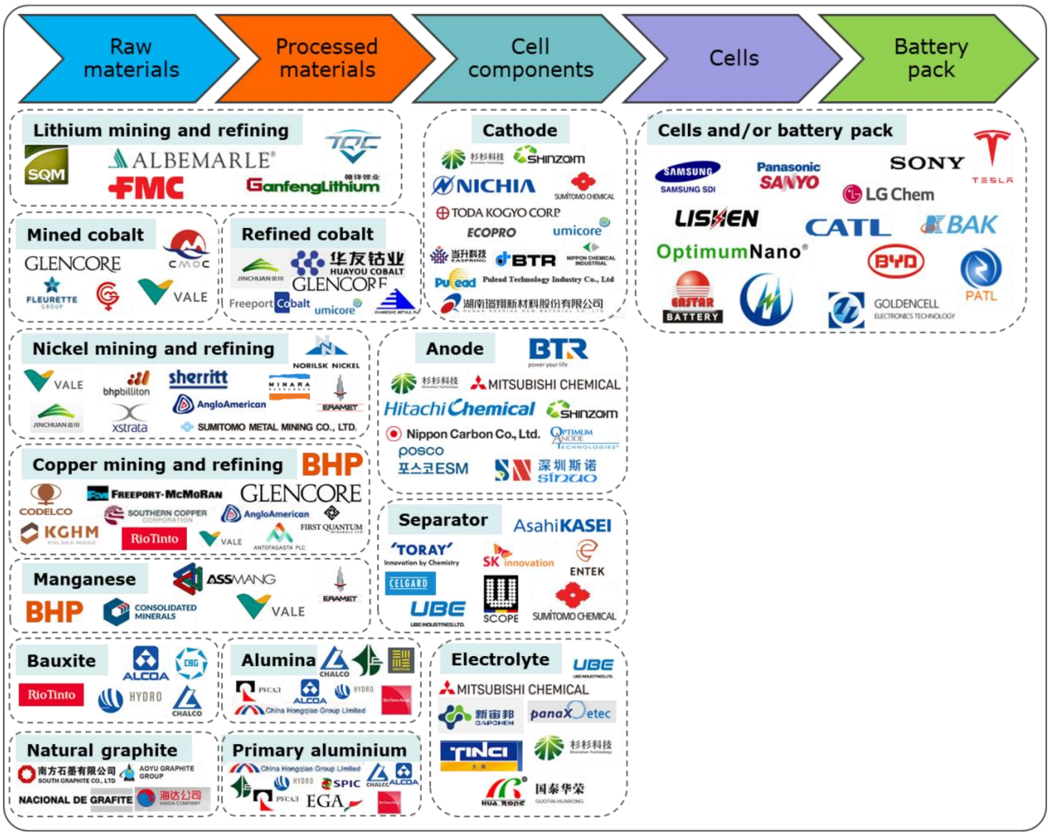
[33] European Commission, Europe on the move – Sustainable mobility for Europe: safe, commented and clean. Annex 2 – Strategic Action Plan on Batteries. COM(2018) 239.

While the development of battery cells is a crucial step along the value chain, industry players are moving towards battery packs/modules with more efficient design and structure. For example, the power source of electric cars is in the form of a pack, whose specifications are closely correlated with the overall design of the vehicle. To keep some control and profit margins, the majority of OEMs producing electric vehicles want to maintain their technological core competence around battery pack design and the battery management system, leading to fierce competition for better module/pack design, not to mention all their efforts to achieve a higher battery cell energy density. This competition has created new solutions and improved state-of-the-art pack technologies, for example installing cells directly into a pack without the need for modules. [34]

The specific conditions around the manufacture of lithium-ion batteries in different regions have led to different strategies by global OEMs. While Japanese and Chinese OEMs typically keep control of all value chain steps, the European OEMs, in the absence of a significant cell manufacturing capacity, are trying to keep their leadership in design and battery pack assembly.[35] Some companies such as Toyota, Bollore, Sony, Samsung and LG are totally integrated, manufacturing both the cell and the battery pack.

The key players in the global industrial battery market, along the supply chain, from raw materials mining to pack assembly, are summarised in Figure 13.

Figure 13 Key industrial players along the lithium-ion battery supply chain



Source: JRC

[34] Samsung SDI, Technology – the composition of EV batteries, 2018. Available at: http://www.samsungsdi.com/column/all/detail/54344.html
[35] N. Lebedeva, F. Di Persio and L. Boon-Brett, Lithium ion battery value chain and related opportunities for Europe, EUR 28534 EN, Publication Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-66948-4, doi:10.2760/6060, JRC105010.

2.5.3 Supply chain of civil versus military battery applications

Since the demand for lithium-ion batteries in civil end-use applications, especially consumer electronics is much higher than in the defence sector, their development and manufacture are currently driven by non-defence-related applications. As Asia is the region in which hand-held and portable electronic applications, and more recently electric cars, are mostly produced, it is also the primary location of battery components and cell manufacture. This applies to both civil and defence applications. As such, it is not surprising that many lithium-ion batteries for common military applications are currently assembled from commercial cells manufactured in Asia.

As with civil applications, defence battery supply chains begin with the raw materials used to produce battery components, and cover all other stages in cell manufacturing until assembly of the final military product. For military purposes, the battery often needs to maintain performance in combat conditions and more stringent environments. Battery characteristics, in terms of dimension, capability, storability, etc., need to be specifically designed to meet military specifications, especially for weapons or support systems. The first steps in the battery value chain, such as supply of raw materials, their processing, and electrode manufacture, are likely to be the same for both the civil and defence sectors. Since the battery has to be more resistant to physical damage and stable in extreme operating conditions specific to military operations (e.g. explosive decompression, submersion, thermal and mechanical shock, sand and dust storms), more emphasis is laid on pack design and assembly, including the controlling systems, electronics and thermal management.

According to a Rand study [21], the military manufacturing industry generally follows a dual-use acquisition strategy for battery cells, as they are produced with economies of scale, while still meeting high technical requirements such as high specific energy, storability, long operating life, reliability and safety. Without this dual-use approach, the defence industry might be forced to pay a much higher price for the development and manufacture of their own battery systems, especially for soldier-portable applications. This already happens for specialised military applications, including space-based systems, avionics and weapons.

By taking into account the ongoing shift in military preferences towards secondary rechargeable batteries and their increasing demand in the coming years, a secure supply chain is needed for rechargeable lithium-ion batteries in particular. There are three major concerns regarding the supply of lithium-ion batteries: 1) security and ability to meet unexpected increases in demand for battery cells; 2) the very high cost of establishing new manufacturing facilities for these cells outside Asia, and 3) the possible incompatibility of battery requirements in terms of safety and reliability for specialised military purposes with the commercial production of the component cells. [21]

The rechargeable batteries used in defence applications, in particular lithium-ion, are almost entirely assembled from processed materials and cell components manufactured outside the EU, especially in Asia. Defence ministries typically limit their risks by contracting with national battery-manufacturing integrators that understand their defence requirements. These companies procure cells from outside suppliers (primarily in Asia), integrate them into batteries together with procured supporting electronics, and provide the battery management system to manage the power needs of the military system for which the battery is designed. In the same way, defence ministries fund the development and production of defence-specific, application-specific integrated circuits by trusted suppliers to meet military specifications for sensitive high-performance military applications (e.g. electronic warfare systems).

Table 5 shows a list of some manufacturers of batteries for military applications. It is important to pay attention to the distinction between cell, module and battery. The listed companies are among the providers of rechargeable lithium-ion cells. It should also be noted that some of the companies buy cells or modules and then assemble them into modules or batteries.

Table 5 Example of manufacturers of lithium-ion batteries for military applications

Company	Country	Website
EU companies		
Diehl & Eagle Picher	Germany	www.eaglepicher.com www.diehl.com/eagle-picher/de/diehl-eagle-picher/products/battery-packs#lithium-ion
Saft	France	www.saftbatteries.com
Sunlight Systems SA	Greece	www.systems-sunlight.com
Lithium Werks BV	Netherlands	https://lithiumwerks.com
Non-EU companies		
Epsilor	Israel	www.epsilor.com
Mathews Associates Inc	USA	www.maifl.com
MIL Power Limited	United Kingdom	www.milpower.co.uk
Kokam	Korea	http://kokam.com/module-military/
Ultralife Batteries	USA	www.ultralifecorporation.com
EnerSys	USA	www.enersys.com
Bexel Corporation	South Korea	www.bexel.co.kr
Bren-Tronics	USA	www.bren-tronics.com

There are also providers who are repeatedly associated with rechargeable lithium-ion cells, or who have occasionally advertised. These include, for example, Epsilor from Israel [36] and Golden Season from Singapore. [37]

Behind the USA company, EnerSys, hide a large number of subcontractors who offer rechargeable lithium-ion cells under their own name. These include: Absl Power, Quallion LLC, PowerSafe, DataSafe, Hawker, Genesis, ODYSSEY, CYCLON, IRONCLAD, General Battery, Fiamm Motive Power, Uranio, Oldham and Express. The USA company, Valence, also offers military products. **It should be noted, however, that the number of lithium-ion cells supplied by non-Asian manufacturers is far behind that of Asian companies. This also means that increasing use of lithium-ion cells in military applications can lead to a critical dependence.**

Military procurement agencies look at what is technically feasible before developing a specification and will look at all available components/technologies, including Asian 'low-cost' components. Cost is a key issue. Military specifications are typically more demanding than civil needs and at the upper end of what can be achieved, but defence ministries are prepared to pay for the development and production of batteries that meet their needs within the affordability constraints set by their overall defence budgets. As such, low-cost materials, components, cells, modules or batteries will not find their way into military applications; defence applications will not rely on low-cost components, as the sector can afford higher prices. The nations (EDA and NATO) are currently working separately on specifications for each component of the value chain. This individual procedure arises from different national strategies and their implementation. However, each of the nations is aware that sooner or later, lithium-ion technology is finding its way into military use. Civil sector is the main driver for lithium-ion battery. The cell producer can be also the battery assembler as in the case of French company, Saft, a good example of integrated value chain production.

[36] www.epsilor.com
[37] www.goldenseason.com.sg

In addition, ‘low-cost’ materials, components, cells, modules and batteries show too much variation in quality, leading to frequent failure, which is unacceptable in military applications. Requirements for electrical power supply might prioritise as follows: 1) availability, 2) safety and 3) reliability.

Since the military typically needs a relatively small number of batteries compared with civil markets, **defence ministries have to invest in development and production to create a national supply source to meet their needs.** For example, the USA Bradley Armoured Fighting Vehicle uses lead-acid batteries that require users to open the cells and refill them with acid. For other applications, industry has moved away from liquid electrolytes to solid materials that are safer and perform better. The USA Defence Logistics Agency (DLA) is therefore investing in manufacturing capability for new lead-acid batteries for armoured vehicles (such as the Bradley Fighting Vehicle) that use absorbent glass-mats which do not require users to open cells and refill them with acid. These materials will be safer, lengthen the life of the battery, charge more quickly, hold the charge longer and cause fewer disposal issues. The USA Army challenge in upgrading these batteries was that large producers of lead-acid batteries were not interested in delivering small volumes that only meet a military specification, as this was not commercially viable. The DLA subsequently found a company producing environmentally friendly solid electrolyte batteries for the civil market (protected by patents), and contracted with them in 2018 to develop and produce military-specification prototypes for testing and qualification that are safer and more powerful than the current batteries. In another example, in 2015, the DLA supported a project to ramp up manufacture of an improved lithium carbon mono-fluoride battery that powers radios and other small electronics to reduce the number of batteries and weight carried by USA soldiers. The improved battery delivers a 110 % increase in energy capacity; a 30-50 % decrease in weight (depending on battery size); and an increased shelf life of 5 to 15 years. The DLA supported the two technology companies that developed the battery with funding for the cost of engineering, materials and testing to move from producing a few prototypes to producing hundreds of units in a fully functioning manufacturing line. [38]

In an analogous way, Intel is a good example of where USA government support was essential to help create a national supplier of semiconductor chips for defence and civil purposes. The USA government encourages and funds civil exploitation of defence technologies and vice-versa to reduce defence procurement costs.

Some defence ministries are concerned about security of supply of materials and components, and will most likely invest in national battery development and production, but will tend to rely on their own system suppliers to manage the risks associated with security of supply. System suppliers respond to defence ministry requirements. There is a need for coordination of potential research and investment in batteries for military applications at the European level. The oil and gas industry is similar, in that it has very specialised battery requirements (such as extremely long battery life in very difficult environments) but is prepared to invest in development and production of specialised batteries that meet industry needs.

For military users, whether industrial or defence ministries, long-term availability is a very high priority. Long-term availability extends in the military sense over several years to decades. **The increasing replacement of old, armoured accumulator technologies (nickel and lead) by lithium-ion technologies in the civilian sector is carefully analysed by military actors. However, the consequences of this technological change on the military sector are still unclear, notably in terms of strategic planning.**

Today’s defence material and weapons systems are all based on long-term availability. The respective ministries of defence regulate this through various approaches:

[38] Defence Logistics Agency Loglines, May-June 2016.

- ensuring logistical availability
- military stockpiling/stockholding
- interchangeability.

Due to simple storage technologies (lead and nickel), which do not require any special measures in terms of ensuring logistical availability, military stockpiling/stockholding and interchangeability, the military industry and ministries of defence have only shown superficial concern. Of course, the corresponding suppliers and components have been qualified and checked. However, these storage technologies have been considered and used as a distinct component. Technological developments have been minimal over the years, and even decades, so it was not necessary to develop a specialist competence in the field of storage technologies or to possess a qualification beyond what was necessary. The cells, modules and batteries used were taken from civil product lines and given a 'green coat'. In some cases, special components were used, but in 90 % of cases, they were civilian products. Only the shape of the modules and batteries has been adapted to meet military conditions or requirements. These circumstances did not require closer cooperation between the defence industry and cell manufacturers. Rather, they worked with assemblers, module or battery manufacturers. These in turn had closer contact with cell producers.

The development cycles of lithium-ion technology are currently very fast. The composition of cell components changes about every two years. Consequently, price developments and new materials or compositions follow this development process. This is not a problem for the civilian user as the majority of product cycles are between two and five years. If a product has reached the end of its life, a new one is purchased. For products with lithium-ion technology, this always means acquiring a new charger with a cell/module or battery management system adapted to the respective technology. In the automotive industry, product cycles are higher: up to around 10 years. However, the numbers of these civil applications, and the cells/modules or batteries installed in each case, go into the millions. Thus, a producer who uses lithium-ion technology can also make appropriate technological product-related specifications. Cell producers, module manufacturers and battery manufacturers work more closely with product developers and producers. Specific requirements are acknowledged and implemented.

The quantities of defence material or weapons systems of the respective producers are very small in comparison with civilian products. For military producers, this means that cooperation with cell manufacturers is virtually non-existent. Due to the foreseeable quantities, the willingness of the cell manufacturers to cooperate will be very low. This means that forays for logistical availability, military stockpiling/stockholding and interchangeability over years and decades cannot be perceived. Among other things, these pillars are based on defence and structural planning.

Moreover, developments in the defence industry have no direct impact on cell, module or battery manufacturers as the numbers are simply too low.

However, as the integration of lithium-ion technology into military applications increases, there is still no significant manufacturer in Europe. This means that there is no direct access to a supply chain within Europe. In times of crisis there is no guarantee of logistical availability, military storage or interchangeability.

A comparison with the automotive industry shows that this industry often enters into cooperation agreements with producers from Asia. According to an analysis by the Industrial Economics & Knowledge Center (IEK) and Industrial Technology Research

Institute (ITRI)[39], large growth rates in production capacity are expected to be realised by Chinese companies in the coming years (Table 6).

Table 6 Expected increasing of production capacity for lithium-ion cells in the short term

Company	Production capacity (GWh/year)	
	2017	Planning
CATL	18	50 (@2020)
BYD	16	26 (@2019)
Optimum	20.4	28 (@2018)
GXGK	10	20 (@2020)
BAK	8	15 (@2020)

For civil transport, there are several government initiatives across Europe to help industry develop electric vehicle battery technology. For example, in 2017, the UK Government launched the Faraday Challenge programme (GBP 246 million over four years) on battery development for the automotive electrification market comprising:

- A new 'application-inspired' research programme coordinated at national scale
- An innovation programme to support collaborative research and development which involves co-investment from industry
- A scale-up programme to allow companies of all sizes to move new battery technologies to market rapidly, delivered through an open access facility with technology scale-up capabilities to ensure that solutions are ready for manufacturing technologies at high volume.

The issue of creating manufacturing capability by enabling EU companies to scale up production is key for battery and fuel cell technologies, as in other emerging technology areas. For example, Europe is a leader in smart systems integration research and development, but many barriers hamper entry into the market by SMEs and other innovators with new ideas that could become important products, in applications such as healthcare and the internet of things. An EU study conducted for DG/CONNECT[40] identified barriers inhibiting pull-through into manufacturing of smart integrated systems in Europe that have similarities to those for batteries and fuel cells (access to technical infrastructure for prototyping, skills, etc.) and proposed measures to help build scalable innovation models leading to production (such as combining SME support measures for scale-up and manufacturing).

Defence industry R&D battery investment is quite limited since the military need for relatively small battery numbers specific to their requirements is not a major market driver: company R&D investment will be based on potential revenues from various civil applications. This is why defence ministries usually need to invest in battery development to acquire systems that meet their needs.

However, it is important to differentiate between cell manufacturers and companies that use cells in modules and batteries and then offer them to the military industry. **Cell manufacturers are unlikely to respond to the specific needs of the military**

[39] Lu Hsueh-lung, Future Development of the Asian Electric Vehicle Battery Market and Related Technologies-Chinese Situation, presented at the conference "Advanced Battery", Münster (Germany) 2018.

[40] Final Report for DG/ CONNECT, Smart Systems Integration & Smart Objects: How to Enable a 'Fast Track to Manufacturing' in Europe, November 2016.

industry. This is attributed to the small numbers of cells required by the military industry. Only smaller manufacturers will listen to and examine the industry's R&D needs with a guaranteed acceptance of their products. The situation is different with assemblers, which usually take larger amounts of individual cells and can therefore exert greater pressure on the cell manufacturers. **These companies are already starting to develop new battery concepts, but the number of those offering products for the military market is very low. This means that bottlenecks can also occur due to the transition from one battery technology to another.**

The defence industry is therefore not investing in the development of battery cells. This is also due to the fact that there are still only small quantities installed in their systems. In the future, however, this situation will change dramatically.

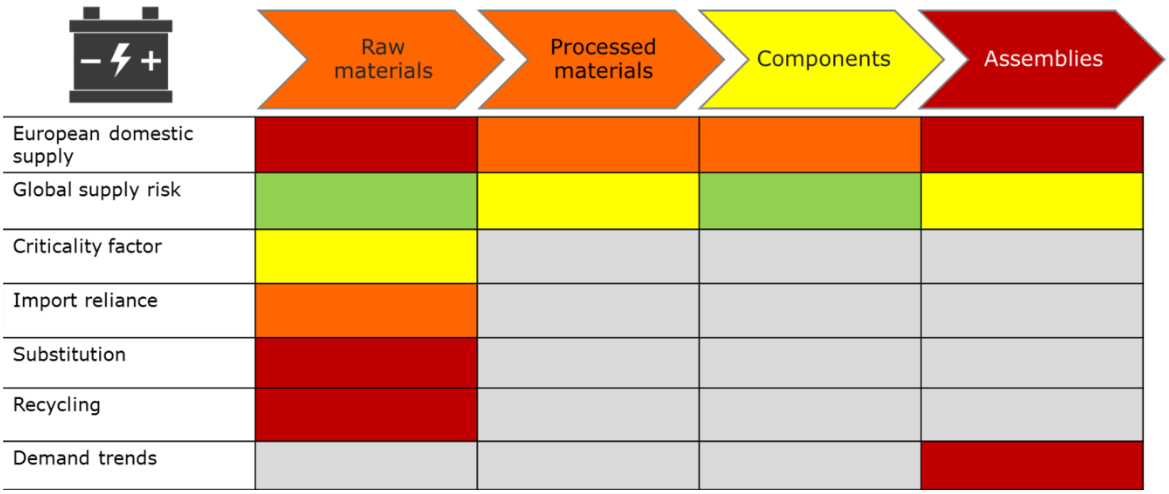
In order to make itself independent of cell manufacturers and assemblers, it is strongly recommended that the military industry build extensive know-how in the field of electrical energy storage and conversion in electrochemical cells and fuel cells. It is therefore of strategic importance that future European defence/security funding programmes include electrochemical energy storage and conversion as mandatory research components, and foster cooperation among research organisations and the defence industry to promote knowledge in this field.

A look across the Atlantic shows that the USA is making significant financial efforts to develop lithium-ion technology for military purposes. There are also many programmes on military fuel cells.

2.5.4 Overview of the supply risks for the Li-ion batteries supply chain

An overview of the various supply risks (issues) and bottlenecks for Li-ion batteries are visualised in Figure 14. **Very high supply risk is observed for the last step of the supply chain – Li ion cells production**. **High risk of bottlenecks is detected also for the supply of raw and processed materials, while medium risk is estimated for the supply of components.**

Figure 14 Overview of supply risks and bottlenecks in the supply chain of Li-ion cells/ batteries



Source: JRC

2.6 Opportunities for research and policy actions for batteries

2.6.1 Research opportunities

Lithium-ion batteries will most likely dominate the civil and military markets in the years to come. As battery developments and associated dependencies (resources, production capacities and application scenarios) will change dramatically, it would be useful to update this report every two years, particularly with regard to electrochemical energy storage and conversion.

The current know-how of lithium-ion battery production was developed primarily by civil companies serving especially consumer electronics markets, creating over time geographically located robust supply chains and production experience. In order to position itself independently of the cell manufacturers and battery assemblers, the military industry needs also to build-up a sound knowledge of the advances in cells and chemistries, as well as corresponding development paths for the cathode and anode and the resulting requirements for the electrolyte.

Several 'dual use' research topics can be identified from the performed analysis.

Various roadmaps show that the development of high-energy systems will rely on higher nickel usages in the coming years. In addition to the technological advantages of realising batteries with high energy densities, benefits include **conservation and more efficient usage of material resources.** Further research is needed to reduce the amount of critical materials (such as cobalt) in lithium-ion cells. The question of **substitution of critical materials in emerging technologies** also merits further funding. The potential consequences of substituting one material with another (e.g. cobalt with nickel) should be carefully examined in order not to create a bottleneck elsewhere.

European research approaches in the fields of energy storage and batteries are important to pursue. However, the **development of alternative cathode and anode materials** also requires efforts in the field of electrolytes. Today, there are no **long-term stable electrolytes** for some materials.

In the future, transition metal oxides (MnxOy, NiO, FexOy, CuO, Cu2O, MoO2 etc.) might represent a valid **alternative to cathode materials** in Li-based batteries. Manganese and iron are of particular interest from the perspective of resource availability. Technologically, however, developments are not yet advanced. **Specific problems include volume changes, high potential differences and the resulting stability of the cycles and their number**, all representing topics for future research. If the transition from research into concrete applications is successful, the recovery of materials from batteries (via batteries recycling) would be an advantage, e.g. currently graphite is not recovered but used instead as an energy source.

There is already an ongoing effort at industrial level to substitute the carbon anode with an anode composed largely of silicon (Si/C composite) in order to increase the energy density of a battery and prolong its life. This could be of particular interest for military applications. However, suitable electrolytes must still be developed. Material bottlenecks with the use of silicon are not expected. Although silicon anodes are generally viewed as the next development in lithium-ion battery technology, further research is required to understand and quantify the silicon expansion in batteries which can cause battery malfunctioning.

In the long term, **Li metal** is an ideal anode for replacing the carbon-based anode in state-of-the-art Li-ion batteries. It is also widely used in Li-S and Li-air batteries. Challenges to be addressed in future research activities include **safety concerns** and short cycle life, but such problems are likely to be solved with solid electrolytes or special liquid electrolytes with additives.

Substitution opportunities exist not only at materials level but also at technology level. Supercapacitors or ultracapacitors offer an **alternative power source** which can replace Li-ion batteries and revolutionise how energy is stored. Graphene is often suggested as a replacement for activated carbon in supercapacitors. [41] Other long-term alternatives are graphene-based batteries and hybrid materials (e.g. hybrid of vanadium oxide and graphene). [42]

Considerable **research is necessary in the field of electrolytes** for the practical implementation of next generation cathodes and anodes. None of these new research approaches will result in bottlenecks in resources. **Solid electrolytes** will play an important role, improving ionic conductivity and diffusion in solid polymers up to the level of a liquid electrolyte. Work is also underway to produce composite electrolytes using ceramic or metal-organic nanoparticles. Another possibility is the development of fully ceramic electrolytes and **solid state batteries** that do not contain liquid electrolyte.

The integration of lithium-ion battery technology into vehicles, aircraft, ships, weapons etc., should also be considered in future research opportunities, especially in the field of military applications. Keywords at this point are **thermal management under various operating and storage conditions, safe determination of capacity** and **aging state or electromagnetic compatibility**.

With regards to specific **'defence' related research needs**, several research opportunities have been identified. **Research on system management** should be considered to address specific military requirements such as thermal management, electromagnetic compatibility and safety of the battery. This will facilitate the integration of advanced Li-ion batteries in vehicles, aircraft, ships, weapons applications meeting the military needs. System management is performed directly by the military manufacturer or by the battery assembler. Hence having battery assemblers in Europe will help responding to the specific military needs especially in times of crisis and will contribute to the development of European battery power systems able to meet the defence industry needs.

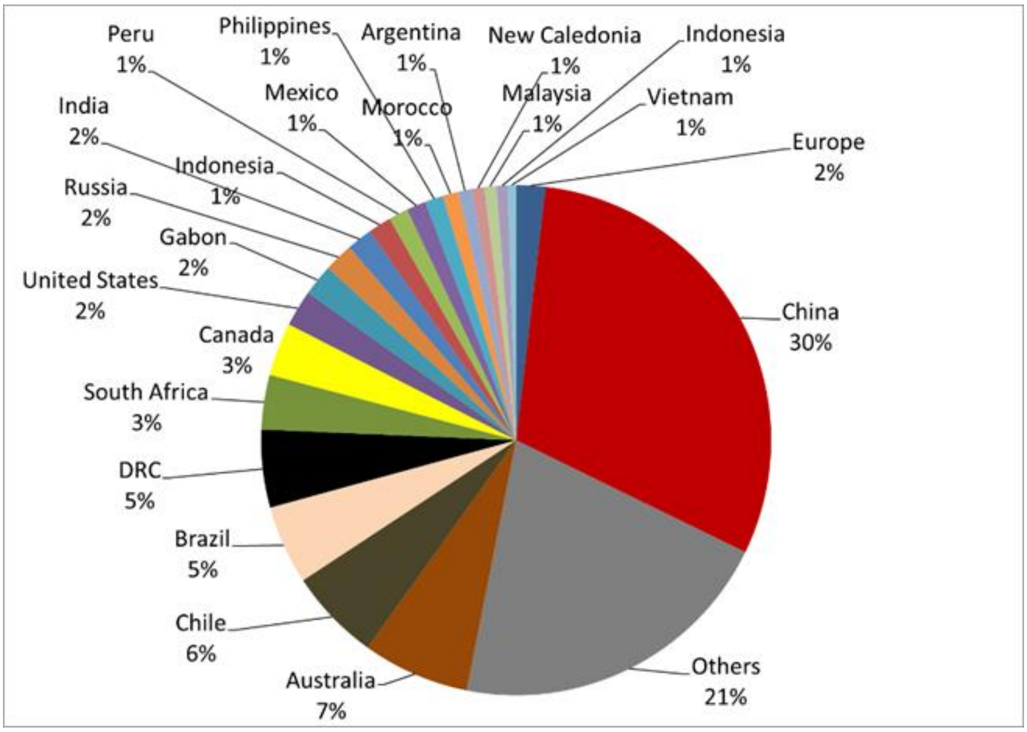
Research on lithium-ion batteries with **lithium iron phosphate** as the cathode material and **lithium titanate** replacing the graphite in the anode to improve the specific energy and reduce discharging and costs. These battery types [43] are of interest to the **naval and land defence sectors**, **especially for military vehicle applications in relation to providing 'silent watch' conditions.**

2.6.2 Opportunities for policy actions

Two main policy actions could be identified as potential mitigation measures at the level of raw materials, namely **diversifying the supply** and **boosting recycling activities in Europe**. More than 50 % of the raw materials used in Li-ion batteries for civil and defence applications are supplied from various smaller suppliers which gives opportunity for supply diversification. Securing trade agreements with such suppliers could be way out in case of crisis or war, leading to potential supply interruptions. The overall suppliers of raw materials for Li-ion batteries are shown in Figure 15.

[41] https://www.wired.co.uk/article/graphene-batteries-supercapacitors
[42] https://www.graphene-info.com/graphene-batteries
[43] Although lithium iron phosphate and lithium titanate batteries are commercially produced, they are normally not utilised for powering vehicles. They are anyhow attractive solution to be used in military vehicle to assure silent watch of the vehicles but further integration work needs to be done.

Figure 15 Raw materials suppliers for Li-ion batteries: overview



Source: European Commission, 2017, Study on the review of the list of critical raw materials

Access to the central raw materials for lithium-ion cells must be secured. **Effective recycling strategies must be developed with urgency** to serve the civil sector. Boosting recycling of lithium-ion batteries in Europe is seen as no regret solution allowing **key materials such as cobalt, lithium, manganese and nickel** to be recovered and reused in the production of new batteries. **Recycling of military batteries** inside the EU or reuse in stationary energy storage applications needs also to be encouraged. It is important for **Europe** to have **its own recycling companies,** capable of processing special military batteries too.

The recycling of Li-ion batteries still faces several challenges. The volume of material available for recycling is limited due to poor collection systems for portable batteries and their reuse as utility-scale storage. Specifying the critical materials to be recovered from batteries is an important aspect which is not currently fully accomplished. European battery recyclers point to low collection rates and the lack of recovery targets for specific materials. The 'recycling-unfriendly' design of some batteries and a lack of knowledge of the materials present inside are other issues which lead to inefficiencies and safety issues. Another challenge is that reducing the amount or presence of 'expensive' materials in batteries also reduces the economic incentive for recyclers.

Although recycled battery minerals such as lithium, cobalt, nickel and manganese can already be found in new batteries today, the amounts are minuscule (especially for lithium) when compared with the current raw materials demand for batteries. [44] It is expected that more than 66 % of the lithium-ion batteries will be recycled in China by 2025, feeding the country's fast-growing battery material industry. [45,46] The proportion

[44] https://waste-management-world.com/a/in-depth-lithium-battery-recycling-the-clean-energy-clean-up

[45] https://blogs.anl.gov/wp-content/uploads/sites/41/2014/10/Li_Challenges-and-Opportunities-of-Recycling-Spent-Lithium-ion-Batteries.pdf

will be even larger (76 %) for the important cobalt-containing batteries without taking production scrap or other sources into account. **By the time there is enough volume for recycling in Europe and North America, the Chinese recycling industry is expected to have a strong competitive advantage through proven technology and available capacity.**

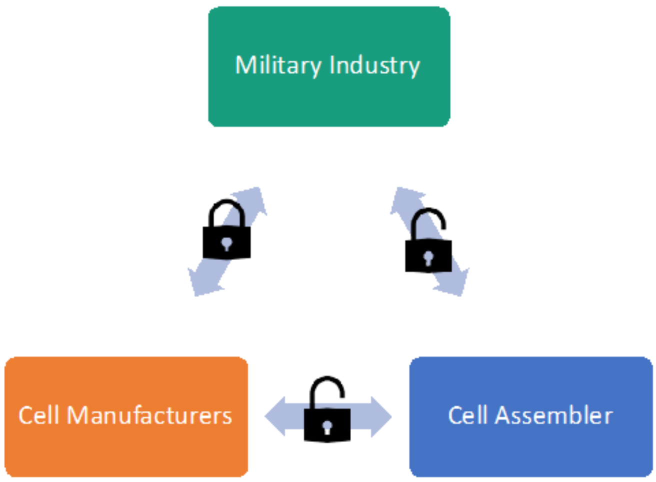
This civil market is flanked by the equally increasing **integration of the technology into military applications.** In the case of military application, the following issues are critical:

- security of technology (in use under diverse military applications);
- consistent quality;
- long-term security of supply;
- the highest possible energy densities.

The situation related to the supply of lithium-ion cells for military use is much more complex than for civil use. On the one hand, military users cannot exert direct pressure on cell manufacturers to ensure that their requirements are taken into account, due to relatively low demand. Experts agree that the only way to influence cell manufacturers is via the battery assemblers, who procure large amounts of cells and therefore have the negotiating power to convey such requirements. On the other hand, the military industry must be able to adopt and convert technologies regardless of the offerings of cell manufacturers or assemblers. Most importantly, the military industry must be able to **formulate guidelines for future developments,** in particular for applications not found in the civil world, such as in the field of military drones.

Figure 16 illustrates a relationship triangle showing the link between the military industry and cell manufacturers from the civil market, which comes through the cell assemblers. The lack of direct access for the defence industry to cell manufacturers makes it even more important for Europe to build up its own cell production capacities. Therefore, **establishing of European production capacities of Li-ion batteries across the entire supply chain** with complete electronics and packaging suitable for both civil and military applications is a potential policy action.

Figure 16 Procurement pathway of Li-ion batteries for the defence sector



Source: JRC, private communication with experts

[46] https://circularenergystorage.com/news/2017/11/30/press-release-recycled-lithium-to-reach-9-percent-of-total-lithium-battery-supply-in-2025

More opportunities can appear via **targeted innovation funding programmes and cooperation, involving co-investment also from military industry** and leading to the implementation of **special military requirements for lithium-ion cells.**

Another way to implement military requirements lies in the **further development of battery systems,** including, for example, electronic control as part of the management system. Such developments (including geometric dimensions and integration possibilities of the cells in modules/batteries; heat development and the need for thermal management; and the safety of the cells) can be done by the assembler or the military manufacturer. It is therefore important in the **framework of possible European funding programmes** to integrate the 'system aspect'. Creating targeted funding programs and cooperation between companies for initiating and scaling-up production of lithium-ion cells addressing specific military requirements is therefore another possible policy action.

Scale-up actions that provide **open access support to companies,** including SMEs, to take battery technologies through to high manufacturing readiness can play an important role in developing new battery products. For example, the USA DLA Battery Network (BATTNET) programme is developing and scaling up important new defence battery manufacturing capabilities which also have civil potential, and there are good European examples (e.g. the UK Faraday initiative).

To conclude, innovation in cell chemistries, formats, manufacturing technologies and processes in terms of technical, safety and sustainability performance can help to reinforce a competitive battery manufacturing industry in the EU. Supply of the necessary raw materials should be secured in parallel with effective recycling and potential substitution of the critical materials.

2.7 Li-ion batteries: summary

Li-ion battery technology has grown in recent years, becoming an emerging technology across a wide range of civil and defence applications. Demand for lithium-ion batteries for various applications is expected to skyrocket (>30 %) in the next 10 years. This is mainly due to the increasing introduction of electric vehicles (EV), mobile electrical appliances (3C) and stationary decentralised energy storage systems (ESS). Although defence applications represent less than 1 % of total battery demand, the lithium-ion battery is the technology of choice for many military applications. The challenges of securing the raw materials for Li-ion batteries along the supply chain in the European civil sector are becoming more evident, and the Commission is already acting to implement its strategic action plan on batteries.

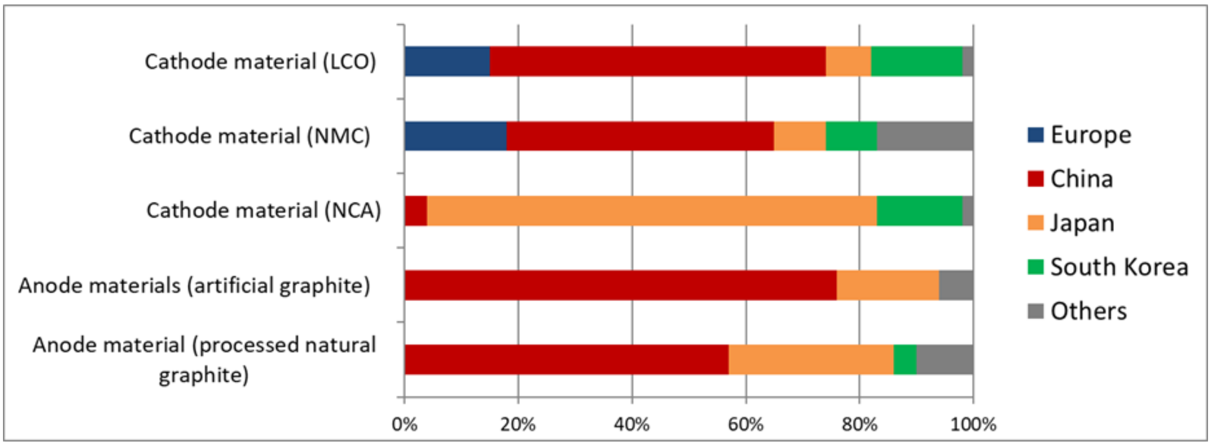
Various estimates suggest that the civilian industry in **Europe requires up to 30 % of cells produced world-wide**. This means that **cell production capacity needs to be built up in Europe to make it independent of the Asian market.** Analysis of the civil market shows that the **necessary quantities in Europe cannot be serviced in the coming years even by combining the capacities of Asian and European cell manufacturers**.

In total, 13 raw materials and five processed materials relevant to Li-ion batteries have been identified and selected for further supply chain analysis. Europe is fully dependent on the supply of 11 raw materials. Five materials, namely Co, C (natural graphite), Si, F, and P, are flagged as critical in the 2017 CRM list. China is delivering one third of the raw materials required in Li-ion batteries and is the major supplier of 8 out of the 13 raw materials selected as relevant for Li-ion batteries in this study. The rest is supplied by Australia (7 %), Chile (6 %) and numerous smaller suppliers, providing together more than 50 % of the required raw materials for batteries. This gives a good margin for raw materials supply diversification. Europe makes a marginal contribution of 2 % to the global supply of raw materials for batteries.

Asia dominates lithium-ion batteries cell production with a robust upstream supply chain ranging from processed materials to complete cell manufacture. Asia, represented by China, Japan and South Korea, delivers 86 % of the processed materials and components for Li-ion batteries globally. In particular, China leads the supply of processed materials (48 %) and components (48 %) for batteries, followed by Japan and South Korea. In the short term, a large increase in production capacity for Li-ion cells is expected to be realised by Chinese companies, which will guarantee the country's dominance of the battery market in the near future. It is also expected that global OEMs, cell manufacturers and suppliers will compete with each other to secure their battery supply chains and access to the five essential battery raw materials – lithium, cobalt, nickel, graphite and manganese.

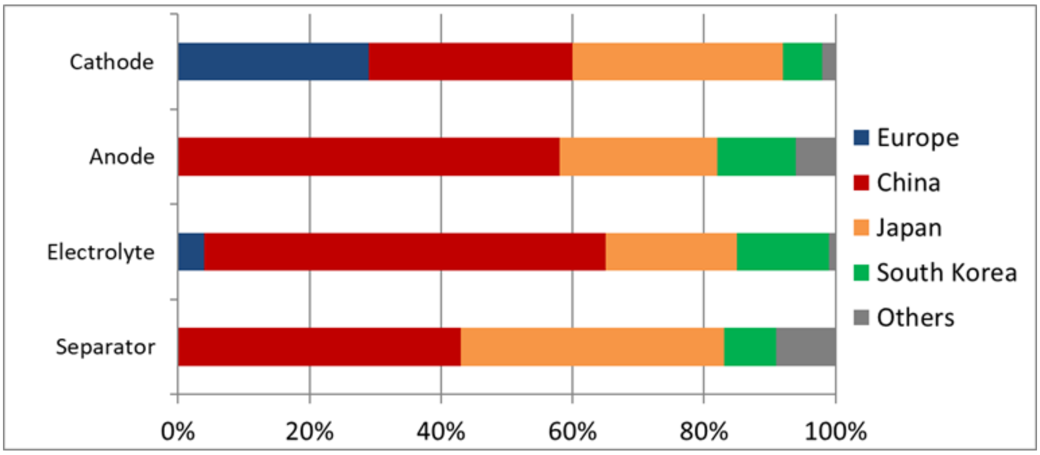
Europe has a relatively small share of the supply of processed materials and components: 7-8 %. Other countries deliver only 6-7 %, offering very little margin for supply diversification. In particular, **Europe is fully dependent on the supply of processed natural graphite, artificial graphite, NCA cathode material, anodes and separators** (Figure 17 and Figure 18).

Figure 17 Country production shares of processed materials relevant to Li-ion batteries



Source: BNEF, 2019. Bloomberg New Energy Finance, Battery Manufacturing database, retrieved March 2019.

Figure 18 Country production shares of components relevant to Li-ion batteries



Source: BNEF, 2019. Bloomberg New Energy Finance, Battery Manufacturing database, retrieved March 2019.

China is definitely the major player in manufacturing Li-ion cells at 66 % of global production. Other suppliers are South Korea and the USA, with 13 % each. Europe has a very marginal production of 0.2 % of Li-ion cells. Other suppliers produce around 8 % of global supply; leaving the margin for supply diversification limited here too. However, using the location of company headquarters for data analysis has its limitations; if the geographical location of the companies is considered, Europe would be shown to supply around 5 % of Li-ion cells globally.

In summary, Europe is almost fully dependent on imports of both battery cells and their constituting raw and processed materials, exposing the industry to supply uncertainties and potential high costs. The study has found that the vast majority of lithium-ion batteries for defence applications are assembled from commercial cells manufactured largely in Asia, meaning that in times of crisis there is no guarantee of logistical availability, military storage or interchangeability.

The performed bottleneck assessment shows potential **very high supply risk for the last step of the supply chain – Li ion cells production**. **High risk of bottlenecks is detected also for the supply of raw and processed materials, while medium risk is estimated for the supply of components.**

3 Fuel cells and hydrogen storage and production technologies

3.1 Description of fuel cell and hydrogen technology and relevance to civil and defence sectors

Despite significant progress over the last 20 years, fuel cells and hydrogen systems still face major challenges in terms of facilitating their market breakthrough in applications such as stationary power, portable power and transportation. In the medium term and, mainly, in the long term, fuel cells and hydrogen are expected to offer a high potential energy option, contributing significantly to a sustainable and secure energy supply system. The great opportunity for fuel cells issues from the fact that this technology connects two basic future energy carriers: electricity and hydrogen.

Fuel cells (FCs) are electrochemical devices which convert chemical energy into electrical energy. They use external sources of fuel such as hydrogen to produce energy. Hydrogen reacts with oxygen in the fuel cells to form water and release electrons which flow through the external circuit producing an electric current. Most fuel cells are based on a standard design in which two electrodes are separated by an ion-conducting electrolyte.

Fuel cells are compact, lightweight, highly efficient devices capable of producing clean, reliable electricity from hydrogen (or other fuels) on site and can be used in a variety of ways. **A fuel cell requires less maintenance and zero lubricants; increases endurance; ensures high specific energy and power density beyond the capacity of conventional battery power; and reduces sound and thermal signatures.**

A single fuel cell consists of a membrane electrode assembly (MEA) the main component and two flow-field plates. Just like batteries, individual cells are stacked to achieve a higher voltage and power. This assembly of cells is called a fuel cell stack, or just a stack. A stack is finished with end plates and connections for ease of further use.

Several fuel cell types have been developed so far, capable of operating under different conditions and therefore usable in different applications (given in Table 7[47]).

PEMFC technology is the most popular type of fuel cell with regard to unit production and shipment. It finds applications in automotive, telecommunications, forklifts, primary systems, data centres, and backup power systems. Based on its higher power density compared with other fuel cells, a PEM fuel cell offers the advantages of low weight and volume, making it suitable for example in the automotive fuel cell market for both passenger and commercial vehicles. The heart of a PEM fuel cell is the membrane electrode assembly (MEA), which includes five basic components: membrane, anode catalyst layer, cathode catalyst layer and two gas diffusion layers (GDLs) one for each electrode (Figure 19). There are two predominant methods of manufacturing a MEA: catalyst coated membrane (CCM) and gas diffusion electrode (GDE) manufacturing.

Further details, including advantages and disadvantages of different types of FCs, are given below.

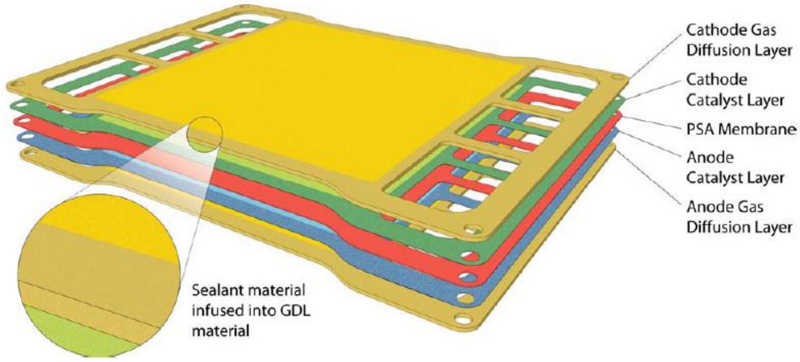
[47] https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf

Table 7 Overview of fuel cells types, characteristics and main applications

Fuel cell type	Applications	Power and temperature range
Low-temperature Polymer Electrolyte Membrane Fuel Cell (LT-PEMFC)	Transportation Portable power Backup power Distributed generation Medium-scale CHP Electrical utility Specialist vehicles	< 1 - 100 kW < 120°C
High-temperature PEM Fuel Cell (HT-PEMFC)	Soldier portable power supply Battery changing Small to medium scale CHP BEV range extender Aircraft APU	20 W-100 kW 120- 180 °C
Phosphoric Acid Fuel Cells (PAFC)	Distributed generation Auxiliary power Medium-scale CHP	5 - 400 kW 150-200°C
Alkaline Fuel Cell (AFC) (*)	Military Space Backup power Transportation	1–100 kW < 100°C
Molten Carbonate Fuel Cell (MCFC)	Electrical utility Natural gas, biogas, and coal-based power plants Distributed generation Medium-scale CHP Military Industrial	100 kW–3 MW 600–700 °C
Solid Oxide Fuel Cell (SOFC)	Auxiliary power Electrical utility Distributed generation Medium-scale CHP Military	1 kW - 2 MW 500-1000 °C
Direct-Methanol Fuel Cell (DMFC) (**)	Transportation Small portable applications (cell phones, computers - under development) Backup power Military (man-portable tactical equipment, battery chargers, and autonomous power for test and training instrumentation - emerging applications)	20 W – 1 kW– 1kw < 100°C

(*) Not applied for commercial use; (**) Applications at early stage

Figure 19 Schematic representation of a membrane electrode assembly (MEA)



Source: National Renewable Energy Laboratory (NREL)[48]

LT-PEMFC: mainly used in mobile applications with a direct (pure) hydrogen supply (e.g. Toyota MIRAI or buses for public transport). Operating temperatures are mostly around 80°C. This technology may also emerge for defence applications, especially for land vehicle power trains. One example is the Chevrolet Colorado ZH2, developed by General Motors, featuring a silent engine that could provide the Army with a stealth mode of land transportation.[49] The USA Department of Energy Hydrogen and Fuel Cells Program is developing a JP-8 based FC power system to meet the noise, range, and power requirements of the Squad Multi-purpose Equipment Transport (SMET) unmanned vehicle. This large robotic vehicle must have a low noise signature and exportable power, and be able to traverse difficult terrain over long distances without refuelling[50]. LT-PEMFC technology is already in use in the power train of submarines in the German and Scandinavian navies).[51] The German submarines, class U-212 and U-214, use a special type of PEMFC operated with hydrogen stored in metal hydride tanks and pure oxygen from liquid oxygen tanks. PEMFCs have also undergone successful testing for marine applications in Arctic conditions within the MARANDA project, financed by the Fuel Cells and Hydrogen 2 Joint Undertaking.[52] PEMFC technology and next-generation fuel cell concepts are also being explored for space vehicle applications, such as the Mars Flyer, and for aircraft power and propulsion systems. NASA PEMFCs may also produce electricity for spacesuits, airplanes, uninhabited air vehicles, and reusable launch vehicles.[53]

One of the restrictions for its application is the use of high quality hydrogen gas, to avoid performance decreases and accelerated deterioration of the cells. LT-PEMFC has a very low tolerance to impurities in fuel, thus requiring 99.99999% pure hydrogen, which is costly to produce. The heat produced from LT-PEMFC is also of a low temperature and is therefore difficult to transfer away for use in other processes. In addition, due to the nature of the membrane, a water management system is needed to prevent flooding/drying out of the membrane electrode assembly, both of which lead to a loss in performance. These issues can be overcome through the use of HT-PEMFC.

HT-PEMFC: its main advantages are theoretically better performance compared to LT-PEMFC, and that it does not require high quality hydrogen gas. When hydrogen is

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[48] D. Wheeler and G. Sverdrup, National Renewable Energy Laboratory, 2007 status of manufacturing: polymer electrolyte membrane (PEM) fuel cells, March 2007.
[49] https://www.armytimes.com/news/your-army/2017/07/11/army-begins-testing-off-road-vehicle-powered-by-hydrogen-fuel-cell/
[50] https://www.hydrogen.energy.gov/pdfs/review18/ia001_darling_2018_o.pdf
[51] https://nationalinterest.org/blog/the-buzz/why-germanys-new-super-stealth-submarines-could-take-any-21021
[52] https://www.vtt.fi/sites/maranda
[53] https://www.nasa.gov/centers/glenn/technology/fuel_cells.html

extracted from other fuels by a reforming process carbon monoxide concentrations are significant. CO will lead to a process called "catalyst poisoning", which results in a deactivation of the catalyst (platinum is especially sensitive to this process). The adhesion of CO on platinum catalyst decreases as the temperature increases. Therefore, HT-PEMFCs are not as sensitive to CO in the anode gas as LT-PEMFCs will be (e.g. LT-PEMFC performance is significantly reduced from a CO concentration of 20 ppm in the anode gas, HT-PEMFC can operate at much higher CO concentrations (10 – 100 time higher than LT-PEM) without significant performance losses). Stable operation with fuel gas containing 2 vol% of CO was demonstrated by Schmidt and Baurmeister in 2008.[54]

PAFC: Phosphoric Acid Fuel Cells were the first fuel cells to become commercially viable due to their ability to run on fuels already available, and this is why they remain the most popular choice for remote installations and backup power generation. PAFCs are moderately high temperature fuel cells. While their electricity generating efficiency ranges from 37 to 42%, their overall efficiency can reach 80% when they are combined for heat and power applications. However, catalyst poisoning is of concern for PAFC due to operation with hydrocarbon fuels. This problem can be overcome by producing electrodes made of carbon paper coated with a finely dispersed platinum catalyst. While this solves the carbon monoxide poisoning issue, it also makes these fuel cells exceptionally expensive to produce. Other critical engineering challenges include handling the corrosive phosphoric acid, maintaining its concentration and choosing acid resistant materials. Though the operating temperature is higher in comparison with LT-PEMFC, better tolerance to impurities in the reactants is an advantage. Overall power to weight ratio is lower than that of PEMFC. But PAFC has much longer service life.

AFC: AFC has a long history in the space programme. AFCs were used in space shuttles to power on-board systems by combining the pure hydrogen and oxygen stored in the rocket fuelling system.[55] AFCs have the fastest kinetics and they can use metallic bipolar plates, leading to reduced cost. The main difficulties with this fuel cell type are their vulnerability to poisoning by CO and CO_2 - always formed during hydrogen production by reforming hydrocarbon or alcohol fuels. CO poisoning is attacking the precious metal catalyst, while CO2 is detrimental for the alkaline electrolyte due to forming of carbonates which partly can precipitate and thus mechanically block electrodes. The main entrance of CO2 poisoning for AFC as well as for the emerging AEMFC is environmental air. As such, applications are essentially limited to those where both pure oxygen and hydrogen can be used. Corrosion of the electrodes and dilution of alkali in the cell are other issues encountered in AFCs.

MCFC: MCFC are high temperature fuel cells that can use natural gas, biogas, and coal as fuels. They are currently under development for industrial and military uses, mainly used for stationary power generation in the 50 kW to 5 MW range. [56,57] There is a great deal of interest in using MCFC to produce electricity in place of coal-fired power plants. Because MCFC must operate at temperatures of 650 °C, there is no need for precious metals to be used as catalysts. This has tremendous cost saving benefits. Also as a result of their high operating temperatures, MFCFs do not require the fuel to be reformed prior to entering the fuel cell. This dramatically reduces the number of parts, which increases reliability and reduces maintenance costs. MCFCs are also highly efficient, achieving approximately 50 % efficiency where waste heat is not captured and 85% efficiency when it is. Because they do not contain platinum catalysts they are not susceptible to carbon monoxide or carbon dioxide poisoning. In fact, they can use carbon monoxide as fuel. Carbon dioxide is required as co-feed to the air on the cathode side as it is consumed in the cathode reaction. This makes them very attractive for energy production in countries that have large natural reserves of coal. The primary

[54] T.J. Schmidt and J. Baurmeister, J. Power Sources 176, 2008, pp 428 – 434
[55] https://www.nasa.gov/centers/glenn/technology/fuel_cells.html
[56] http://www.fuelcell.co.uk/molten-carbonate-fuel-cells/
[57] https://www.doitpoms.ac.uk/tlplib/fuel-cells/mcfc_history.php

disadvantage however of MFCFs is that their high temperatures decrease cell life due to corrosion issues. Research is currently underway to find corrosion- resistant materials for use at high temperatures. Another drawback is their susceptibility to poisoning by sulphur, which is found at high concentrations in many types of coal. This problem is currently addressed by using sulphur absorption, which requires frequent changing of components. MCFCs also use hydrocarbon fuels. While this may be seen as advantageous in terms of supply and production over hydrogen, it is a tremendous disadvantage in terms of greenhouse gas emissions and, in the case of coal, acid rain-producing sulphur emissions.

SOFC: SOFCs, also called 'the third-generation fuel cell technology', operate at the highest operating temperature (up to 1000 °C), thus assuring higher efficiency. SOFCs exhibit many advantages when compared to other FCs: since all the components are solid, there is no need for electrolyte loss maintenance and electrode corrosion is eliminated. However, evaporation of certain components of steel built elements in particular chromium need to be avoided. Expensive catalysts such as platinum and ruthenium are totally avoided thanks to the high operation temperatures. Also because of high-temperature operation, the SOFC is better able to tolerate the presence of impurities, increasing its service life. Costs are reduced for internal reforming of natural gas. The negligible release of pollution is also a commendable reason for the SOFC's popularity today. Due to the numerous advantages mentioned above, SOFC are being considered for power generation and for use in space, portable electronic devices, cars, and aircraft.[58] However, due to high operation temperatures, the materials used as components are thermally challenged: the anode should withstand a very reducing high temperature environment whilst the cathode has to survive a very oxidising high temperature environment. The relatively high cost and complex fabrication are also significant problems yet to be addressed.

DMFC: Today, methanol fuel cells produce only limited power; the power range for typical DMFC fuel cell systems is in the range of 20W to 1kW. They cannot, therefore, power larger vehicle drive trains, but are ideal for consumer goods, e.g. mobile phones and laptops. The use for material handling vehicles and back-up power systems is also addressed. Higher outputs are however possible, when combining multiple systems. The advantages of DMFC essentially boil down to the advantages as a fuel of methanol over hydrogen. Methanol is dense (due to hydrogen bonding) containing far more energy per litre than even highly compressed hydrogen, and can be stored at ambient conditions. Methanol is more readily available from both renewable and non-renewable sources and by its nature can bind more readily to active sites on the fuel cell/fuel cell catalyst bed. The downside is the intermediate oxidation/combustion product, carbon monoxide, which is a problem with any carbon-based fuel in a fuel cell. A further advantage of using aqueous methanol solution as fuel is the permanent equally wet state of the cell, rendering it insensitive to start-stop cycling compared with most other fuel cell technologies.

Application areas

Fuel cells are currently used in three main areas: stationary power generation (c. 67 % market share), transportation (c. 32 %), and portable power generation (<1 %).[59] In addition, fuel cells have long been used in the space programme to provide electricity and drinking water for astronauts.

Civil applications

Stationary applications: stationary fuel cell applications (or power systems) are applications for fuel cells that are either connected to the electric grid (distributed generation) to provide supplemental power and as emergency power systems for critical

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[58] https://www.nasa.gov/centers/glenn/technology/fuel_cells.html

[59] Technavio, Global fuel cells market for industrial and military application, 2017-2021.

areas, or installed as a grid-independent generator for on-site service. Stationary fuel cells can provide electricity and heat, but are not designed to be moved. They can be used as combined heat and power (CHP) units, uninterruptible power systems (UPS) and primary power units. In addition, fuel cells can be used as a backup or emergency power source. CHP units measure between 0.5 kWe and 10 kWe and take advantage of the fact that fuel cells generate heat alongside electricity. UPS systems provide a guaranteed supply of power in the event of grid interruption. Backup power systems provide power when the primary power source is disrupted. Fuel cells used for backup power come in many sizes and types and typically use hydrogen as their fuel. Backup fuel cells can be commercialised more quickly than other fuel cells because they do not depend upon the implementation of a hydrogen infrastructure. Some backup power applications include computer systems, manufacturing facilities, homes, and utility substations. The PEM fuel cell with compressed hydrogen fuel is the most popular fuel cell type used for backup power applications. The most common fuel cell type for stationary applications is the PEMFC, but, SOFC, MCFC, AFC and PAFC have also been used.

Transportation: FCs can offer vast potential to replace the internal combustion engine in vehicles and to provide power in stationary and portable power applications because they are energy-efficient, clean and fuel-flexible.[60] Fuel cells for transport are units providing propulsive power to a vehicle, directly or indirectly (i.e. as range extenders). FCs can power a variety of vehicles, such as two/three-wheeler vehicles, cars, vans, forklifts, buses, trucks, marine vessels, trains, manned light aircraft, unmanned aerial vehicles (UAVs) and unmanned undersea vehicles (UUVs). Automobile applications use the PEMFC and DMFC fuel cell types. Fuel cell buses use PAFCs, PEMFCs, DMFCs, and ZAFCs. Utility vehicles, scooters, and bicycles primarily use PEMFCs[61]. PEM and SOFC are the most relevant for maritime applications. [88]

Portable applications: The main drivers for FCs in portable applications are off-grid operation, longer run-times compared with batteries, rapid recharging, significant weight reduction potential (for soldier-borne military power), convenience, reliability, and lower operating costs. FCs can be used to power laptops, printers, radios, cellular phones, power tools, battery chargers, unattended sensors, education kits and toys. Auxiliary Power Units (APU) systems comprise the largest MW share of the portable applications. Proton exchange membrane fuel cells and direct methanol fuel cells are considered the most suitable FCs for portable applications. However, SOFC can also be used.

Other civil applications include power supply or backup power for: oil & gas industry (chemical injection pumps, SCADA systems, etc.), wind turbines (obstacle lights, measurement of wind, etc.), traffic engineering (roadside meteorological stations, speed trap cameras, etc.), security & surveillance (mobile and stationary surveillance systems), environmental measurement and telecommunication. The technology is also often used for recreational purposes, e.g. as an energy source for boats, caravans etc. Emerging applications for DMFC technology are forklifts and robotics.

Military applications

The defence sector can benefit significantly from the unique features of fuel cells. They can save energy and reduce the operating costs associated with dependence on foreign oil. FCs can be used in remote locations to assure electric power for battery charging, auxiliary power for surveillance and regular power for communications equipment. There is strong military interest in FCs as a means of reducing the logistics burden. Military forces deploy internationally in areas where fuels available locally often do not comply with European/USA standards and are not suitable for use in military vehicles (e.g. due to high Sulphur content). This is important because of the cost of transporting fuel over long distances and because logistics convoys are hard to protect and potentially vulnerable to attack by hostile forces. Fuel cells (with reformers to

[60] https://www.hydrogen.energy.gov/fuel_cells.html
[61] http://www.fuelcellstore.com/blog-section/intro-fuel-cell-applications

generate hydrogen for the cells) allow military forces to generate power in the operational theatre (for example for power generation in military bases) using local fuels or other sources (e.g. diesel, petrol, ethanol, propane, JP-8, biomass renewables), reducing the need to transport fuel with associated logistics costs and risks.

Fuel cells are rapidly establishing a foothold in the **civilian stationary generation market**, acting as a source of backup power or allowing consumers to unplug from the grid entirely, and military customers are following suit.

The most discussed application for military is the power supply for dismounted soldiers in particular in combination with central power supply as part of 'dismounted soldier systems'. With regard to safety and the agility of the soldiers, compressed gaseous fuels is not an option for this application today. Methanol is used either in combination with direct methanol fuel cells (DMFC) or with reformed methanol fuel cells (RMFC) based on HT-PEMFC. Alternatively PEMFC with metal hydride storage is employed. All these fuel cell applications are still in the test phase.

The German-based company – SFC Energy AG – supplies various fuel cell power systems for uses in different armed forces. A NATO stock number is available for these systems.[62] Many defence organisations uses or have tested FC technology. Some of them are: German Bundeswehr, UK Ministry of Defence, FMV Swedish Defence Material Administration, Armasuisse, Finland Defense Forces Materials Command, USA Air Force and Army etc.

Marine applications are another largely discussed topic for military. In 2017 the USA Navy placed a contract for the supply of power from two fuel cell power plants with a total output of 7.4 megawatts to be located on the USA submarine base in Groton, Connecticut, to supply an existing electrical substation and provide cost-effective resilience and grid independence to key military infrastructure and assets. [63]

This technology can also be used for vehicles APUs. The fuel cell charges the vehicle batteries in continuous operating mode, to prolong 'engine off time' during silent watch, meaning that the battery will be able to power all necessary military equipment for longer while waiting to engage and/or move in the theatre.[64] Auto companies are already working with fuel-cell suppliers to develop electric vehicles that use on-board fuel cells to charge batteries, rather than charging them from an external source. The challenges for this application, however, are far more severe than for stationary applications, because of size, weight, maintenance, heat, performance, and refuelling constraints in vehicles.[65]

FCs operating at high temperatures are less sensitive to catalyst poisoning than technologies operating at lower temperatures. Therefore technologies like SOFC are predestined for applications, where the quality of the hydrogen gas mixture is not optimal (e.g. diesel reformat). In addition to its application for APUs etc., fuel cell technology may become relevant for power supply in military encampments in remote areas. Fuel cells can achieve a higher degree of efficiency, than diesel generators and as an added bonus, waste heat from the power generation process, can be used for heating and service water (CHP application).

As regards specific technical requirements, fuel cells for military application need to operate in challenging environmental conditions: below 0°C (down to -40°C in some cases) and up to 60°C, the typical operational temperature interval for defence systems. With regard to Arctic conditions, methanol appears to be a good choice of fuel as the 60 vol% methanol solution in water used in a reformed methanol fuel cell (RMFC) has a freezing point of about –60°C. This mixture, in combination with DMFC, has been tested

[62] https://www.sfc-defense.com/page/portable-power.
[63] GlobeNewsWire, 'FuelCell Energy Finalizes 7.4 Megawatt Utility Project to Power a Strategic Military Installation', October 19 2017.
[64] https://www.sfc-defense.com/page/power-military-vehicles.
[65] https://www.edn.com/design/power-management/4358740/Inverter-is-key-to-fuel-cell-success

successfully in desert conditions. PEMFC was also tested for marine vessels operating in Arctic conditions (MARANDA project[66]). Requirements regarding maintainability and transport for military applications can also differ from civil applications.

Fuel cells for transportation (mobile) military applications: fuel cell vehicles can be used for quiet operation, to export power, to generate water for field uses, to generate sufficient current to power high wheel torque for off-road driving, and they can be refuelled in a few minutes, providing especially low fuel consumption at idle. The wheel torque depends on the electric motor. In this case the provision of very high torques as required for heavy military vehicles, e.g. 8x8, is a challenge, and heavy tracked vehicles like MBT will require a single source or synchronised multiple sources of high torque and power. Hydrogen fuel cell technology could bring stealth to army vehicles, in terms of both low acoustic signatures for near-silent operation (such as when on silent-watch operations) and low thermal signatures, making detection by ground and airborne sensors much harder. Stealth for silent-watch type operations is one of the most promising benefits of hydrogen fuel cell technology when it comes to military applications. The on-board fuel cells can support long missions of about 300 to 400 miles without needing to be recharged.

Unmanned air vehicles (UAVs) and **unmanned underwater vehicles** (UUVs) requiring long endurance also need agile power sources. Hydrogen FCs can increase UAV time in the air and rapidly refuel on the ground in less than 15 minutes. There are no moving parts - meaning the fuel cell-powered UAV requires less maintenance and zero lubricants. Ballard Power Systems subsidiary, Protonex, was contracted to supply 13 600 W PEM fuel cell propulsion systems to the USA Navy in 2018 for UAV Trials using the USA Naval Research Laboratory Hybrid Tiger UAV Platform. This PEMFC system runs on compressed hydrogen (oxygen comes from the air): a previous version of this system demonstrated performance improvements (for a 15 kg UAV) over five times that of Li-ion batteries in endurance terms. Besides PEMFC, SOFC systems in combination with LPG are also being tested for UAVs.

The benefits of fuel cells for UUVs are that they are compact, lightweight and reliable, with high specific energy and power density compared with conventional batteries (efficiencies of ~ 50-65 %), allowing bigger payloads and longer run-times. Fuel cells also allow for rapid turn-around between missions. Hydrogen fuel cells (PEMFCs) operating at ~ 80 degrees C and solid oxide fuel cells operating at ~ 800 degrees C are both being considered. [67] The USA Navy has started using fuel cells instead of batteries in UUVs to allow bigger payloads and longer runtimes. The USA Navy aims to develop large displacement UUVs which have more than 60 days endurance for service by 2020, and carried out trials of General Motors' fuel cell (PEMC) powered prototype UUVs in 2017. PEMFCs are the most mature of the fuel cell technologies for propulsion due to their suitability to the application and to significant investment by the automotive industry.

The 2nd generation of fuel cells (FC-2G), along with lithium-ion batteries and autonomous submarine energy modules (MESMA), can improve submarine capabilities[68]. MESMA and FC-2G are AIP technologies, i.e. Air Independent Propulsion. FC-2G AIP extends the conventional submarine autonomy to remain submerged and operate at low speed for two to three weeks, about five times longer than conventional AIP. As fuel cells are not a new technology, the major breakthrough relies on the ability of the FC-2G to produce hydrogen from gasoil without needing hydrogen storage which is highly reactive and dangerous for the boat and its crew. Moreover, fuel cells are quieter than other AIP

[66] https://www.vtt.fi/sites/maranda
[67] ECS Transactions 75 (14) 479-489 (2016), 'Hydrogen fuel cells for unmanned undersea vehicle propulsion', October 2016.
[68] http://www.periscope24.com/news/2019/6/14/japan-goes-back-to-the-future-with-lithium-ion-battery-powered-submarines

systems, which represents an advantage for submarine furtiveness. The technology is packaged in a single large section of the hull, which makes it modular. Another important advantage is that it can be integrated in to new conventional submarines and during retrofitting of existing ones.

Unmanned Underwater Vehicles (UUVs) and **Unmanned Ground Vehicles** (UGVs) will enable more efficient maritime operations by performing tasks currently carried out by manned submarines, surface ships and aircraft. They can enable access to areas that are too time-consuming, costly or dangerous to reach with manned platforms. Applications include remote detection and neutralisation of threats, mine clearance, protection of naval vessels, monitoring of potential threat vessels and submarines, and protection of critical maritime infrastructure such as ports.

Ground Vehicles: the USA Army is evaluating fuel cells as an alternative to petrol/ diesel in military vehicles as they offer the following significant potential advantages:

- Low acoustic signatures enabling near-silent operation for 'silent-watch' capability
- Low thermal (IR) signatures (fuel cells do not produce much heat) making detection by ground and airborne sensors much harder
- Low fuel consumption when the engine is idling
- High-wheel torque at all speeds from electric drive transmission aiding off-road driving
- Ability to export power for use by auxiliary systems outside the vehicle (e.g. sensors, communication systems) without draining batteries (as at present)
- Ability to generate water for field uses
- Low refuelling times (less than five minutes) as for current petrol/ diesel vehicles, unlike battery powered electric vehicles.

The General Motors ZH2 Colorado off-road light-duty truck was tested in extreme environments (2017-2018) by the USA Army to evaluate its military utility. [69] The truck is fuelled by compressed hydrogen gas converted into power by a PEMFC. The vehicle can export 25kW continuous power (50kW peak) and potentially generate up to two gallons of water per hour. The fuel tank can be filled in approximately three minutes and with 5-6 kg of hydrogen the vehicle can travel around 200-300 miles, which GM believe can be increased to 400 miles with a re-designed hydrogen tank. The concept of operations is that a refuelling system (that can be deployed in a container) will produce hydrogen for such vehicles from any source of electricity, from military JP8 fuel to local fuels and renewable power sources, reducing the logistics burden of transporting fuel. Trials are looking at for example reconnaissance/ silent watch capability, powering a mission command post, powering a field hospital, using JP8 fuel to produce hydrogen and its storage and transportation. Future potential USA Army vehicle applications include the High Mobility Multipurpose Wheeled Vehicle ('Humvee'), the M1 Abrams Tank and the M2 Bradley infantry fighting vehicle (armed with a 25 mm automatic cannon and a TOW anti-tank missile launcher), all of which use a lot of fuel when the engine is in idle mode to power on-board equipment.

The USA army's light duty trucks will be powered by fuel cells.[106] General Motors (Chevrolet) is building a hydrogen fuel-cell transport vehicle platform (Silent Utility Rover Universal Superstructure) for the Army that act as a modular platform for multiple vehicle models and applications.[70] PEMFC[71] and SOFC[71] can be used in military vehicles.

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[69] https://www.armytimes.com/news/your-army/2017/07/11/army-begins-testing-off-road-vehicle-powered-by-hydrogen-fuel-cell/
[70] https://www.engadget.com/2017/10/05/chevy-army-fuel-cell-transport/
[71] http://www.dtic.mil/dtic/tr/fulltext/u2/a616384.pdf

Fuel Cells for portable military applications

The increasing deployment of electronic equipment for soldiers in the field – from night vision goggles, computers, communication devices to GPS and sensors – has increased the military's need for lightweight, reliable and portable electrical power supplies away from the grid. Primary (single use) batteries of different types have until recently been the accepted solution for soldier power. Secondary (rechargeable) batteries are, however, the preferred solution. For instance, the Conformal Wearable Battery (CWB), developed as part of the Nett Warrior system project, is a thin, lightweight, flexible Li-ion rechargeable battery that integrates with the end-user's load carrying equipment.[72] It reduces the number of spare batteries the operator needs to carry, it sustains dismounted operations in remote/austere environments, and features a state of charge indicator for quickly checking its remaining power capacity. The CWB is safer than other common Li-ion batteries; it can even be shot without bursting into flames or blowing up and operates at extreme temperatures ranging from -20 °C to 60 °C. The Conformal Wearable Battery is currently in use in many units. However, batteries have to be replaced or recharged, requiring frequent interruptions to missions, complicating logistics and adding weight to soldiers' equipment. Meeting the power demands of advanced equipment requires a sophisticated approach than that offered by batteries alone.

Today the use of primary batteries with the exemption of button cells for very low power consumers is becoming largely obsolete for most NATO armies. But even rechargeable batteries are heavy. Against this backdrop, wearable power systems – fuel cells - offer the potential to reduce the weight of batteries carried by soldiers significantly. A typical soldier can carry a dozen devices, all requiring electrical power. According to the USA Army, a platoon typically carries 700 pounds (318 kg) of batteries for a three day mission, which is a battery weight per soldier of approximately 16 pounds (7 kg) [73,20,74], but a soldier may carry between 10 and 30 pounds of batteries (4 – 13 kg) depending on their role in the platoon.[75] That weight slows down soldiers on foot, tethers them to constant resupply, and contributes to muscular and skeletal injuries caused by excessively heavy packs. Relying solely on battery technology for power is problematic in the field. Batteries lose their charge, add significant weight (also considering the battery management system) and are insufficient to meet the needs for accessible energy. With a fuel cell system, all electronic devices, navigation tools, medical equipment and other electronics can be charged and operable in the field. The 'wearable power systems' of the USA army will be powered by fuel cells. [106] The USA Army's goal is to reduce the weight of Lithium-Ion batteries carried by soldiers by 50% using fuel cell technology, allowing them to carry more ammunition and operationally important equipment. [76] One example of such a complementary fuel cell system is the portable JENNY 1200 fuel cell - an addition to the JENNY series which is already field-proven and has been used by the German Armed Forces (Bundeswehr) and other international defence organisations for years. The JENNY 1200 fuel cell is a DMFC with a nominal power output of 50 Watt.[77] Other advantages of using complementary fuel cells in the military include: significant weight reduction for soldiers, highly efficient and lightweight battery recharging, and easy handling - new equipment can be integrated by exchanging a single cable. Another example of a system in development for the USA Army is the SAFC Inc/ UltraCell 50 W

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[72] http://soldiersystems.net/tag/conformal-wearable-battery/

[73] International Defence, Security and Technology, 'Powering the Future Global Soldiers with Wearable, Wireless, Energy Harvesting and Smart Energy Solutions', May 8 2017.

[74] Institute for Defence Analyses, 'IDA Contributions to the Soldier and Small Unit Operational Energy Program', April 2018.

[75] Army Technology Interview with Head of Electrochemistry Branch of US Army Research Laboratory, 'Super cells: developing the next generation of soldier batteries', June 2014.

[76] US Department of Energy Office of Energy Efficiency and Renewable Energy, '4 Ways Fuel Cells Power Up the U.S. Military', September 13 2017, https://www.energy.gov/eere/articles/4-ways-fuel-cells-power-us-military.

[77] https://www.sfc-defense.com/page/portable-power

propane-fuelled Solid Acid Fuel Cell. The German army already uses DMFC systems as a portable energy source. In the future, in the context of dismounted soldiers, portable fuel cells systems (when not needed as portable power sources) can become an energy source as part of a central power supply solution, e.g. many portable small fuel cells connected together to form a microgrid to be used to generate power.

The need for mobile auxiliary power units (APUs) is widespread in the military where communications and reconnaissance systems are operational while the vehicle engine is not running. The present battery systems do not run as long as desired. Diesel generators give off undesirable, detectable emissions such as noise, heat, vibrations and particulate matter, making their operation around personnel problematic.

Solid Oxide Fuel Cell (SOFC)[78], Solid Acid Fuel Cell (SAFC), direct methanol fuel (DMFC)[79],[80] and polymer electrolyte membrane (PEM) fuel cells[81] can be used in portable military applications. SOFCs and HT-PEMFC[82] are considered the most promising type for military applications where fuel availability is the major concern.[83]

New types of fuel cells have been researched for industrial as well as military applications. Two types of bio-based fuel cell exist: enzymatic and microbial. Real enzymatic fuel cells exist in small laboratory scale room temperature. Using enzymes to help produce electricity, these new fuel cells have the potential to power everything from portable electronic devices to cars and off-grid power systems. This has allowed the engineers to avoid past constraints associated with metal catalysts that would rapidly break down when exposed to sulphur-heavy compounds like kerosene (JP-8). Hexane and octane, which are chemically comparable to JP-8, were also tested in the fuel cell and shown to work in a comparable fashion. Further experiments by the researchers also found that adding sulphur did not reduce power production in the enzymatic fuel cell as it did in a standard metal-catalyst device.[84] Further advances in size and capacity are required for this technology to be taken up widely in military and civilian spheres.

Microbial fuel cells use living single-cell organisms as mediator for the electrode reaction. Depending on the environment, such biofilms can be long-lasting, as they can regenerate themselves. However, power density is very low. Nevertheless, the USA Office of Naval Research has successfully demonstrated the use of microbial fuel cells to power off shore sensors on the floor of San Diego Bay.

3.2 Fuel cell and hydrogen technology development stage

The fuel cells market for the automotive industry is expected to grow significantly to 2021 (CAGR of around 9 % by 2021), with increasing demand for fuel cells in material-handling vehicles, light-duty vehicles, buses, and the aerospace sector. Emission targets for climate change mitigation supported by government incentives for fuel cell vehicle buyers are encouraging automotive manufacturers (e.g. Toyota, Daimler, Hyundai, Honda) to commercialise fuel cell electric vehicles globally, focusing on areas where there is supporting infrastructure.

Although FC technology has come a long way in technology maturity, large-scale deployment in domestic and industrial segments has not yet taken place. Other forms of energy conversion remain competitive, and ongoing R&D is focused on cost reduction and life cycle cost management.

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[78] https://www.wattfuelcell.com/portable-power/watt-imperium/
[79] https://www.sciencedirect.com/science/article/pii/S1464285906708860
[80] https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2009/power/May5BDominick.pdf
[81] https://www.sciencedirect.com/science/article/pii/S1359028604000828
[82] IAPUNT project: Development of an innovative auxiliary power unit for military purposes based on high-temperature PEM fuel cell and reforming technology for military logistic fuels
[83] https://link.springer.com/content/pdf/10.1007%2F978-1-4020-8295-5_6.pdf
[84] https://newatlas.com/jet-fuel-electricity-room-temperature-fuel-cell/34594/

Stationary applications: More than 800 MW of large stationary fuel cell systems with a rated power above 200 kW have been installed globally for distributed generation and combined heat power applications. The largest shares of the installations are found in the USA and South Korea. [85] A few larger stationary fuel cells are already available today, and they show tremendous potential for providing cost-effective distributed power, especially where there is little or no grid infrastructure. Five technology types serve the large stationary market: SOFC, MCFC, PEMFC, PAFC and AFC. Three of them, MCFC, SOFC and PAFC, dominate the market. Only limited large-scale application of AFC and PEMFC has been initiated. Furthermore, one specialist company dominates the production of each FC type: FuelCell Energy (MCFC), Bloom Energy (SOFC) and Doosan Fuel Cells (PAFC). Fuel cells used for backup power come in many sizes and types and typically use hydrogen as their fuel. Backup fuel cells can be commercialised more quickly than other fuel cells because they do not depend on the implementation of a hydrogen infrastructure. Some backup power applications include computer systems, manufacturing facilities, homes, and utility substations. The PEM fuel cell with compressed hydrogen fuel is the most popular type used for backup power applications.

Transportation: Fuel cells have so far seen limited use in cars and vans but this is set to change. Initial locations for this rollout will most likely concentrate around clusters of early hydrogen refuelling infrastructure in Japan, Germany and the USA, and additional infrastructure under development in China and South Korea, and will then spread outwards from these centres as the market is established.

The fuel cell bus sector is showing year-on-year growth, with more prototypes being unveiled. Many bus manufacturers began demonstrating their first fuel cell buses in the early 1990s. As with fuel cell automobiles, the fuel type most often used is compressed hydrogen, although the use of methanol has also been demonstrated. Fuel cell buses have been running in British Columbia, California, Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Porto, Reykjavik, Stockholm, and Stuttgart. [86]

'Niche' transport consists of a number of sub-applications with differing levels of commercial success to date. Material-handling vehicles account for over 90 % of niche transport shipments, with PEMFC technology dominating. This market has seen much success in the USA so far.

The use of fuel cells for maritime applications is a hot topic at the moment. [87] The world's first battery-powered ferry, Ampere, has being launched in Norway in 2015. In addition there are several ongoing pilot projects under development in Norway. [88] Still, fuel cell technology has to be optimised and further adapted to suit maritime applications.

FC application in unmanned aerial vehicles (UAVs), e-bikes, trains and more is still under development with limited deployments to date.

Portable applications: The portable application market is restricted today almost entirely to defence and safety. Consumer appliances for portable fuel cells are to a large extent not addressed. The first products to be introduced to the market on a large scale might include portable fuel cells to replace batteries in computers, wheel-chairs and mobile phones.

[85] Global Deployment of Large Capacity Stationary Fuel Cells, JRC technical report, EUR 29693 EN
[86] http://www.fuelcellstore.com/blog-section/intro-fuel-cell-applications
[87] http://compositesmanufacturingmagazine.com/2018/07/composites-will-be-part-of-first-hydrogen-fuel-cell-boat-in-the-united-states/
[88] https://www.uib.no/en/energy/116261/fuel-cells-and-hydrogen-maritime-applications

3.3 Materials used in fuel cells, hydrogen production and hydrogen storage

An overview of the materials required in the different types of fuel cells, considered in this study is shown in Table 8. The Membrane Electrode Assembly (MEA) is the core component of a fuel cell that helps produce the electrochemical reaction needed to separate electrons. On the anode side of the MEA (of a PEMFC), a fuel (e.g. hydrogen) is oxidised producing ions, which diffuse through the membrane and meet on the cathode end an oxidant (oxygen or air) which bonds with the ions and receives the electrons that were separated from the fuel. In other cells like the SOFC, ions are produced at the cathode. Catalysts on each side enable reactions and the membrane allows protons or the relevant ions to pass through while keeping the gases separate. In this way current is drawn from the cell, producing electricity. The most commonly used catalysts include carbon-supported platinum and platinum/ruthenium for the best catalyst dispersion and utilisation for PEM fuel fells. Gas diffusion layers (GDLs) are key components in various types of fuel cell, including PEM, DMFC and PAFC stacks. A GDL is a porous sheet that must provide high electrical and thermal conductivity and chemical/corrosion resistance, as well as controlling the proper flow of reactant gases (hydrogen and air) and managing the water transport out of the membrane electrode assembly (MEA). Carbon fibre paper and carbon fabric (cloth) have been used as GDL in several fuel cell types for decades and have proven durability.

A bipolar plate is a multi-functional component within the PEM fuel cell stack. It connects and separates the individual fuel cells in series to form a fuel cell stack with the required voltage; it aids uniform distribution of fuel gas and oxygen over the whole active surface area of the membrane-electrode assemblies (MEA), conducts electrical current from the anode of one cell to the cathode of the next, facilitates water management within the cell, and supports thin membrane, electrodes and clamping forces for the stack assembly, among other things. In applications where volume and weight of the fuel cell have to be minimized, the bipolar plates are usually made from stainless steel. However, stainless steel bipolar plates have to be coated in order to protect the bipolar plate from the corrosion, reduce the energy losses stemming from the contact resistances and reduce the amounts of leaching ions which lowers the PEMFC lifetime. Typical examples of coating materials with excellent properties are gold and other noble metals. However, due to the high cost of noble metals, it is desired to find alternative coating materials. Bipolar plates can be made also of graphite because of its low surface contact resistance and high corrosion resistance.

Carbon materials are fundamental for the manufacture of fuel cells. Several fuel cell components are made entirely of carbon in a graphitic form. Setting aside the membrane all the other components, electrodes and collector plates are made almost entirely of graphitic carbon. Catalysts are a major cost driver and a current focus area of research. Catalysts with reduced platinum group metal (PGM) loading or no PGMs, increased activity and durability and lower cost are under development. Noble metals including Pt and Pd or their alloys Pt/Pd and Pt/Ru have traditionally been employed as catalysts in fuel cells. However, high-priced platinum (Pt)-based electrocatalyst contributes to about 45 % of the cost of the stack. [89] As for the electrodes, carbon-based materials have been developed, such as mesoporous carbon, carbon nanomaterials (graphitised carbon, carbon nanotube, graphene, and carbon nanocoils), and heteroatom-doped carbons (nitrogen- and boron-doped carbons). Relevant materials for the types of fuel cell considered are listed in Table 8. [90,91]

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[89] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5827662/

[90] Fuel Cell Handbook (Seventh Edition) By EG&G Technical Services, Inc. Under Contract No. DE-AM26-99FT40575, U.S. Department of Energy, 2004.

[91] LCA approach and LCA of materials represented in FCH technologies, HyTechCycling, FCH JU Workshop, 20 March 2018

Table 8 Overview of materials used in fuel cells

Fuel cell type	Materials
Polymer Electrolyte Membrane Fuel Cell (PEMFC)	Electrodes: porous carbon , carbon black Catalyst: Pt, Pt-Ru alloys Electrolyte/Membrane: perfluorosulphonic acid /solid polymer membrane GDL: woven carbon cloth or non-woven carbon paper coated with polytetrafluoroethylene (PTFE) Bipolar plates: graphite, stainless steel alloys with protection coating (TiO_2) Current collector: Cu, Al, Au (for plating) End plate: Al, stainless steel Gaskets: Si Fuel: hydrogen
High-temperature PEM (HT-PEM)	Electrodes: porous carbon, carbon black Catalyst: Pt, Pt-Ru alloys Electrolyte/Membrane: poly benzimidazol, concentrated phosphoric acid (H_3PO4) (high temperature polymer electrolyte membrane) GDL: woven carbon cloth or non-woven carbon paper coated with polytetrafluoroethylene (PTFE) Bipolar plates: graphite, stainless steel with protection coating (TiO_2) Current collector: Cu, Al, Au (for plating) End plate: Al, stainless steel Gaskets: Si Fuel: hydrogen, methane via reforming step, methanol (and derivates) via reforming step
Phosphoric Acid Fuel Cells (PAFC)	Electrodes: teflon-bonded silicone-carbide matrix Catalyst: Pt dispersed on carbon Electrolyte/Membrane: phosphoric acid /polymer/H3PO4 Bipolar plates: graphite Electrolyte reservoir: graphite Fuel: hydrogen, methane via steam reforming (also from biogas)
Alkaline Fuel Cell (AFC)	Electrodes: Ni, carbon Catalyst: require no rare metal catalyst, e.g. Fe, Co, Ni, Ag, manganese or precious metals (Pt/Pd, Au/Pt for UTC-Orbiter) Electrolyte/Membrane: potassium hydroxide/ porous matrix or alkaline polymer Electrolyte reservoir plate-ERP: porous sintered Ni Fuel: OH-
Molten Carbonate Fuel Cell (MCFC)	Electrodes: Ni-Cr (or Al) and oxidised sinter Ni Catalyst: non-precious metals can be used as catalysts, e.g. Ni Electrolyte/Membrane: molten Li, Na, and/or P carbonates Bipolar plates: High temperature stainless steel, Ni coated on anode side Fuel: hydrocarbons, CO Oxidant air with added CO_2
Solid Oxide Fuel Cell (SOFC)	Electrodes: anode is typically Ni oxide mixture with yttria stabilised zirconia; cathode is La-Sr manganite Catalyst: non-precious metals can be used as catalysts Electrolyte/Membrane: ceramic - yttria stabilised zirconia Bipolar plates: stainless steel for high temperature End plates: stainless steel for high temperature (Cro-Fer22) Sealing: Mica, glass Fuel: hydrocarbon, CO
Direct-Methanol Fuel Cell (DMFC)	Electrodes: Pt, Pt/Ru carbon supported catalyst, nafion Catalyst: Pt/Ru Electrolyte/Membrane: polymer membrane, nafion or sulfonated poletherether ketone (sPEEK)), Bipolar plates: graphite, stainless steel with protection coating (TiO_2) Current collector: Cu, Al, Au (for plating) End plate: Al, stainless steel Gaskets: Si Fuel: methanol, (methanol water mixture at elevated ambient temperatures)

Although not a unique challenge to fuel cell technology, high performance sealing technology is relevant for the safe application of FCs. Due to high operating temperatures in several FC types, as well as the need for chemical resistance, materials suitable for the application are not commonly found. A material, which can to withstand high operating temperatures (up to 900 °C) and is at the same time resistant against hydrogen, sulphuric acid, carbon monoxide and steam, can only be found in the Phyllosilicates group.

Scrap and flake mica is considered in the analysis as a sealing material. The biggest producer of scrap and flake mica in 2017 was Finland, followed by Turkey and the USA.[92] Other sealing materials used in FC are glass/glass ceramics (SOFC), elastomers and thermoplastics (PEMFC). Europe has significant manufacturing capacities for all of these and no supply shortages should be expected. These materials are therefore given little attention in the analysis.

Hydrogen production

The production of hydrogen can be achieved via various process technologies, including thermal (natural gas reforming, renewable liquid and bio-oil processing, biomass, and coal gasification), electrolytic (water splitting using a variety of energy resources), and photolytic (splitting of water using sunlight through biological and electrochemical materials). Nowadays, around 50 % of global hydrogen demand is produced by the steam reforming of natural gas, a process which leads to massive emissions of greenhouse gases. 30 % is produced from oil/naphtha reforming from refinery/chemical industrial off-gases, 18 % from coal gasification, 3.9 % from water electrolysis, and 0.1 % from other sources. [93]

Hydrogen can be generated from hydrocarbon fuels by a number of reforming techniques, with the most common practices being steam reforming and autothermal reforming. A multi-stage process is needed to convert the hydrocarbon-fuel to a hydrogen-rich stream suitable for PEM fuel cells. The first stage is catalytic steam reforming or an autothermal reforming process. This process requires high temperatures (700-850 °C) to convert the hydrocarbons, steam and/or air to a stream containing hydrogen, carbon monoxide, carbon dioxide, water, and trace amounts of low molecular-weight hydrocarbons. This stream must then be cooled and passed over another catalyst to increase hydrogen content and to reduce carbon monoxide. A third stage is then required to remove the remaining carbon monoxide so that the stream is suitable for PEMFC consumption. For those reforming systems using commercial and military grade fuels, an additional stage may be needed to remove sulphur and other impurities. The catalysts used in reforming processes can be divided into two types: nonprecious metal (typically nickel) and precious metals from Group VIII elements (typically platinum or rhodium). For industrial purposes generally the less expensive catalyst (nickel) is used. Other catalysts used for the reforming and secondary processes are calcium oxide, titanium oxide, cobalt, ruthenium or palladium.

Electrolysis is a highly efficient process but requires a large amount of energy to produce a relevant amount of hydrogen from water. After the process of electrolysis the gas needs to be compressed or liquefied for storage. It is therefore only feasible on a large scale with good infrastructure (power and water supply, as well as trained personnel). For military purposes, a significant quantity of process equipment needs to be shipped into the country of the mission, which makes electrolysis unsuitable for ground missions. Electrolysers are therefore not considered in the report.

For military purposes, operating fuel cell systems independently from a hydrogen infrastructure is an essential factor. The hydrogen needs to be produced on site. This aspect is especially important for mobile FC applications,

[92] https://minerals.usgs.gov/minerals/pubs/commodity/mica/mcs-2018-mica.pdf
[93] https://www.hindawi.com/journals/cpis/2013/690627/

but also for defence applications in general, with regard to logistics. The most feasible way to produce hydrogen for military purposes is reforming diesel fuel or kerosene, as both fuels are readily available in the armed forces and logistics are available for this type of fuel. For diesel reforming, two different catalysts are currently in use: aluminium oxide with a rhodium coating and cerium oxide with a rhodium coating. However, logistic fuels contain some sulphur, with the specific sulphur-containing compounds dependent on the fuel type and source. **Desulphurisation is considered a very important step in fuel processing technologies**. Sulphur must be completely removed from the fuel so as not to affect the reformer catalyst - it poisons the noble metal catalysts. CO must also be removed to avoid the degradation of the fuel cell's platinum catalyst.

Hydro desulphurisation (HDS) is the most prevalent desulphurisation technology, widely used to remove sulphur (S) from natural gas and from refined petroleum products, such as gasoline or petrol, jet fuel, kerosene, diesel fuel, and fuel oils. Today, virtually all petroleum refineries worldwide have one or more HDS units. The main HDS catalysts are based on molybdenum disulphide. Several alternative technologies have been reported to be effective in sulphur removal from liquids such as catalytic oxidation, biological sulphur removal and membrane separation. [94] A substitute process called adsorptive desulphurisation for removing sulphur from logistic fuels is proposed for SOFC for military operations. [95] Adsorptive desulphurisation appears to be a promising alternative to hydrodesulphurisation. It can be portable and applied on site on JP-8 stocks already in the field. Precious metals such as Rh, Pt or Pd are still needed as catalyst. However, desulphurisation should not be an issue for military applications if good quality fuel (e.g. S15 diesel) can be supplied. Alternatively, it may be done on site, if the space, equipment, and enough power and personnel are available. It may therefore be an option for main military bases in the country of the deployment. Import of high quality fuels from another supplier may also be a way to overcome this issue. Non-desulphurised hydrogen can, however, be safely used in certain types of FC, such as high temperature PEMFCs without disturbing the functioning of the cell.

Ethanol can offer an alternative to logistic fuels as a raw material used in the reforming process for hydrogen production. Ethanol is already in use in combustion engines (mainly motorsports) and is sulphur-free. Reforming of ethanol would, in comparison, provide a higher quality process gas for fuel cells (e.g. SOFC) than diesel. Also, new developments in DMFC replace the methanol with ethanol, resulting in less toxic DEFC fuel cells.

Other Fuels used in FC

For high temperature systems such as molten carbonate and solid oxide cells, it is possible to supply a hydrocarbon (e.g. natural gas) directly to the fuel cell without prior reforming. The high temperature allows the reforming stage to take place within the fuel cell structure. In practice, some preliminary reforming or purifying of the fuel is often carried out.

The exception to this is direct methanol fuel cells, in which a catalyst on the anode direct oxidises methanol water mixtures to CO_2 and protons, eliminating the need for a fuel reformer. Therefore, as the name suggests, pure methanol can be used as fuel.

Hydrogen Storage

The most popular fuel cell type used for backup power applications and vehicles is PEMFC with compressed hydrogen fuel although other fuel options do exist, such as propane, natural gas, methanol, metal hydrides and sodium borohydride.

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[94] https://apps.dtic.mil/dtic/tr/fulltext/u2/a532466.pdf
[95] https://pubs.rsc.org/en/content/articlepdf/2018/ra/c7ra12784g

An important issue that arises when dealing with hydrogen is the fact that hydrogen leakage is very high. Hydrogen can be stored in gaseous or liquid form. It can also be stored in solid form, in chemical combination with other elements; a number of metals can 'absorb' large amount of hydrogen (> 10 wt%). Hydrogen is released from these compounds by heating or upon addition of water. Other storage media are being investigated, for example carbon nanotubes [96] and glass microspheres. [97]

Gaseous Hydrogen: Compressed hydrogen offers the simplest and least expensive solution to fuel storage and also has the advantage of not needing pre-processing. Since gaseous hydrogen has a very low energy density, high pressures are usually applied (up to 690 bar), in order to maximise hydrogen content. These high pressures mean that very heavy storage vessels need to be used to avoid mechanical failure. The hydrogen bottles can be made out of high strength steel, aluminium or composite fibre. [98] Composite tanks can have seven to eight times lower weight and higher pressure resistance, allowing more hydrogen to be stored in a relatively small volume. Thus, composites fibre is the preferred option for mobile applications. For stationary application where the weight is not a decisive factor, metallic tanks can be used.

Operational difficulties to be taken into account are that tanks suffer from hydrogen embrittlement after several recharges [99] and are an explosive hazard if not handled properly. [100] The primary driver of the storage system cost is materials. Carbon fibre for instance, represents 40 % to 80 % of the tank cost, offering significant opportunities for cost reduction. [101] Though the cost of tanks is highly dependent on fibre costs, the exact recipe of the resin is kept secret by the manufacturers.

Liquid Hydrogen: Liquid hydrogen has a higher energy density than gaseous, but is still low. They require very low temperatures - less than 20.15 K - and must therefore be stored in cryogenic dewars - multi-shell flasks made of stainless steel with an evacuated interstitial space and multi-layer Mylar insulation to reduce heat transfer through the flask and to avoid boil-off of the gas. The storage of liquid hydrogen has several issues, like high cost, complexity and safety concerns. There are also logistical issues such as limited availability and refuelling which requires special equipment and skills. It is therefore not the optimum option for military application.

Solid storage: Researchers have demonstrated in computer models that the 3D architecture of hybrid nanomaterial would be able to store enough hydrogen to become a practical fuel for light-duty vehicles. [102] Nanomaterial hybrids could make hydrogen storage economically feasible for next-generation vehicles. More attention is therefore paid to metal hybrid solid storage in this report.

A large group of metal alloys can react with hydrogen reversibly to form metal hydrides. [103,104] However, only a few of them are suitable for hydrogen storage. The alloy must

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[96] https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/30535an.pdf
[97] http://www.eolss.net/sample-chapters/c08/e3-13-07-03.pdf
[98] Rob Baumert Danny Epp. Hydrogen Storage for Fuel Cell Powered Underwater Vehicles, Engineering in Harmony with Ocean, Proceedings OCEANS '93.. IEEE. Victoria, 1993. - Vol. 2. - 0-7803-1385-2.
[99] Swider-Lyons, Karen E.; et al. Technical Issues and Opportunities for Fuel Cell Development for Autonomous Underwater Vehicles. Proceedings of the 2002 Workshop on Autonomous Underwater Vehicles, IEEE, 2002. 2. P 200. 0-7803-7572-6.
[100] Gish Lynn Nadrew. Design of an AUV Recharge System, Department of Ocean Engineering. MIT, 2004.
[101] https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/merit03/44_quantum_neel_shirosh.pdf
[102] Oxygen- and Lithium-Doped Hybrid Boron-Nitride/Carbon Networks for Hydrogen Storage; Farzaneh Shayeganfar and Rouzbeh Shahsavari; Langmuir 2016 32 (50), 13313-13321; DOI: 10.1021/acs.langmuir.6b02997
[103] G. Sandrock and G. Thomas, IEA/DOE/SNL Hydride Database, http://hydpark.ca.sandia.gov.

react and release hydrogen readily at moderate pressure and temperature, and must be stable to maintain its reactivity and capacity over thousands of cycles. This special group includes materials from the AB5, AB2 and AB types, where A and B are metal elements. Examples are LaNi5-xAlx, TiV2-xMnx and FeTi1-xMnx, where x is a variable for adjusting the equilibrium pressure and stability of the material. [105]

Metal hydrides are heavy, making them feasible only for large vehicles. However, aluminium hydride is considered a promising material that can be used for storing hydrogen in portable fuel systems. [106] They suffer from high cost and sensitivity to water, carbon monoxide and oxygen and also lose storage efficiency over multiple cycles.[107] Hydrogen production rates can be controlled, making it the safest medium.

3.4 Trends in fuel cells and hydrogen storage technology

A fuel cell is a promising power source with high potential, which can play an important role in meeting the power needs of both the industrial and military sectors. Supportive government policies in the USA, EU, China, Japan and South Korea for technologies powered by alternative fuels, with a less detrimental impact on the environment, have boosted market growth. This is also seen as an opportunity to reduce fossil fuel dependence.

In the early 2000s, fuel cells were expected to be in high demand for military purposes, but these expectations have not been realised. Today, the main drivers for fuel cells are material handling vehicles in the USA, stationary residential power supply in Japan, automotive applications, and more recently, heavy duty automotive power supply.

In the future, demand from military applications might represent one driving factor of the FC market alongside growing demand for efficient and cleaner technologies (industrial applications). [108]

The key trends impacting the FC market are: rise in distributed power generation, increase in R&D investments and activities and increased interest in CHP.

The key market challenges are high implementation costs (high investment required by market players), stiff competition from alternative sources (batteries for energy storage and fossil-fuel generators for stationary power) and uncertainties associated with low crude oil prices. In addition the number of alternative catalyst/fuel suppliers is limited.

The global FC market for industrial and military applications is expected to grow from 207.76 MW in 2017 to 355.63 MW by 2021. [108] It is an accelerating market: year on year annual growth is expected to increase from c. 13 %, registered in 2017 to more than 15 % in 2021. The FC market for industrial and military applications comprised around 42 % of the global FC market in 2016. [108]

The Asia-Pacific (APAC) region represents the biggest FC market share – around 60 %, followed by Americas – 33 %, whilst EMEA (Europe, the Middle East and Africa) countries account for a relatively small share of about 7 %. However, the biggest growth for the period 2017-2021 of about 18 % CAGR is expected to occur in EMEA.

The FC market for stationary application is expected to increase by a CAGR of around 15 % by 2021, transportation applications by 13 % and portable applications by 18 %.

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[104] Hyakudome, Tadahiro. Design of Autonomous Underwater Vehicle. International Journal of Advanced Robotic Systems, 2011, 8, 122-130.
[105] https://pdfs.semanticscholar.org/b781/192e2624db103d1b615502dd44354eff9b52.pdf
[106] https://www.energy.gov/eere/articles/4-ways-fuel-cells-power-us-military
[107] Swider-Lyons, Karen E.; et al. Technical Issues and Opportunities for Fuel Cell Development for Autonomous Underwater Vehicles. Proceedings of the 2002 Workshop on Autonomous Underwater Vehicles, IEEE, 2002. 2. P 200. 0-7803-7572-6.
[108] Technavio, Global fuel cells market for industrial and military application, 2017-2021.

In the longer term, the transport sector is expected to account for the greatest share of FC deployment. Availability of hydrogen refilling infrastructure is a key enabler for the large-scale deployment of FC vehicles. Producing hydrogen by using renewable energies is also crucial to achieving the desired environmental effect. According to the Hydrogen Council, hydrogen demand could increase tenfold by 2050. [109]

The USA, Germany, and Japan have the greatest number of stationary fuel cell power stations.

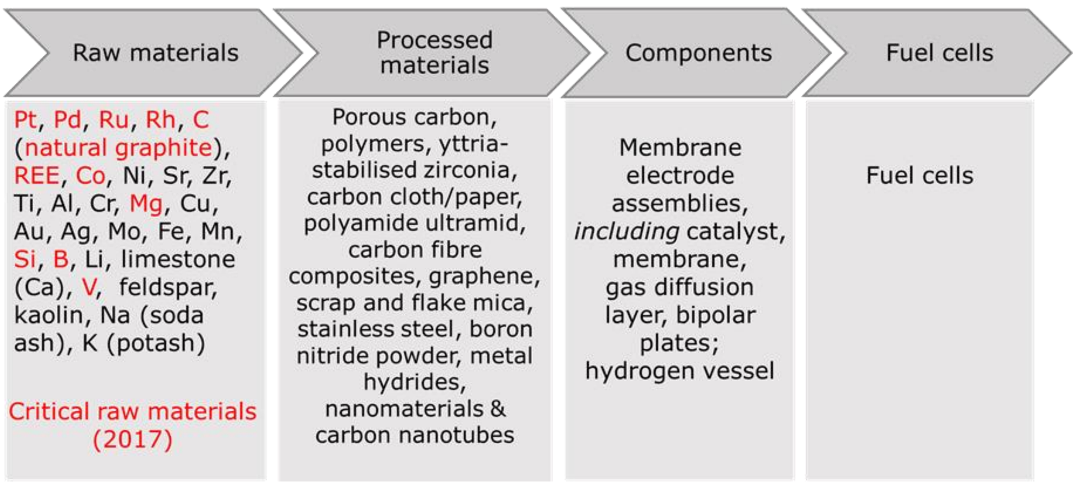
3.5 Materials supply chain in fuel cells, hydrogen production and hydrogen storage

3.5.1 Main steps of the fuel cell, hydrogen production and storage supply chain

The fuel cell and hydrogen supply chain is in its early days. A commercially embryonic technology compared with traditional energy sources, it is difficult to perform a thorough analysis comprising all manufacturing players.

The schematic representation of the supply chain for FC and hydrogen production and storage is shown in Figure 20. Hydrogen production is the first step of the supply chain (mainly catalysts required for hydrogen production), while hydrogen storage (tanks or vessels) is reflected in the first 3 steps.

Figure 20 Fuel cells and hydrogen technologies: an overview of raw materials, processed materials and components considered in the analysis



Source: JRC

Step 1: Raw materials in FC, hydrogen production and hydrogen storage

Around **30 raw materials** were found to be the most significant in the manufacture of fuel cells and hydrogen storage technologies. Of these materials, 11 materials namely Co, Mg, REE, Pt, Pd, B, Si, Rh, Ru, graphite and V are deemed critical for the EU economy according to the 2017 CRM list. Pt, Pd, Rh and Ru belong to a family known as platinum group metals (PGMs). Their unique chemical and physical properties make PGMs excellent as a raw material, as catalyst for the automotive industry (as catalytic converters which reduce gas emissions) and as an ingredient for other manufacturing processes. In fuel cells, platinum is used as a catalyst, facilitating the combination of

[109] Hydrogen Council, Hydrogen scaling up, A sustainable pathway for the global energy transition, November 2017.

hydrogen (or other fuel) and oxygen. Today, platinum demand for fuel cell applications is insignificant compared with other end-use applications. The quantity of platinum requested depends on the end-use application. For example, a fuel cell vehicle needs about 28 grams of platinum, 10 times more than the PGM loading for the average gasoline or diesel vehicle.

The high price of platinum is one of the major challenges that fuel cell vehicles face; platinum represents about 50 % of the cost of a fuel cell stack.[110] Hence, researchers are continuously trying to reduce the need for platinum in fuel cells. A significant reduction has been achieved in the recent years. According to Bart Biebuyck, executive director of the European Commission's fuel cell and hydrogen joint undertaking, the amount of platinum in the next generation of fuel cell vehicles has already been cut to levels similar to that used in the catalytic converters of diesel vehicles, which corresponds to 3-7 grams. Due to lower production of diesel vehicles in Europe, which cut platinum demand from vehicle manufacturers by a few percentage points, the global demand for platinum is expected to remain low in 2018, after a modest surplus in 2017.

Platinum is produced mainly in South Africa (71 % of global production), followed by Russia (16 %) and Zimbabwe (6 %). The three largest platinum producers are Anglo American Platinum (South Africa), Impala Platinum (South Africa) and Lonmin (UK). In order to spur the demand for platinum in the fuel cell sector, these top world mining companies are investing in projects related to fuel cell technologies.

The other PGMs, namely **Pd**, **Rh** and **Ru** are also supplied predominantly by three key suppliers: Russia, South Africa and Zimbabwe.

Step 2: Processed materials in fuel cells

In total 12 materials are identified and analysed as the most relevant processed materials for FC and hydrogen storage/production technologies, namely porous carbon, Yttria stabilised zirconia, polymers (e.g. perfluorosulphonic acid - PFSA), carbon fibre composites (CFC), stainless steel, graphene, scrap and flake mica, boron nitride powder, nano materials & CNT, carbon cloth/paper, polyamide ultramid and metal hydrides.

Porous carbon materials play a significant role in fuel cell applications, especially for polymer electrolyte membrane fuel cells, alkaline fuel cells and phosphoric acid fuel cells. They are used in bipolar plates, catalyst supports and for microporous layers for the flow of reactants and products. The properties of carbon with respect to the components play a major role in optimising the electrochemical reactions without carbon corrosion. Porous carbon has a controllable specific surface area, can be formed into various structures and shapes, and has good electric thermal conductivity. Top players of porous carbon are: Mersen (France), SGL Group The Carbon Company (Germany), Toyo Tanso Co.,Lt (Japan), Schunk (Germany), Sinosteel Corporation (China) and Fangda Carbon New Material Co., Ltd (China) (Annex 2 Table 33). Shares are calculated based on the number of companies per country, considering HQ locations.

The *polymer electrolyte* plays a major role in fuel cells by providing ionic conductivity while preventing the passage of electrons; it acts as a barrier to reactants and maintains chemical, thermal and mechanical stability. The development of PEMFC is strongly related to improvements in performance of the polymer electrolyte membrane. A major breakthrough for PEMFC started with the invention of a perfluorinated sulphonic acid (PFSA) membrane, introduced by DuPont in the 1960s under the name Nafion. Since then significant achievements have been demonstrated in the field of fuel cell durability and mitigation, including understanding the degradation mechanism of the PFSA polymer membrane and other components. Today, the most common membranes used in PEMFC are the thinnest Nafion 112 and 111, while the DMFC prefer Nafion 117 and Nafion 115.

[110] A. Sieron, will the fuel cells vehicles save platinum and palladium?. August 2017. Available at: https://www.sunshineprofits.com/gold-silver/free-alerts/will-fuel-cells-vehicles-save-platinum-and-palladium/

A challenge for PFSA development is to lower the price. PFSA polymer membranes for fuel cell applications are commercialised today by a few key players such as Chemours (USA), Solvey (Belgium) and Dongyue (China); see Annex 2 Table 35.

While the commercial PEMFCs and DFMCs are based on the Nafion polymer membrane, solid oxide fuel cells (SOFC) mostly employ *yttria-stabilised zirconia* (YSZ) ceramic material. In fact, the state-of-art SOFC uses nickel and YSZ composite for its anode. Yttria stabilised zirconia offers high ionic conductivity and electronic resistivity over a wide range of oxygen partial pressures. In addition, it is chemically stable at high temperatures in oxidizing and reducing atmospheres, chemically and mechanically compatible with the other cell components and gas tight. [111] Some challenges associated with YSZ for solid oxide fuel cell applications are linked to the development of nanoscale ordered structure with a large surface area. Other emerging applications for YSZ are textiles, nanofibres, electrolyte micro layers, ceramic applications and thermal coatings. Some of the market players functional in the market of yttria-stabilised zirconia are Zircomet Ltd. (UK), Inframat Advanced Materials (USA), and Elan Technology (USA).[112] See Annex 2 Table 34 for more companies considered in the analysis. Shares are calculated based on the number of companies per country, considering HQ locations.

Stainless steel is used in bipolar plate flow channel substrates in proton exchange membrane fuel cells (PEMFCs).

Composite fibres are an important part of the advanced hydrogen storage vessels. Data on CFC production per country are taken from Statista. [113]

Carbon nanotubes (CNTs) hold applications in various fuel cell components. They have several properties, such as high thermal conductivity and surface area, making them valuable as electrode catalyst supports in PEM fuel cells. Owing to their high electrical conductivity, they may also be used in gas diffusion layers, besides current collectors. The high strength and toughness-to-weight characteristics of CNTs may also prove useful as part of composite components in fuel cells that are used in transport applications, where durability is paramount. [114]

Nanomaterials and nanotechnologies can improve fuel cells. For instance, companies are using nanoparticles of platinum to reduce the amount of platinum needed, or using nanoparticles of other materials to replace platinum entirely and thereby lower costs. Nanotechnologies can also be used to create more efficient membranes, which will allow for lighter weight and longer lasting fuel cells. [115]

Companies producing nano-materials and CNT considered in the analysis are listed in Annex 2 Table 38. Shares are calculated based on the number of companies per country, considering HQ locations. [116]

Scrap and flake mica are used as sealant materials in FC. Sealing is critical to the performance and safety of fuel cell stacks. USGS data are used to calculate the shares.[117]

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[111] S-J. Hao, C. Wng, T-L. Liu, Z-M. Mao, Z-Q. Mao and J-L. Wang, Fabrication of nanoscale yttria stabilized zirconia for solid oxide fuel cel, International Journal of Hydrogen, 42 (2017) p. 29949-29959.
[112] Transparency Market Research, Yttria-stabilized Zirconia (YSZ) Market - Global Industry Analysis, Size, Share, Growth, Trends and Forecast 2017 – 2025.
[113] https://www.statista.com/statistics/380549/leading-countries-by-carbon-fiber-production-capacity/
[114] https://www.azonano.com/article.aspx?ArticleID=4842
[115] http://www.understandingnano.com/fuel-cells.html
[116] https://www.nanowerk.com/nanotechnology/nanomaterial/suppliers_plist.php?subcat1=cnt
[117] https://minerals.usgs.gov/minerals/pubs/commodity/mica/mcs-2018-mica.pdf

Graphene is essential for the safe storage of hydrogen for new next-generation fuel cell technologies. [118] It is therefore also considered in the evaluation. Shares are calculated based on the number of companies per country. [119]

Carbon cloth/paper is used in the gas diffusion layer (GDL), which is a core component of a fuel cell. The main function of GDL is to provide conductivity, and help gases to come in contact with the catalyst. Shares are calculated based on the number of companies per country, considering HQ locations (for companies see Annex 2 Table 39).

Finally, *polyamide ultramid* is used to manufacture the anode- and cathode-end plates in fuel cells. Shares are calculated based on the number of shipments per company [120] (for companies see Annex 2 Table 40).

Storing hydrogen in *metal hydrides* is an emerging technology not yet commercialised . There are therefore few companies supplying powders for solid-state hydrogen storage. Metal hydrides, such as MgH_2, $NaAlH_4$, $LiAlH_4$, LiH, $LaNi_5H_6$, $TiFeH_2$ and palladium hydride, with varying degrees of efficiency, can be used as a storage medium for hydrogen, often reversibly. [121] The most promising hydrides include the magnesium, lithium, boron, and aluminium based compounds. La-Ni based hydrates also have potential for portable military applications.[122]

The following companies are known to deliver hydrogen storage grade metal hydrides (Table 9 and Annex 2 Table 36):

Table 9 Companies delivering hydrogen storage grade metal hydrides

Company (country)	**Details**
McPhy Energy (France)	Developed the first industrial product, based on magnesium hydride, already sold to some major clients such as Iwatani and ENEL. [123]
MBN Nanomaterialia S.p.A. (Italy)	Leader in storage material development tasks, experience in producing materials for hydrogen storage. It has a production capacity of Mg based materials in the range of kg/day. [124]
GKN (UK)	Supplier of metal hydrides for hydrogen storage
Sigma Aldricht (USA)	Supplier of variety of hydrogen storage grade powders such as La-Ni alloy, Ca hydride, Li-Al hydride, Sc chloride, Mg powder [125]
Alfa Aesar (USA)	Supplier of La-Ni powder hydrogen storage grade. [126]
American element (USA)	Supplier of metal hydrides for hydrogen storage. [127]
Changsha Easchem Co. (China)	Supplier of La-Ni powders. [128]

118 http://www.digitaljournal.com/tech-and-science/science/essential-science-graphene-holds-the-key-to-next-gen-fuel-cells/article/502682
119 https://www.graphene-info.com/companies
120 https://panjiva.com/Manufacturers-Of/polyamide+ultramid
121 https://ijerat.com/uploads/2/3329_pdf.pdf
122 S. Satyapal, US DoE, Hydrogen and fuel cells overview, April 2017.
123 https://www.greentechmedia.com/articles/read/update-mcphy#gs.1N6VJIM
124 http://www.h2eden.eu/consortium/mbn-nanomaterialia-spa
125 https://www.sigmaaldrich.com/nederland.html
126 https://www.alfa.com/en/
127 https://www.americanelements.com/Hydrogen-Storage.html
128 https://www.alibaba.com/product-detail/LaNi5-Alloy-Powder-with-Alias-Lanthanum_60360028333.html

Europe features as a supplier of hydrogen storage grade powders, bearing in mind that Sigma Aldricht and Alfa Aesar also have offices in Europe.

Boron nitride powder and *carbon nanomaterials* are also considered promising as a solution for hydrogen storage [129], and are therefore included in the supply chain analysis. Companies producing boron nitride powders are listed in Annex 2 Table 37. [130]

There are several other hydrogen storage solutions currently under investigation. The possibilities include carbon nanotubes, doped polymers, glass capillary arrays, and glass microspheres. Keratine, a compound found in bird feathers, has been found to be useful for increasing the surface area of hydrogen storage tanks, with lower manufacturing costs than other mechanisms. However, these options are still at R&D stage. [131]

Step 3: Components in Fuel cells

The next step in the fuel cell value chain is the manufacturing of MEA elements, followed by assembling a MEA and bonding the MEA to the bipolar plates to form a cell stack. The MEA is the heart of the fuel cell and is unique to the PEM fuel cell. It is made of a membrane, the catalyst layers and the gas diffusion layers (GDL). The bipolar plates in the PEM cell are the final component used in a PEM fuel cell. The MEAs can be fabricated in various sizes depending on the intended power and/or voltage output and the electrodes may differ in catalyst–ionomer composition tailored to specific operating conditions.

The *membrane* material is perfluorinated sulphonic acid (PFSA), which in some cases is reinforced with polytetrafluoroethylene (PTFE) to improve its mechanical strength.

The *catalysts* (electrodes) are usually made of a porous mixture of carbon-supported platinum and/or platinum alloys for cathode and anode respectively and ionomer (i.e., electrolyte). The catalysts are usually deposited as nanoparticles on the high-surface-area carbon (e.g. Ketjenblack EC300 or Vulcan XC-72), which is further deposited either on the membrane (the CCM manufacturing approach) or deposited onto the GDL (the GDE manufacturing approach). PFSA ionomer is infused into the catalyst layers, often from an alcohol solution. The PFSA ionomer must be thermally treated via hot pressing to preserve the ionomer and assure its stability in PEM fuel cell operation. The ionomer promotes the transport of protons through the catalyst layer since proton transport across the carbon particles is hindered. A catalyst layer that will have precious metal nanoparticles deposited on carbon will include a PFSA ionomer. Catalyst layers containing unsupported platinum blacks (e.g. fine particles of platinum) do not need the ionomer addition since the protons can move rapidly over platinum black surfaces.

A *gas diffusion layer* (GDL) is made from carbon cloth, carbon paper, or carbon felts. Carbon cloths are typically prepared by weaving carbon or graphite fibres. Carbon papers are prepared from a slurry of carbon particles and fibres to form a pulp which is cast and dried. Carbon felts containing a high carbon fibre content are processed with felting machines that use needles to disperse the carbon fibres in three dimensions. The felting process increases the strength of the carbon paper. The thickness, porosity, air permeability, and electrical resistance are important properties that can be modified to provide the specific property requirements. For example, the micro-layer on the GDL made up of carbon particles and PTFE assists in the transport and distribution of liquid water and reactant gases to and from the catalyst layers. Some carbon micro-layers are fabricated from Ketjenblack or XC-72 carbon supports. Additives such as Teflon provide a way to control the hydrophobic properties of the micro-layer.

Bipolar plates connect adjacent cells in the cell stack. One side of the bipolar plate is the anode preform for a cell while the other side is the cathode preform for the adjacent cell.

[129] https://pdfs.semanticscholar.org/3856/047976ebdcb6455cc39da2f06d0bb7b7c3d6.pdf
[130] https://www.industrystock.com/html/boron-nitride-powder/product-result-uk-181788-0.html
[131] http://www.fuelcell.co.uk/hydrogen-storage/

Ideally, in operation, the bipolar plates are electrically neutral; however internal resistance will develop a small potential across the bipolar plate. The plates have channels for directing the flow of reactants through the cells. Bipolar plate manufacturing is strongly influenced by the construction materials. The material options for bipolar plates are graphite-resin polymer composite, expanded graphite flake fabricated into a flexible graphite foil or sheet metal.

In view of the anticipated growth of fuel cell vehicles, a recent analysis focusing on the regional strength of fuel cell manufacturing components (e.g. elements of membrane electrode assemblies) and compressed gas storage revealed that the fuel cell supply chain is pragmatic for small-scale production.[132] However, supplier choice remains limited, costs are still high, material supplies are not always guaranteed, and manufacturing capability is generally inadequate. These issues might make it difficult to ensure quality and industry readiness in some regions and for some components for large-scale manufacture (over 100 000 fuel cells per year) (Figure 21).

Figure 21 Technology and manufacturing readiness of fuel cell components and hydrogen storage tanks for two manufacturing scales of fuel cell vehicles

	Technology Readiness																			
	Bipolar Plate				Catalyst				Gas Diffusion layer				Membrane				H2 Vessel			
	US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia	
			Japan	China			Japan	China			Japan	China			Japan	China			Japan	China
1-10k	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
100k	M-L	MOD	MOD	LOW	MOD	H-M	H-M	MOD	MOD	MOD	MOD	LOW	H-M	H-M	H-M	H-M	H-M	H-M	H-M	H-M

	Manufacturing Readiness																			
	Bipolar Plate				Catalyst				Gas Diffusion layer				Membrane				H2 Vessel			
	US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia	
			Japan	China			Japan	China			Japan	China			Japan	China			Japan	China
1-10k	H-M	HIGH	HIGH	HIGH	H-M	HIGH	HIGH	HIGH	H-M	HIGH	HIGH	HIGH	H-M	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
100k	M-L	MOD	MOD	LOW	MOD	H-M	H-M	LOW	M-L	MOD	MOD	LOW	LOW	MOD	M-L	LOW	M-L	M-L	M-L	M-L

Readiness Legend:

HIGH	Currently sufficient to produce to stated demand
HIGH TO MODERATE	Capability and capacity exist, although no current production demonstrated at stated demand
MODERATE	Requires some advancements or capital investment to produce to stated demand
MODERATE TO LOW	Requires some advancements capital investment, and no current production demonstrated at stated demand
LOW	Requires major advancements or major capital investments to produced to stated demand

Source: GLWN[132]

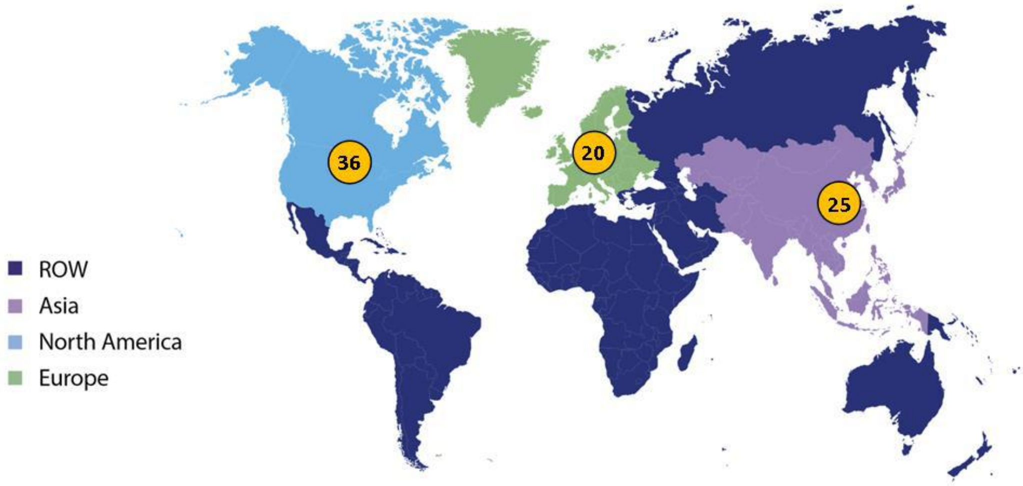
For low output production levels (up to 10 000 fuel cells vehicles per year) both Asia and Europe reflect a high production capability for the fuel cell components and hydrogen pressure vessels. At high production volumes (above 100 000 per year) there is a mix of capability across regions for the technology or manufacturing readiness of various components. Overall, Europe and Japan are in the best position for both technology and manufacturing readiness of fuel cell and hydrogen storage tanks (Figure 21). For fuel cell components, the EU is best placed, with key suppliers producing these components at lower volumes who could ramp up the major investment. For hydrogen pressure vessels, the technology exists and additional manufacturing capability could be added to meet high output unit volumes.

Figure 22 shows the estimated number of OEMs and suppliers by region that are actively producing or could potentially produce fuel cell components (e.g. bipolar plates,

[132] P.H. Fullenkamp and D.S. Holody, GLWN – Global Wind Network, US clean energy hydrogen and fuel cell technologies: a competitive analysis, October 2017.

catalysts, gas diffusion layers, membranes) and hydrogen vessels at the quality and volume required for automotive applications. For instance, in the EU there are many suppliers of fuel cell components located in Germany. The numbers are used for calculation of the shares related to components supply.

Figure 22 Fuel cell components suppliers for automotive applications by region



Source: GLWN[132]

Vessels (tanks) for hydrogen storage are included and assessed as a 'component' in the current analysis.

Tanks for gaseous hydrogen storage

Compressed hydrogen storage tanks are currently the most popular since they do not require the super-cooling and super-insulation that liquid hydrogen does. However, compressing hydrogen fuel into storage tanks does bring its own unique challenges. Unlike pressurising natural gas, hydrogen is less dense and requires better seals. In addition, hydrogen storage tanks need to be made from lighter materials such as aluminium or carbon / graphite compounds. The four common types of high pressure gaseous storage vessel are shown in Table 10 [133].

Table 10 High pressure vessels types for hydrogen storage

Type 1	Metal tank (**steel/aluminum**) Approximate maximum pressure, aluminum 175 bars, steel 200 bars.
Type 2	Metal tank (**aluminum**) with filament windings like **glass fibre/aramid** or **carbon fibre** around the metal cylinder. Approximate maximum pressure, aluminum/glass 263 bars, steel/carbon or aramide 299 bars.
Type 3	Tanks made from **composite material**, **fibreglass/aramid** or **carbon fibre** with a metal liner (**aluminium** or **steel**). Approximate maximum pressure, aluminum/glass 305 bars, aluminum/aramide 438 bars, aluminium/ carbon 700 bars.
Type 4	**Composite tanks** such as **carbon fibre** with a **polymer liner** (thermoplastic). Approximate maximum pressure 700 bars.

[133] https://www.energy.gov/eere/fuelcells/site-and-bulk-hydrogen-storage

Type 1 vessels are the most common and cheapest. Due to their heavy weight they are predominantly used to transport hydrogen from hydrogen production facilities to transport terminals or end-use locations. When only higher pressures are required, mainly for stationary applications, type 2 tanks are preferred. Type 3 and type 4 vessels are intended for mobile applications, for which weight savings are essential. Currently the costs of type 3 and type 4 vessels are greater than those of type 1 and 2. More recently, type 3 and type 4 have been used for hydrogen trailers. This allows for the transport of larger quantities of hydrogen at lower cost even if the manufacturing cost of these composite cylinders is higher than the manufacturing cost of type 1 cylinders.[134] It is expected that with additional cost reductions in carbon fiber and improved manufacturing methods these technologies could ultimately cost less than the traditional metal type 1 cylinders.

There are plenty of suppliers for tanks of type 1 which are therefore not deemed critical. Composites tanks (especially type 4) are an emerging technology and there are only a few suppliers, listed below.

Hexagon Raufoss (Norway) is the market leader for complete storage and transport systems for gas and fuel cylinders (type 4) for compressed natural gas (CNG, and hydrogen) powered passenger cars and commercial vehicles (natural gas/hydrogen vehicles). [135]

Hexagon X-perion (Germany), a Hexagon Composites company, has specialised in lightweight components and systems made of fiber composite materials. [136] Hexagon X-perion develops and produces composite high-pressure vessels (type 4) for installation into vehicles of all kinds for the storage and transportation of compressed gases, in particular natural gas and hydrogen. They also produce special diving tanks for the Navy.

RAIGI [137] (SME based in France) works on developing materials for hydrogen tanks. In particular, the company develops liners for type 4 hydrogen cylinders up to 700 bar, using an exclusive technology (Commissariat à l'Energie Atomique or Atomic Energy Commission - CEA patent). The company is now looking to scale up and commercialise the process.

ULLIT SA [138] (France) is a high-pressure ultra-light tanks manufacturer. ULLIT SA has partnered with CEA as part of 'StorHy' (acronym for hydrogen storage systems in automotive applications) - a project funded by the European Union to work on accelerating the engineering of onboard gas hydrogen storage technologies for automobiles. The project ended in 2008.

Optimum CPV [139] (Belgium) is now part of Seifert and Skinner Group (SSG) [140], which is one of the world's leading experts in Composite Pressure Vessels.

Faber Cylinders [141] (Italy) manufactures all four types (1, 2, 3, 4) of hydrogen cylinders for different applications such as stationary storage, industrial applications, refilling stations, fuel cell usage and transport. Faber produces the shells, and also fabricates the liners for all types of composites in-house.

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[134] http://www.ichs2013.com/images/papers/132.pdf
[135] http://www.hexagonraufoss.com/
[136] https://www.hexagonxperion.com/en/home.html
[137] http://www.raigi.com/en/en_contact.php
[138] http://ullit.com/index.php/fr/
[139] http://flag.be/flag-member/optimum-cpv/
[140] http://www.seifert-skinner.com/
[141] http://www.faber-italy.com/eng-product-hydrogen.asp

Tenaris [142] (Italy) manufactures steel type 1 cylinders for a wide range of applications: industrial gases, Natural Gas for Vehicles (NGV), large-diameter vessels with a capacity of up to 3000 litres and cylinders for special applications.

Luxfer [143] (USA) produces lightweight high-pressure hydrogen-storage type 3 cylinders, used by a number of the world's largest OEMs that design, develop and manufacture state-of-the-art compressed hydrogen-storage systems for fuel cell and internal-combustion engines. In 2012 Luxfer acquired Dynetek, which has a leading position in compressed natural gas (CNG) cylinders and alternative fuel (AF) systems for buses and heavy-goods vehicles and is a global authority on portable hydrogen containment.

Volute [144] (USA) was founded with support from DOE's Advanced Research Projects Agency-Energy (ARPA-E) and the California Energy Commission. Volute manufactures conformable tanks, allowing high-pressure hydrogen to be stored in spaces of any shape. Vehicle designers can use Volute's tank to make low-cost hydrogen vehicles with more driving range and cargo space. Volute collaborates with Linamar Corporation (Canada) for hydrogen tanks.

Toyota [145] (Japan) produces high pressure hydrogen tanks for its model Mirai, sold in Japan, the United States, and nine countries in Europe.

The companies do not share information regarding their suppliers of fibers. However, *TORAY Industries* (Japan) is believed to be the main supplier of fibers for hydrogen storage tanks. Fibers represent around 63% of the overall manufacturing cost of a tank.[146]

It should be noted that composite tanks for hydrogen storage are still an emerging technology, in many cases at research and demonstration stages. There is therefore not yet any well-established supply chain. Several EU-funded projects, such as COPERNIC (ended in 2016) and its successor Hiphone address this issue. [147] The partners of these projects have included numerous SMEs across Europe.

Tanks for liquid hydrogen storage

Liquid hydrogen is a common liquid rocket fuel for rocketry applications - both NASA and the United States Air Force operate a large number of liquid hydrogen tanks with an individual capacity of up to 3.8 million liters. [148] Liquid hydrogen can also be used as a fuel for internal combustion engines or fuel cells. Various submarines (Type 212 submarine, Type 214 submarine) and concept hydrogen vehicles were built using liquid hydrogen. DeepC, for instance, is an experimental German AUV development project conducted by a consortium coordinated by STN ATLAS Elektronik. [149] BMW H2R is racing car adapted to run on liquid hydrogen fuel. [150] Due to its similarity, developers can sometimes modify and share equipment with systems designed for liquefied natural gas (LNG). However, because of the lower volumetric energy, the hydrogen volumes needed for combustion are large. Storing liquid hydrogen in automobile tanks requires special handling and materials to contain the fuel and keep it cool. Hydrogen does not liquefy until -253 °C (20 degrees above absolute zero). Much energy is needed to achieve such temperatures. Liquid hydrogen can also be used for some industrial applications. Texas

[142] http://www.tenaris.com/en/Products/IndustrialAndMechanical/GasCylinders.aspx
[143] https://www.luxfercylinders.com/products/gstorh2
[144] http://voluteinc.com/our-company/
[145] https://newsroom.toyota.co.jp/en/corporate/22647198.html
[146] https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_plenary_leavitt.pdf
[147] https://www.fch.europa.eu/success-story/improved-hydrogen-tanks-fuel-cell-cars-future
[148] *Flynn, Thomas (2004).* Cryogenic Engineering, Second Edition, Revised and Expanded*. CRC Press. p. 401.* ISBN 978-0-203-02699-1*.*
[149] Alejandro Mendez, Teresa J. Leo, and Miguel A. Herreros, Current State of Technology of Fuel Cell Power Systems for Autonomous Underwater Vehicles, Energies 2014, 7, 4676-4693; doi:10.3390/en7074676.
[150] http://www.greencarcongress.com/2006/03/bmw_to_display_.html

Instruments in Stafford, Texas, uses the USA's largest commercial liquid hydrogen storage tank to supply hydrogen for semiconductor processing.[151]

Cryogenic liquid storage tanks, also referred to as dewars, are the most common way to store large quantities of hydrogen. Super-insulated low pressure vessels are needed to store liquid hydrogen at -253 °C. The pressure of liquid hydrogen is no more than 5 bar. Stainless steel is a convenient material to make dewars.

Suppliers: Cryogenic vessels have been in common use for more than 40 years for the storage and transportation of industrial and medical gases. There are many liquid hydrogen tanks suppliers (including European suppliers) and are therefore not deemed critical for supply chain analysis.

Tanks for solid-state hydrogen storage

Solid-state hydrogen storage solutions are theoretically able to store more hydrogen per unit volume than liquid or solid storage systems. Metal hydride hydrogen storage systems are normally used in applications where weight is not an issue, for instance forklift applications [152] or as APUs. [153] Solid-state hydrogen storage in metal hydrides and fuel cell technology is also implemented in modern submarines, which allows long stay under water and less noisy operation. [154,155] Solid-state hydrogen storage could also be an interesting solution for portable military applications as wearable soldier power.[156]

Metal hydride tanks could be the future for hydrogen storage for hydrogen cars, though there remain many issues to be solved. The purity of the hydrogen is one of these issues: as the metallic alloys sponge up hydrogen they also sponge up impurities that will eventually clog up the tank, affecting its lifetime.

Traditionally, metal hydride tanks are made of aluminium alloy or stainless steel.

There is now a well-established supply chain for solid-state hydrogen storage tanks. In most cases they are still at demonstration / prototyping stage. Some companies working in the field are listed below:

McPhy is a French company providing solid-form hydrogen storage solutions for stationary applications, mainly for integration of renewable energy sources. They also supply electrolyzes for hydrogen production. [157]

Pragma industries [158] (France) produces metal tanks for solid-state metal hydride storage.

Work is being carried out in Europe researching materials for hydrogen storage and developing prototype hydrogen tanks. Several European projects are focusing on using metal hybrids for hydrogen storage, such as SSH2S [159], EDEN [160], BOR4STORE. [161] Scientists from Helmholtz-Zentrum Geesthacht in collaboration with other European research organisations and universities, have developed a new chemical system for storing solid hydrogen. [162] HYDROCAR PREMIER [163] is a project conducted jointly by Riot

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151 http://infohouse.p2ric.org/ref/12/11198.pdf
152 https://www.hydrogen.energy.gov/pdfs/review11/st095_jensen_2011_p.pdf
153 https://www.sciencedirect.com/science/article/pii/S0306261918301090
154 D. Thomas, Canadian Naval Rev. 3 (4) (2008) 35.
155 H. Pommer, et al. ThyssenKrupp techforum (1) (2006) 64.
156 https://www.energy.gov/sites/prod/files/2017/06/f34/fcto-h2-fc-overview-dla-worldwide-energy-conf-2017-satyapal.pdf
157 https://mcphy.com/en/our-products-and-solutions/storage-solutions/
158 https://www.pragma-industries.com/products/hydrogen-storage/#
159 http://www.ssh2s.eu/
160 http://www.h2eden.eu/
161 https://cordis.europa.eu/project/rcn/104227_en.html
162 https://www.hzg.de/institutes_platforms/materials_research/news/076763/index.php.en
163 https://www.agh.edu.pl/en/blog-naukowy/info/article/hydrocar-premier-hydrogen-vehicle-from-agh-ust/

Technologies – a spin-off company of the AGH University of Science and Technology – and the Military University of Technology in Warsaw. The HYDROCAR PREMIER 2-seat sports car of the roadster type is a hydrogen vehicle which was demonstrated at the MOTO SHOW fair in Krakow in 2016.

Data on manufacturing shares per country for FC components, including BOP, Catalyst, GDL, Membrane and hydrogen vessels are based on the number of companies, given in the GLWN database. [132]

Step 4: Fuel cells

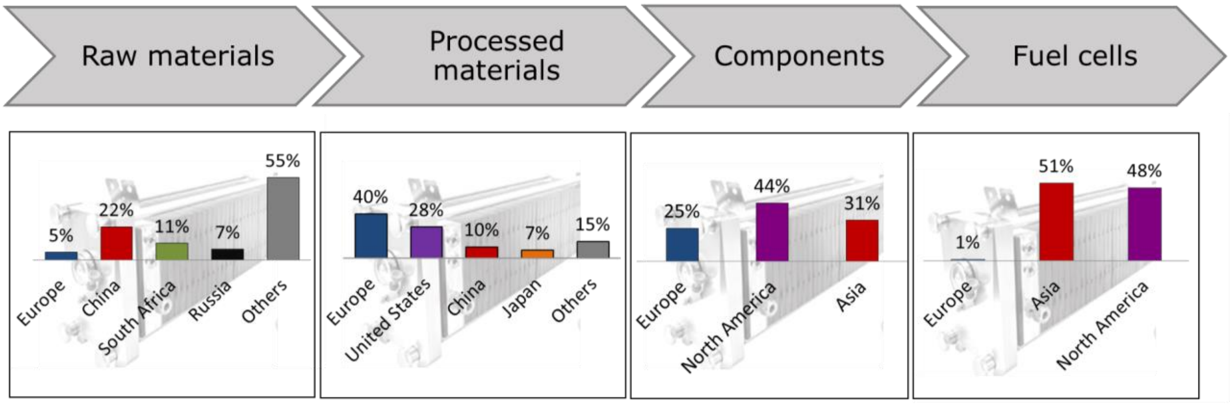
The manufacture of fuel cells by integrating different components is step 4 of the supply chain. Data on fuel cell manufacturing shares per country are taken from Fuel Cell and Hydrogen Annual Review 2017. [164]

Information on fuel cell stack assembly and system integration is given below, but not considered in the supply chain analysis.

3.5.2 Key players and market share along the fuel cells, hydrogen production and hydrogen storage value chain

The key players involved in the fuel cell supply chain are displayed in Figure 23. It should be noted that shares also account for materials used in hydrogen production (Step 1) and hydrogen storage (Steps 1, 2 and 3).

Figure 23 Fuel cells and hydrogen technologies: key players in the supply chain

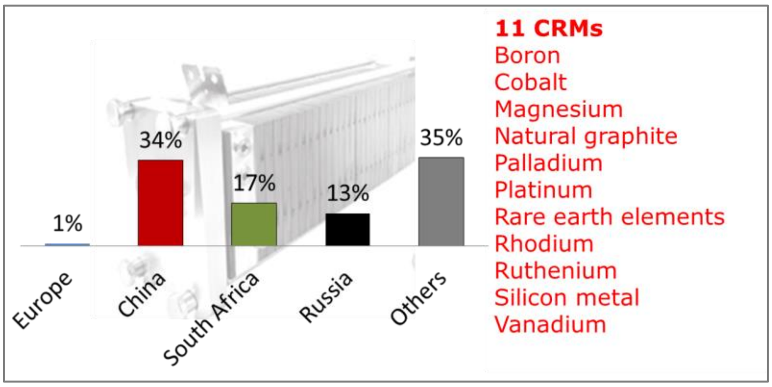


Source: JRC

The supply of raw materials required in fuel cell technology is rather diversified; more than half of the materials come from a variety of suppliers, each with a small supply share of less than 7 %. China, with more than 20 % share, is the major supplier of raw materials, followed by South Africa and Russia. With regard to the supply of critical raw materials (CRM), China is the major supplier of more than one third of CRMs for fuel cells and hydrogen storage/production. South Africa and Russia are other key suppliers of CRMs for FC and hydrogen production/storage (Figure 24).

[164]https://static1.squarespace.com/static/59f093254c0dbf084e7c521b/t/5a34089971c10b467be38de0/1513359529546/FuelCellandHydrogenAnnualReview2017.pdf

Figure 24 Supply of CRMs for fuel cells and hydrogen technologies: key players



Source: European Commission, 2017, Study on the review of the list of critical raw materials

Europe is well performs well in the supply of processed materials and components for fuel cells. Around 40 % of processed materials and 25 % of FC components are supplied by European companies. The major producers of fuel cells are Asia (mainly Japan and South Korea) and North America (Canada and USA). [165]

It is difficult to identify all players involved in the manufacture of each fuel cell type and component. Overall, key manufacturers of fuel cell systems are Ballard Power Systems (Canada), Hydrogenics Corp. (Canada), Nuvera Fuel Cells (USA), Oorja Fuel Cells (USA), Plug Power (USA), UTC Power (USA), Bloom Energy (USA), Doosan Fuel Cell America, Inc. (USA), FuelCell Energy (USA), ElectroChem Inc. (USA)and POSCO Energy (South Korea).

Toyota is at the forefront of Japan's efforts to use hydrogen and fuel cells to power cars, heat homes and keep factories running. Other Japanese companies pursuing the technology include Panasonic Corp., Toshiba Corp. and JX Nippon Oil & Energy Corp.

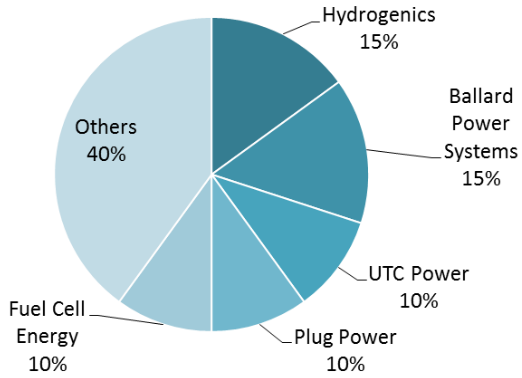
European companies manufacturing fuel cells for different applications include Siemens (Germany), Opel (Germany), Daimler Chrysler (Germany), SFC Energy (Germany), AFC Energy (UK), Heliocentris Energy Solutions (Germany), Haldor Topsoe (Denmark), Genport (Italy), Ceres Power Holdings (UK), Nedstack (Netherlands), NEL hydrogen (Norway) andKemtecnia (Spain). Ceres Power has announced the building of a fuel cell manufacturing facility in Redhill, Surrey. Manufacturing capacity will initially be 2 MW, expandable to 10 MW. [166] Germany accounts for more than 70 % of fuel cell installations in Europe due to huge government support. [167]

The market share of some of the major companies involved in fuel cell manufacturing for both industrial and military applications is shown in Figure 25.

In 2016 it was estimated that all companies together had installed about 184 MW and it was expected that the fuel cells market would increase at 356 WW in 2021. [168]

[165] Fuel Cell Technologies Market Report 2016, DoE.
[166] https://theenergyst.com/ceres-power-build-fuel-cell-manufacturing-plant-surrey/
[167] https://www.energymanagertoday.com/european-fuel-cell-market-2027-0175658/

Figure 25 Global market share for fuel cells by sales



Source: JRC representation with data from Technavio[168]

Fuel cell stack assembly and system integration

The last two steps of the fuel cell supply chain (not considered in the analysis) are the assembly of cell components into a stack and its integration in the final system. The stack design and cell assembly are very important parameters that can influence the performance of fuel cells and distribution of reactants in the cell stack. The cell assembly will also affect the contact behaviour of the bipolar plates with the membrane electrode assembly (MEA). Manufacturers must align precisely the repeating components (e.g. MEAs, bipolar plates and seals) and non-repeating components (e.g. end plates, tie rods, compression load system, and external manifolds) to maintain stack durability and performance. About 36 companies were identified that integrate fuel cell systems for various applications (Table 11).

Table 11 Companies involved in fuel cell integration

EU companies			Non-EU companies		
Audi AG (Germany)	HEXIS (Germany)	Serenergy (Denmark)	Ballard (Canada))	Doosan Fuel Cell America Inc (USA)	Oorja Protonics Inc (USA)
Bosch Thermotechnik GmbH (Germany)	Hoppecke (Germany)	SFC Energy AG (Germany)	Altergy (USA)	Energyor technologies Inc (Canada)	Intelligent Energy Limited (UK)
BMW AG (Germany)	Groupe PSA (France)	Siemens (Germany)	Acumentrics (USA	Enocell (UK)	Plug Power (USA)
Cellkraft (Sweden)	Liebherr-Aerospace Lindenberg GmbH (Germany)	SOLIDpower GmbH (Germany)	Bloom Energy (USA)	Hydrogenics (Canada)	Redox Power Systems (USA)
Eberspächer Climate Control Systems GmbH & Co. KG (Germany)	NuCellSys GmbH (Germany, a Daimler AG company)	Viessmann Werke GmbH & Co. KG (Germany)	UTC Power (USA)	Fuelcell Energy Inc (USA)	Shanghai Everpower Technology Co. Ltd (China)
EC POWER A/S (Denmark)	Proton Motors (Germany)	Daimler AG (Germany)	Ceres Power Holdings Plc (UK)	Horizon Fuel Cell Technologies (Singapore)	Sumitomo Corporation (Japan)

[168] Technnavio, Global fuel cells market for industrial and military applications 2017-2021, 2017.

3.5.3 Supply chain of civil versus military fuel cells, hydrogen production and storage applications

There is a large overlap between civil and military needs, such as high-energy density (greater than currently available lithium ion technology), low parasitic power, simplified BOP, high degree of safety, and wide power range.

In general, military power requirements can be classified into soldier power, auxiliary power units (APU), autonomous systems and distributed power plants.[169] The USA department of defence (DoD) has identified several distinct areas: soldier wearable and portable power; auxiliary power units for ground vehicles, ships and aircrafts; non-tactical light-duty vehicles; and propulsion power for ships, submarines, autonomous underwater vehicles (UUVs) and unmanned aerial vehicles (UAVs).[170]

Several companies operate in both the civil and defence sectors, including ACAL Energy (UK), Accumetrics (USA) and Plug Power (USA). There are other interesting examples where companies have used international partnerships to strengthen the fuel cell supply chain, which may suggest an approach that could strengthen EU battery and fuel cell supply chains more generally. In both cases the companies concerned have strong presences in military and civil domains and have partnered to increase the size of the markets they can access and enable them to offer new technologies to their customers:

General Motors (GM) and Honda have been collaborating on fuel cell technology development since 2013, as part of which they have set up a Fuel Cell System Manufacturing joint venture (January 2017) to produce next generation hydrogen fuel cell systems for both companies' future military and civil products, starting in 2020.[171] The aim is to reduce the cost of development and manufacture. This has increased the potential return on their joint R&D investment by addressing both military and civil markets and enabling the companies to achieve better economies of scale in production. GM have already produced a prototype Colorado ZH2 military fuel cell off-road tactical vehicle (based on a civil off-road vehicle) that was demonstrated to government and industry stakeholders in 2016 and tested by the USA Army in 2017 and 2018.

SFC Energy (Germany) teamed up with ZeroAlpha Solutions (UK) to trial SFC Fuel Cell technology with the UK MOD in 2017 in the Army Warfighting Experiment and Information Warrior exercises.[172] The fuel cells provided extended 'silent watch' capability and enhanced endurance for both vehicle and dismounted applications. SFC Energy is a provider of hybrid power solutions to the stationary and mobile power generation markets, while ZeroAlpha Solutions supplies sustainable power solutions to UK and European defence and security markets. ZeroAlpha customised SFC technology to meet military users' requirements. The two companies have set up a defence industry sales partnership.

There are good examples of R&D partnerships between companies involved in civil and military markets to develop and exploit fuel cell technologies in both markets, thereby helping to improve the business case for investment (e.g. GM and Honda in the transport field where USA military R&D investment is complementing and building on automotive fuel cell investment). Where joint (dual use) military and civil needs in fuel fells can be identified the business case for investment can be increased.

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[169] A.S. Patil, T.G. Dubois, N. Sifer, E. Bostic, K. Gardner, M. Quah, C. Bolton, Portable fuel cell systems for America's army: technology transition to the field. J. Power Sources 136, 220–225 (2004)

[170] T.J. Gross, A.J. Poche, Jr., K.C. Ennis, Beyond Demonstration: The Role of Fuel Cells in DoD's Energy Strategy, Chap. 2, p. 5

[171] Forbes, January 30th 2017, GM Teams Up With Honda To Manufacture Fuel Cells Near Detroit.

[172] SFC (https://www.sfc-defense.com), May 4th 2017, New UK partner ZeroAlpha Solutions successfully trials SFC Energy's fuel cells with UK Ministry of Defence.

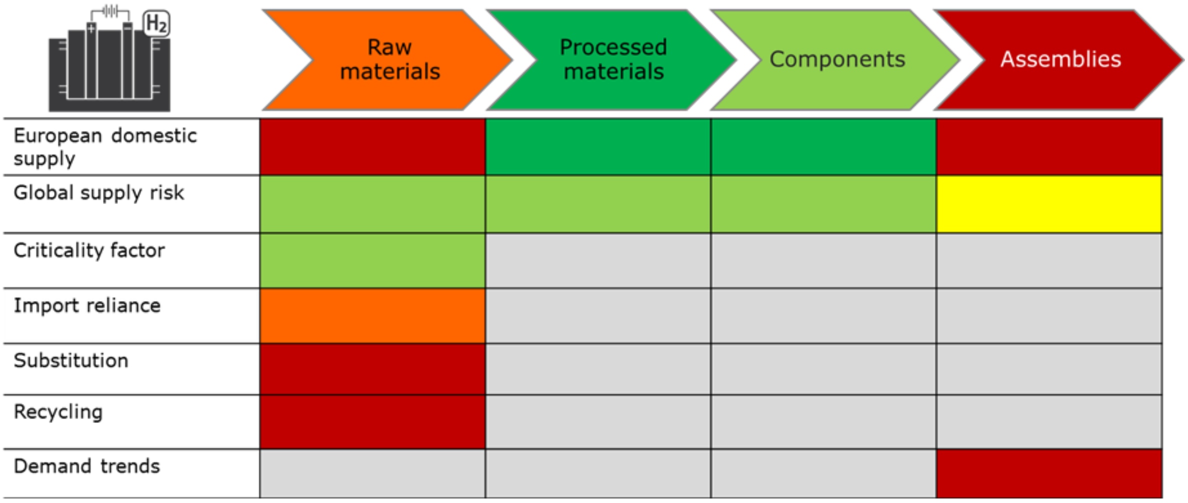
Currently both Europe and Japan are well placed in terms of technology readiness and manufacturing readiness of fuel cells and hydrogen storage systems. Fuel cells offer a good opportunity for European and Japanese R&D and procurement collaboration.

USA military R&D investment in fuel cell applications in portable power (e.g. for soldiers) and vehicle technologies (e.g. off-road vehicles), including R&D instruments such as the Small Business Innovation Research (SBIR) programme designed to lead to procurements if successful - is helping to develop new industrial capabilities with civil potential.

3.5.4 Overview of the supply risks for the fuel cells, hydrogen production and storage supply chain

An overview of the various supply risks and bottlenecks for Fuel cells and related hydrogen technologies are visualised in Figure 26. The performed bottleneck assessment has shown potential very high supply risk for the supply of fuel cells. High risk of supply issues is estimated for the first step of the supply chain - raw materials. No supply issues should be expected for the other two supply chain steps.

Figure 26 Overview of supply risks and bottlenecks in the supply chain of fuel cells and hydrogen technologies



Source: JRC

3.6 Opportunities for research and policy actions for fuel cells, hydrogen production and storage technologies

3.6.1 Research opportunities

Since 2008, the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), has been the European research and innovation instrument to set and achieve research and innovation goals in the field of fuel cells and hydrogen technologies and its value chains. This Joint Undertaking is an industry-led Private Public Partnership with an overall EC contribution of approximately EUR 440 million in the 7th Framework Programme and almost EUR 670 million in H2020 (in H2020 it is called FCH 2 JU). In addition, but to a lesser extent, basic and applied research also takes place in the framework of the European Research Council and other parts of the H2020 programme, while large fuel cells and hydrogen deployment projects can make use of European structural funds, for example for transport and its infrastructure, by means of the Connecting Europe Facility for Transport instrument (CEF).

The FCH JU and the FCH 2 JU funding programmes are principally dedicated to civil research in Europe, and in this respect they do not define specific targets and activities for defence applications. There are only a few examples of FCH JU projects with a dual use dimension, mainly in the fields of portable applications and UAVs.

In the EU, Member States' R&I funding must be added to the FCH JU budget, to get an idea of the overall funding effort. As in the case of FCH JU, this funding is, in the vast majority of cases, for civil applications. Nevertheless, **the majority of the fundamental research challenges and priorities in the field of fuel cells and hydrogen storage technologies are common to civil and military applications.**

At international level, basic and applied research collaboration activities, including techno-economic studies, take place, for example, in the framework of the IEA, and specifically within its Co-Technology Collaboration Programmes on Hydrogen and on Advanced Fuel Cells. The recently formed Innovation Challenge 8 on Renewable and Green Hydrogen, in the framework of the Mission Innovation initiative, is centred on the innovation dimension, focussing on 'hydrogen valleys', lighthouse projects covering the full value hydrogen and fuel cell chain.

The FCH JU and the FCH 2 JU have defined overarching goals, research priorities, multiannual objectives and targets in their multiannual work plans, which are regularly updated[173]. This work covers the whole fuel cell and hydrogen value chain. As mentioned in section 3.2, there is a large overlap between commercial and military requirements, such as high-energy density (greater than currently available through lithium ion technology), low parasitic power, simplified BOP, high degree of safety, and wide power range. Nevertheless, **the main military interests rely on just a part of the overall technology chain, focussing on distributed, thus local, hydrogen production and on specific fuel cell applications.** It is from this viewpoint that the rest of this section has been written.

While fuel cells are becoming competitive for specialised applications, their cost is still the major challenge to their broad introduction to market. Cost reduction is mainly expected from up-scaled production and the related learning curves. A beneficial effect on costs will also be provided by research efforts targeting the replacement of expensive materials and components with cheaper alternatives, whilst retaining the same overall performance. In addition, fuel cells can still improve in terms of durability (lifetime) and, in the case of some types of fuel cell, efficiency.

An important driver for cost reduction is the quality assurance improvement and automation of the manufacturing processes with high production rates for all stack components, and reduction of the failure rate (better quality assurance). Cost, efficiency, and packaging of fuel cell balance of plant (BOP) components for air, thermal, and water management (the latter being particularly relevant to PEM fuel cells which are the main solution for transport applications) are also barriers to commercialisation.

Despite the fact that an optimised manufacturing process will also contribute to improved average performance, durability and lifetime, a better understanding of the fundamental electrochemical processes and improvement in materials and component design are still needed[174]. In terms of efficiency, the PEMFC could profit from being operated at higher temperatures, which also improves resistance to gas impurities and allows for simpler water management. Indeed, transport, and more specifically mobility applications, has been the major driver for the development of hydrogen technologies in the last decade, and PEMFCs are the fuel cell solution to zero emission transport. In the

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[173] The last version of the so-called MAWP is available at: https://www.fch.europa.eu/sites/default/files/MAWP%20final%20version_endorsed%20GB%2015062018%20%28ID%203712421%29.pdf

[174] Behling, N.H., Fuel Cells: Current Technology Challenges and Future Research Needs 2013: Elsevier.

case of PEMFC, key contributors to fuel cell degradation include loss of catalytic surface area and membrane deterioration. Catalysts are a major cost driver and a current focus area for many researchers (e.g. CritCat EU project) aiming to develop catalysts with reduced platinum group metal (PGM) loading or no PGMs, having at the same time increased activity and durability, and lower cost. The implementation of high-performance and durable Pt metal-free catalysts could significantly enable large-scale commercialisation of fuel cell-powered vehicles. Continuing advancements are therefore needed to minimise or eliminate precious metal loading.

Several strategies are possible to tackle this issue: by lowering Pt group metal (PGM) content with catalyst particle morphology and crystal structure; by **developing non-PGM catalysts** or by **utilising Pt-alloys or nanostructured combinations e.g. core-shell, with less expensive base metals** such as Co, Mn and Ni. **Developing novel support materials** such as nanostructured carbon materials (carbon nanotubes, carbon nanofibres, mesoporous carbon), conductive doped diamonds and nanodiamonds, conductive oxides (tin oxide/indium tin oxide, tungsten oxide) and carbides (tungsten carbides) is another potential mitigation strategy.

Demonstration of alternative substitute materials in general, not only for PGMs, is an important area of research. Nanocomposite membranes for instance have been proposed by many researchers to overcome the hydration problem of the Nafion membrane, by adding additives such as ZrO2, TiO2, TiSiO4, and Silica. [175] A number of carbon-based nanostructural materials such as single- and multi-wall carbon nanotubes, carbon fibres, nanohorns and graphene have been investigated as potential GDL. One of the key strategies for improving the performance and durability of PEM fuel cells is to develop cheap bipolar plates with high corrosion resistance. Traditionally, graphite is used to fabricate the bipolar plates for PEMFC. However, graphite is brittle and has a high permeability to gases. Various types of material such as metals (Ti, Ni, Al), alloys (stainless steel alloyed with Cr, Ni and Mo; Ti alloys; Al alloys), and carbon-based composites are being investigated to develop cost-effective and durable bipolar plates to replace the graphite ones. Research has also been done on carbon-based and metal-based corrosion resistant coatings for bipolar plates. Carbon-based coatings include conductive polymers, such as polyaniline (PANI) and polypyrrole (PPY), graphite and composite coatings (using Ti and Ag). The metal-based coatings include noble metals (e.g. Au and Pt), metal (Ti, Cr) nitrides or carbides, and conductive metal oxides (e.g. SnO_2 doped with fluorine; RuO_2).

Substitution alternatives for critical materials used in the SOFC have not been found so far. Another issue is the effect of substitution on the performance of the fuel cells in general. Fuel cell technologies other than PEMFC can offer better solutions for non-transport-related applications, such as industrial applications or co-generation for civil buildings. A list of fuel cell technologies and the overall research challenges to be addressed is given in Table 12.

Despite the progress made in the component and process areas, there has been very little emphasis placed on **fuel cell system integration**. By 2004 several commercial companies had claimed market penetration of DMFC power devices for portable electronics (mobile phones and laptops), but few have developed a reliable unit affordable to the average consumer. **Military fuel cell systems will need to be even more reliable and robust, due to the nature of their operating environments.** To date, most tests and evaluation on fuel cells in real world environments have shown that balance of plant parts, such as fuel pumps and fans unrelated to the fuel cell stacks, often fail first. While optimal system and component performance has been established in lab environments, **more focus must be placed on developing ruggedised**

[175] https://www.researchgate.net/publication/296480680_Materials_in_PEM_Fuel_Cells

systems that will operate reliably while being 'used and abused' in the field: a future research area for defence applications. [176]

Table 12 Challenges and R&D needed in the field of fuel cells, beyond cost reduction

FC type	Challenges and R&D needs
PEMFC	- Increase current density - Minimise or eliminate precious metal loading, maintain the same performance - Improve component durability - Manage water transport within the cell - Develop membranes capable of operation at higher temperatures (up to 120 °C for automotive applications[177] and above 120°C for stationary applications) for better thermal management - Increase durability of the MEA
HT-PEMFC	- Increase current density - Decrease catalyst loading - Develop all solid electrolyte solutions - Develop stable liquid coolants
PAFC	- Decrease or eliminate anion adsorption on the cathode - Handling of the corrosive acid, maintain its concentration and choice of acid resistant materials - Development of durable electrode catalyst and support materials
AFC	- Tolerance to CO_2 - Increase membrane conductivity and durability - Achieve higher temperature operation - Improve water management, power density, and anode electro-catalysis
MCFC	- Limit electrolyte loss and prevent microstructural changes in the electrolyte support leading to early stack failure - Develop more robust cathode materials
SOFC	- Increase survivability during repeated thermal cycling - Decrease long start-up times - Resolve potential mechanical and chemical compatibility/reactivity issues between various stack and cell components due to high temperature operation
DMFC	- Reduce Pt loading - Reduce methanol crossover to increase efficiency - Reduce VOC emissions - Simplify the BOP to increase energy and power density - Increase durability - Optimise system hybridisation and control e.g. with regards to control of CO2 emissions during dismounted/mounted missions

Development of systems that operate on logistic fuels is another specific defence-related topic. Barriers to overcome involve the miniaturisation of systems and the ability to tolerate fuels containing sulphur. One such fuel cell is the recently

[176] https://www.academia.edu/11297639/Portable_fuel_cell_systems_for_America_s_army_technology_transition_to_the_field

[177] To be successful in automobiles, PEMFC system must operate at 110–120 °C, which causes associated performance and degradation issues.

announced Enzymatic fuel cell, which has the potential to power everything from power electronic devices to cars and off-grid power systems. [178] However, advances in size and capacity have to be made to assure large-scale deployment of this technology in both civilian and military markets. **Development of FC systems (and related technologies) capable of operating under harsh environmental conditions** could give the army an advantage in Arctic or desert environments, for example. **Development of reliable stack-sealing concepts**, might be more challenging for defence applications, especially mobile ones, due to more stringent requirements regarding vibrations and shock.

An additional critical component of a fuel cell-based system is the **fuel storage technology and related costs**. Specifically for transportation and portable applications, the increase of the so-called volumetric and gravimetric energy density is very important to minimise weight and volume. [179] For the transportation application, the preferred industrial standard is hydrogen storage in gaseous form, because it can rely on broadly available and well standardised industrial components such as compressors, valves and compressed gas tanks. **In addition to reducing the volume and weight of the hydrogen tanks, the reduction of its cost per unit of energy (the so-called specific cost) is also required.** The strategy here is similar to that of fuel cells, i.e. aiming to **lower the cost of the materials** and to improve mass manufacturing processes. In the case of a compressed gas tank of type 4, consisting of an internal polymer liner and an external carbon-reinforced epoxy composite, the main cost contributions come from the cost of carbon fibres and from the 3-dimensional fibre-winding and epoxy impregnation process for the production of the composite structure. The R&D strategies for cost reduction aim to replace the best performing carbon fibres with low-cost alternatives, whilst still guaranteeing the overall mechanical and chemical performance of the storage system, including the same level of safety.

The long-term performance of hydrogen components, and material-hydrogen compatibility for metallic storage systems and components, are additional areas of current research. Progress in these fields will allow a better understanding of storage degradation mechanisms and eventually contribute to cost reduction by applying an evidence-based safety design instead of the over-cautious safety coefficient adopted so far.

For armoured vehicles, research is needed into the **integration of tanks with the vehicle armour** to prevent risk to the crew and extended damage in the case of a crash. This is even more important with regards to ongoing activities to replace tradition steel armour with polymer-compound lightweight armour. Continuous fibre-reinforced thermoplastic tapes have already been proven for compressed natural gas tanks and the concept has also been tested for hydrogen storage tanks. [180]

Hydrogen storage in solid materials (**metal-, complex- and chemical- hydrides**) or in liquid form (ammonia, methanol or other liquid organic hydrogen carriers) are still options which have not yet been demonstrated in a real world environment, with the exception of a few specific applications. For example, classic metal hydrides operating near ambient temperature have been used for hydrogen storage in submarines, where the very high weight of such a storage system is considered an added benefit. Research is ongoing in this field; the Rice researchers demonstrated in computer models that the 3D architecture of the hybrid nanomaterial would be able to store enough hydrogen to

[178] https://newatlas.com/jet-fuel-electricity-room-temperature-fuel-cell/34594/
[179] This challenge is specific to the case of hydrogen as a fuel: alternative solutions, such as methanol or natural gas, are not characterised by the same grade of difficulty.
[180] https://www.dsm.com/content/prcc/cworld/en_US/informationcenter-news/2017/09/2017-09-04-dsm-developing-novel-materials-solution-for-high-pressure-composite-tanks-for-hydrogen-storage.html

become a practical fuel for light-duty vehicles. [181] Nanomaterial hybrids (such as boron nitride and graphene) could make hydrogen storage economically feasible for next-generation vehicles. **Some of these options may offer solutions for some military applications.**

In the specific case of DMFC systems, methanol is the adopted fuel with a higher energy density and better operability characteristics than gaseous hydrogen. However, **replacing methanol with ethanol** to reduce toxicity issues is a driver for further research.

Most types of FC require hydrogen as a fuel, and this can be produced by various means. Today, most hydrogen is produced by centralised steam reforming of natural gas, which is considered a mature technology and, at the present price of natural gas, also the cheapest. While a major R&I effort is currently underway to produce hydrogen using electrolysis, small scale reformers for on-site production of hydrogen are considered the most viable option for military applications. For some European military forces, in particular air-forces and navies the use of liquid hydrocarbon fuels will remain necessary. Here, additional distributed power supply from fuel cells is desirable on air or naval platforms, for future equipment e.g. directed energy weapons. The enhancement of reformers for liquid fuels therefore remains important. A **focus on future synthetic fuels** is recommended for future military research.

Finally, the infrastructure needed for the production, distribution, storage and dispensing of hydrogen is crucial for the large scale deployment of fuel cell technologies. [182] For fuel cell road vehicles, hydrogen refuelling points are needed along the major trans-European mobility corridors, and in densely populated urban areas. For stationary applications (e.g. small co-generation of heat and power systems (micro-CHP); and back-up power systems), a hydrogen distribution grid must be provided locally, to avoid the use of natural gas reformers. In fact, the major driver in Europe for the adoption of fuel cell technologies is related to their potential for the abatement of CO_2 emissions and to meet the goals of the long-term strategy for climate action. In order to achieve this, the fuel cell must run on hydrogen generated by renewable sources.

In summary, **innovative and optimised materials, novel fabrication methods and design optimisation** (benefiting also from computational methods such as CFD and FEA) can lead to major gains in terms of performance, efficiency, durability, manufacturability and cost-effectiveness.

Recycling of fuel cells is possible today but the issue here is the quality of the recovered materials; for instance lanthanum-based materials recovered with current recycling technologies from SOFC seems not to be good enough to be reused in the manufacture of SOFC. Therefore, either another potential user has to be identified, which can affect the economic benefits of recycling, or the technology must be improved to reach the minimum required quality.

All the requirements mentioned above also apply to military applications; achieving a high level of efficiency, reliability, reproducibility, robustness, maintainability and a low signature are strong prerequisites for the successful large-scale adoption of FC in the defence sector. In some cases, the requirements are more stringent: fuel cell systems will be expected to work under harsher environmental and operative conditions, such as colder or warmer ambient temperatures, for which a civil fuel cell system may not necessarily have been designed, or they will have to be made more mechanically robust (vibration-resistant). Specific performance testing protocols and design adaptations are required. Due to harsher

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[181] Oxygen- and Lithium-Doped Hybrid Boron-Nitride/Carbon Networks for Hydrogen Storage; Farzaneh Shayeganfar and Rouzbeh Shahsavari; Langmuir 2016 32 (50), 13313-13321; DOI: 10.1021/acs.langmuir.6b02997

[182] http://www.fuelcelltoday.com/applications

operative conditions, safety margins which can guarantee high reliability in civil applications may not be sufficient for the military. For example, type approval requirements of hydrogen compressed tanks prescribe the demonstration of resistance to shooting, however the calibre and the shooting conditions foreseen by this test are very probably insufficient for military applications. In this context, **alternative storage solutions to those generally adopted may be more advantageous.** For example, materials for hydrogen solid-state storage may provide more stability than compressed hydrogen. Additional weight, however, would be a disadvantage.

For **military purposes**, **operating fuel cell systems independently from a hydrogen infrastructure** is an essential point. The hydrogen needs to be produced on site. This aspect is especially important for mobile FC applications, but also for defence applications in general, with regards to logistical topics. The most feasible way to produce hydrogen for military purposes is reforming of diesel fuel or kerosine, as both fuels are readily available in the armed forces and logistics are available for this type of fuels. Logistic fuels contain however some amount of sulphur which is detrimental for FC - it poisons the noble metal catalysts. Desulfurization is therefore considered as a very important step in fuel processing technologies. Carbon monoxide (CO) must also be removed to avoid the fuel cell's platinum catalyst's degradation.

Besides steam reforming, other methods are also under investigation as potentially interesting to the military. **Non-thermal plasma-assisted partial oxidation of hydrocarbon fuels (including military logistic fuels) is being looked at for the rapid production of hydrogen-rich syngas with the least amount of electrical power**. The syngas produced can be used to fuel quiet SOFC auxiliary generators, to be added to engines or combustors to extend lean operation (decrease NOx and increase efficiency) or to be further reformed to increase hydrogen yield for low-temperature fuel cells. Unlike catalytic fuel reformers that suffer from coking and tolerance to sulphur and require a warm-up, plasma reforming offers a non-catalytic approach for rapid 'on-demand' hydrogen-rich syngas production (quick startup). [183]

Another important issue to be investigated is the **logistical handling of fuel cell components**. Defence materials are usually procured in public procurement procedures, supplied upon agreement and stored until deployment. Storage logistics for most NATO armies do not allow for intensive care. This situation, which is completely atypical for amortisation-oriented civil use, has not yet been studied, but it is known to lead to substantial economic loss during storage of lithium ion batteries.

3.6.2 Opportunities for policy actions

Although there has been strong growth in fuel cell development and deployment during the last 10 years, it is still uncertain whether this will lead to full commercialisation. Fuel cell manufacturers remain largely dependent on public funding in order to support deployment activities of large-scale stationary fuel cells, whether through technology push or market pull measures. The main barriers at this stage seem to be reliability (availability and lifetime) and cost of the fuel cells.

Promote research synergies between civil and defence sectors in Europe: There are good examples of R&D partnerships in the USA, between companies involved in civil and military markets, to develop and exploit fuel cell technologies in both markets, thereby helping to improve the business case for investment (e.g. GM and Honda in the transport field where USA military R&D investment is complementary to, and builds on, automotive fuel cell investment). Where joint (dual use) military and civil needs in FCs can be identified, the business case for investment can be increased. In Europe, military industry [184] as well as dual use and military research projects can already make use of

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[183] https://pdfs.semanticscholar.org/0d4e/a4ac64eaa6b2821824814fa86bd314eb1da2.pdf

[184] https://www.eda.europa.eu/what-we-do/activities/activities-search/access-to-eu-funding

present European R&I and structural funds.[185] A more strategic R&I collaboration in Europe could increase efficiency and enable the following point.

Align military and civil R&D investments: In the USA, military R&D investment in fuel cell applications in portable power (e.g. for soldiers) and vehicle technologies (e.g. off-road vehicles), including R&D instruments such as the Small Business Innovation Research (SBIR) programme designed to lead to procurements if successful, are helping to develop new industrial capabilities with civil potential. Aligning military and civil R&D investments in fuel cell development where feasible, offers attractive opportunities for Europe. To this end, the most important partner would be the FCH JU. Although the design of the next European research framework programme is still ongoing, it is expected that the concept of a private-public partnership will remain basically the same.

Foster international collaboration: fuel cells and hydrogen technologies profit from an international approach to the development of the required infrastructure, of a global market for great quantities of hydrogen and of global regulations enabling their safe adoption in all parts of the world. Also, in terms of R&I development, international collaborations have been ongoing for many years (see the examples above of the IEA and its Hydrogen TCP). Pre-normative research results are also shared internationally in the framework of a global standardisation and regulatory effort. The best example of this collaboration is the UN-ECE working group which is working on type-approval of fuel cell electrical vehicles (and standardisation (see below)). Furthermore, Europe can take advantage of multi-lateral collaboration opportunities with Japan and the USA, two regions characterised by a considerable deployment of fuel cell technologies which can deliver critical lessons on real world operation.

Infrastructure developments: As mentioned above, steam reforming of natural gas is the preferred option for hydrogen production and can either take place on a very large scale at source, or even locally at the point of use by small reformers integrated with the fuel cell (this would however require a CNG or LNG infrastructure in place).

Support standardisation activities: the existence of performance, safety and permitting standards and technical regulations is considered one of the enablers for a successful development and deployment of new technologies. Standardisation of fuel cells and hydrogen technologies takes place in various working groups of Technical Committee 105 of the International Electrotechnical Commission (IEC TC105) and in Technical Committee 197 of the International Standardisation Organisation (ISO TC197), as well as in the frame of European standardisation bodies (for example in CEN/CENELEC TC6 and CEN TC168). For the reasons mentioned above, related to different operative conditions, it is probable that not all these standards can be used directly for military applications. Nevertheless, they can represent the starting blocks for the development of more specialised protocols and standards. Even more important than these high level standards is the development of industrial standards enabling component compatibility and inter-operability, which contribute to reducing costs and increasing the availability of components. There is still a lot to be done in this area for fuel cell technologies, and recently the FCH JU increased funds dedicated to this challenge. Involvement of military interest in this effort would facilitate the design and operation of dedicated systems.

Actions to support demand increase by a guaranteed purchase plan: MS governments could guarantee to purchase a certain number of zero emission FC vehicles every year so as to stimulate the supply chain for FCs.

Support increase in manufacturing opportunities in Europe by creating an attractive investment environment: Many European companies invest outside Europe, in the proximity of large and rapidly expanding markets, for economic reasons. These facilities serve, first and foremost, the hosting foreign markets. For instance, Umicore, a European company producing catalysts, announced expansion of its

[185] https://www.eda.europa.eu/what-we-do/our-current-priorities/eu-funding-gateway

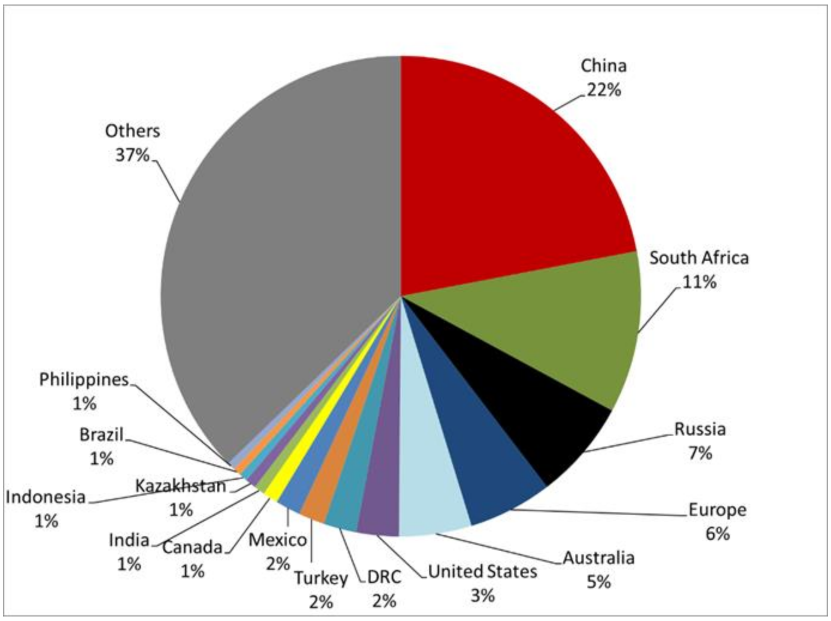
production capacity for fuel cell catalysts in South Korea to support the growth of Hyundai Motors Group as well as other automotive customers. The new plant will be commissioned towards the end of 2019 and is expected to be fully ramped up by the end of 2020. [186] Creating an attractive investment environment for European companies to invest in Europe rather than abroad can make Europe more competitive in the global landscape.

Development of technical skills and competence: the FCH JU is also developing training and educational tools to increase confidence and technical trust in the technologies and to develop a skilled European workforce capable of operating fuel cell systems. This could be another area where military and civil targets overlap and could profit from a collaboration.

In the USA and Japan, hydrogen and fuel cells are considered to be core technologies for the 21st century, important for economic prosperity. There is strong investment and industrial activity in these countries, driving the transition to hydrogen. If Europe wants to compete and become a leading world player, it must intensify its efforts and create a favourable business development environment. [187]

Last but not least, **securing access to raw materials through supply diversification and recycling** is important for the long term development of fuel cells technology in Europe. As for Li-ion batteries, more than half of the raw materials for fuel cells are procured by numerous smaller supplier countries, providing thus good possibility for supply diversification. An overview of the different raw materials suppliers for Fuel cells and supporting hydrogen technologies is shown in Figure 27.

Figure 27 Raw materials suppliers for fuel cells and hydrogen technologies: overview



Source: European Commission, 2017, Study on the review of the list of critical raw materials

Though **recycling** of fuel cells and hydrogen (FCH) technologies can be regulated by legislation that addresses aspects such as design, material selection and end-of-life, the recycling of fuel cells is a new business for recyclers and a potential topic for research. The HYTECHCYCLING project, for instance, deals with existing and new dismantling

[186] https://www.umicore.com/en/media/press/umicore-expands-production-capacity-for-fuel-cell-catalysts/
[187] https://ec.europa.eu/research/energy/pdf/hydrogen-report_en.pdf

technologies and strategies applied to fuel cells and hydrogen technologies, paving the way for future demonstration actions and advances in legislation. Some issues identified in the project are the potential to re-use the materials from recycling routes for the manufacture of fuel cells, as well as the way the substitution of critical and expensive materials (e.g. PGMs) will affect the business case for recyclers; many recyclers believe that this could prove counterproductive. A problem that recyclers face is a lack of knowledge of the technology; it costs them a significant amount of time to dismantle a fuel cell stack. It could take four times longer in a recycling plant than in the hands of the manufacturer, which affects the recyclers' business case. Finally, it's vital to know exactly what the materials are in various fuel cells in order to recycle them properly: this raises confidentiality issues.

In conclusion, a communication channel should exist between recycling plants and manufacturers. It should facilitate the recycling operation and at the same time protect the intellectual property of the manufacturer. Eco-design can be an important tool to facilitate dismantling of FCH technologies and recovery of materials. Adaptation of recycling facilities to recycle FCH technologies is not complicated from a technical point of view; however, authorisation processes can take a long time. Recycling plants have to follow a considerable amount of regulations to be able to operate. The logistics of recycling are also important. A critical mass of FCH technologies must be reached in order to justify specific recovery centres for these technologies. What happens in reality is that devices tend to be sent to recycling centres which are unable to process all the materials, and which send them on to other facilities with dedicated recycling technology.

3.7 Fuel cells and hydrogen production and storage: summary

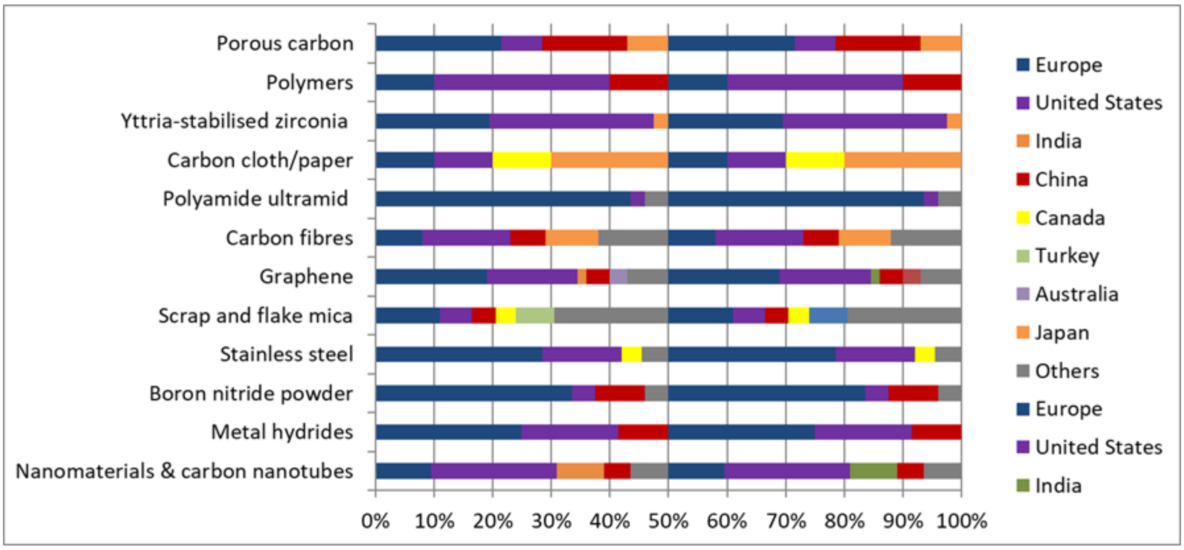
Fuel cells can be used in a wide range of products, ranging from very small fuel cells in portable devices such as mobile phones and laptops, through mobile applications like cars, delivery vehicles, buses and ships, to heat and power generators in stationary applications in the domestic and industrial sector. Transport, and more specifically mobility applications, has been the major driver for the development of hydrogen technologies in the last decade, and PEMFC fuel cells are the solution to zero emission transport. Catalysts are a major cost driver and a current area of focus in research; the aim is cheaper catalysts with reduced platinum group metal (PGM) loading or none at all, and increased activity and durability. The implementation of high performance and durable Pt metal-free catalysts could significantly enable large-scale commercialisation of fuel cell-powered vehicles. Continuing advancements are therefore needed to minimise or eliminate precious metal loading.

Fuel cells are also a promising power source for military applications. The global FCs market for industrial and military applications is expected to grow by 18 % CAGR in the coming years. There is a large overlap between commercial and military requirements, such as high-energy density, low parasitic power, simplified BOP, a high degree of safety and wide power range. Nevertheless, military interests rely mostly on just a part of the overall technology chain, focussing on distributed, thus local, hydrogen production and on specific fuel cell applications. While fuel cells are becoming competitive for specialised applications, their cost is still the major challenge to their broad introduction to market. Cost reduction is mainly expected from up-scaled production and the related learning curves. A beneficial effect on costs, as mentioned above, will also be provided by research efforts targeting replacement of expensive materials and components with cheaper alternatives, whilst retaining the same overall performance. Other issues to be addressed include low power density, low mechanical durability (affecting the lifetime), material degradation and, in the case of some types of fuel cells, efficiency. Many of these issues can be solved by optimising the design and selection and development of materials for the main components.

In total, 29 raw materials and 12 processed materials relevant to fuel cells and hydrogen production/storage have been identified and analysed thoroughly. Eleven materials, namely Co, Mg, REE, Pt, Pd, B, Rh, C (natural graphite), Ru, V and Si, are flagged as critical for the EU economy according to the 2017 CRMs list. For simplicity, REEs are referred to as a single material in the analysis. China delivers more than one third of the critical materials required in fuel cells and associated hydrogen- supporting technologies, followed by South Africa (17 %) and Russia (13 %). China is the main supplier of 10 out of the 29 materials required in this technology. Overall, China delivers >20 % of the raw materials, followed again by South Africa (11 %) and Russia (7 %). Europe delivers around 5 % of the raw materials for fuel cells. As with Li-ion batteries, more than half of the raw materials for fuel cells are procured by numerous smaller supplier countries, providing good potential for supply diversification. Raw materials that are particularly essential for fuel cells and hydrogen production/storage, difficult to substitute, highly priced and with highly concentrated supply are the PGMs: Pt in particular, but also Pd, Rh and Ru.

Unlike Li-ion batteries, Europe appears to be the major supplier of processed materials for fuel cells (40 %), followed by the USA (28 %), China (10 %) and Japan (7 %). Other countries provide only around 15 % of the processed materials. The countries' production shares of FC and Hydrogen technologies relevant processed materials are displayed in Figure 28.

Figure 28 Country production shares of processed materials relevant to fuel cells and hydrogen technologies



Source: JRC

Europe also enjoys relatively strong position in terms of supplying components, providing around 25 % of global supply. The major supplier of components is North America (44 %), followed by Asia (31 %). Europe has the capacity to produce all major components used in FC, namely BPP, catalyst, GDL, membranes and hydrogen vessels.

As for manufacture of fuel cells, European production is marginal – only 1 % of global production. Though Europe is not among the leading manufacturers of fuel cells, it appears to be strong on know-how: several European companies are among the top 20 patenting companies globally. A vast majority of European companies and educational and research organisations are also members of the Technology Collaboration Programme of Research, Development and Demonstration on Advanced Fuel Cells.

The performed bottleneck assessment shows **potential very high supply risk for the supply of fuel cells. High risk of supply issues is estimated for the first step of the supply chain – supply of raw materials**. No supply issues should be expected for the other two supply chain steps.

4 Robotics

4.1 Description of robotics technology and relevance to civil and defence sectors

Robots are multi-functional machines that come in various shapes and sizes and can be programmed to execute a variety of tasks. They are electro-mechanical devices capable of acting independently and making autonomous decisions in order to achieve specific tasks. Robots are used in many applications worldwide, including manufacturing (industrial robots), logistics, consumer appliances, defence, emergency services, agriculture, healthcare, entertainment, research, construction and mining. Unmanned aerial vehicle (UAV) and autonomous vehicle are also sometimes included under the general heading of robotics. However, the market for robots can be categorised into two major segments based on their function and the market needs they are designed for, namely **industrial robots** and **service robots**.

Industrial robots generally refer to robot arms used in manufacturing plants and factories. Industrial robots are used most extensively by the automotive industry. They have revolutionised the manufacturing sector by complementing tasks that are too boring, dirty, or dangerous for humans, or tasks requiring more speed, precision and endurance.

According to the International Federation of Robotics (IFR), service robots operate semi or fully autonomously, and perform services useful to the well-being of humans and equipment, except manufacturing operations. Service robots can be further segmented into various sub-categories, including defence, healthcare, consumer appliances, logistics, agriculture, and personal robots. Personal robots educate, assist or entertain individuals.[188] Robots can also be used for professional or commercial use, for instance cleaning, delivery (logistics), fire-fighting and surgery. Logistics robots are increasingly used in factories, retail outlets, airports and for delivery.

Medical robots (including exoskeletons) that can support, assist and extend the service offered by health workers are already being introduced into healthcare.[189] The use of robots in healthcare represents an exciting opportunity to help a large number of people. They can be used to enable people with cognitive, sensory, and motor impairments, help people who are ill or injured, support caregivers, and aid the clinical workforce. The main types of robot used in the medical sector can be classified as: surgical robots (including remote surgery), rehabilitation robots, biorobots (designed to imitate the cognition of humans and animals), telepresence robots (allowing off-site professionals to look around, communicate and participate from remote locations [190]), pharmacy automation (to dispense oral solids in retail pharmacy, and disinfection robots [191] (capable of disinfecting a whole room in mere minutes – used to fight the Ebola virus).

Exoskeletons are mainly used for the rehabilitation of both civilians and soldiers. Other applications include military exoskeletons (support to soldiers during mission) and civil industry (e.g. support to cargo operators). Step rehabilitation robots are used to help patients with physical disabilities such as paralysis, polio, stroke and spinal cord injury. Exoskeletons are used to help nurses carry and lift patients. They can also support soldiers to carry more weight for longer periods of time. [192] In civil industry, exoskeletons are being used to improve worker safety and to prevent injuries during material handling.

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[188] https://ifr.org/img/office/Service_Robots_2016_Chapter_1_2.pdf
[189] http://medicalfuturist.com/9-exciting-medical-robot-facts/
[190] Corley, Anne-Marie (September 2009) "The Reality of Robot Surrogates". spectrum.ieee.com .Retrieved 19 March 2013.
[191] https://consumer.healthday.com/infectious-disease-information-21/germs-973/robots-may-be-cleaning-your-hospital-room-soon-728054.html
[192] http://exoskeletonreport.com/2016/07/military-exoskeletons/

Industrial and service robotics are included in this analysis. Unmanned (autonomous) systems of different types, namely aerial, ground and maritime, have recently been emerging with significant potential for growth and use for civil and military purposes. Due to the specificities and importance of these systems, they are analysed as a separate technology in this study.

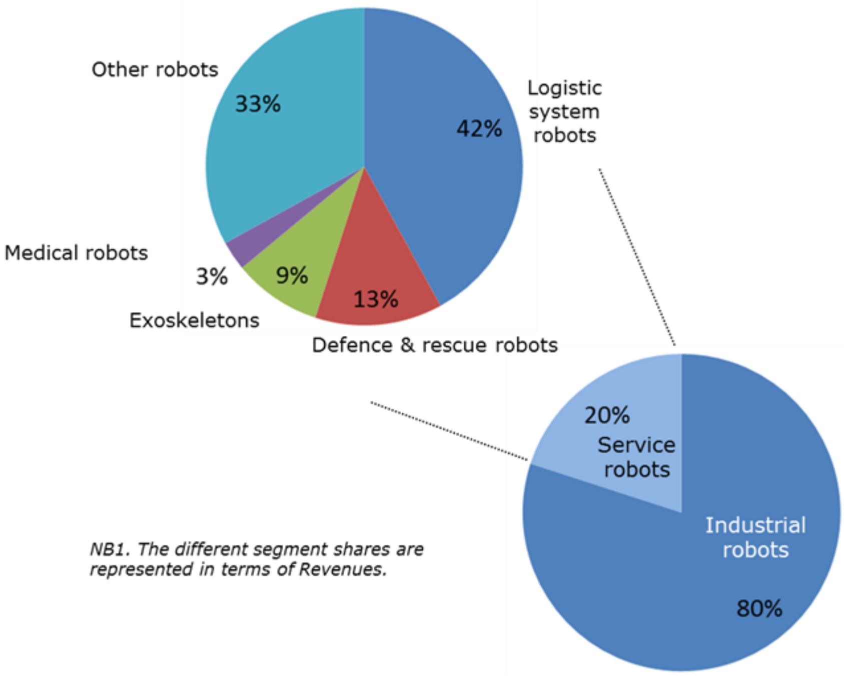
4.2 Robotics technology development stage

Robotics is a fast emerging technology. In jobs with repetitive and monotonous functions they might even become capable of replacing humans completely.

Worldwide sales of industrial robots rose between 2006 and 2016 with a 10 % CAGR.[193] Since 2010, the demand for industrial robots has accelerated considerably due to the ongoing trend toward automation and continued innovative technical improvements. The growth rate in robot installations was unprecedented. In 2017, industrial robots comprised 80 % of the total robotics market, while service robots made up 20 % (Figure 29). Around 433 000 robots were sold worldwide in 2017, earning revenues of USD $ 52 billion.[194] Five countries accounted for 74 % of the global robot sales: China, the Republic of Korea, Japan, the United States, and Germany (Figure 30).[195]

While the industrial robotics market is very well established, the market for service robots is still emerging. Logistic system robots were the largest segment of service robots, accounting for 42 % of sales, followed by defence and rescue robots and exoskeletons (both medical and industrial uses). However, it has to be noted that that the growth potential for the global service robotics market is huge; it is expected to displace industrial robotics in terms of sales and market value, over the next two decades.[196]

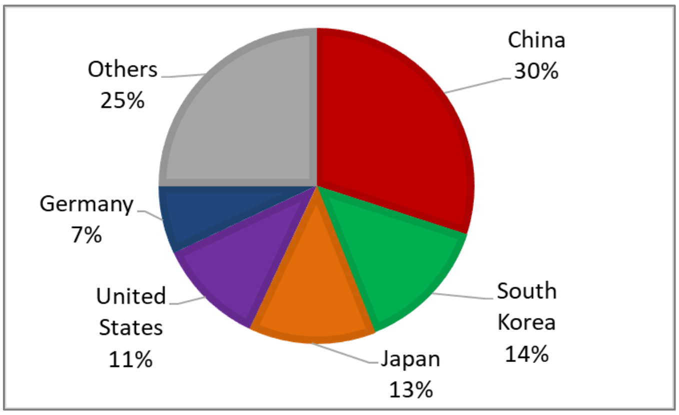
Figure 29 Market shares in the global robotics sector: industrial and service robots



Source: JRC analysis with data from The Business research Company, 2018[194]

[193] https://www.statista.com/statistics/264084/worldwide-sales-of-industrial-robots/
[194] Robotics Market and Supply Chain Long Term Assessment for the EU Market, The business Research Company, 2018.
[195] https://ifr.org/downloads/press/Executive_Summary_WR_2017_Industrial_Robots.pdf
[196] https://www.mordorintelligence.com/industry-reports/global-service-robotics-market-industry

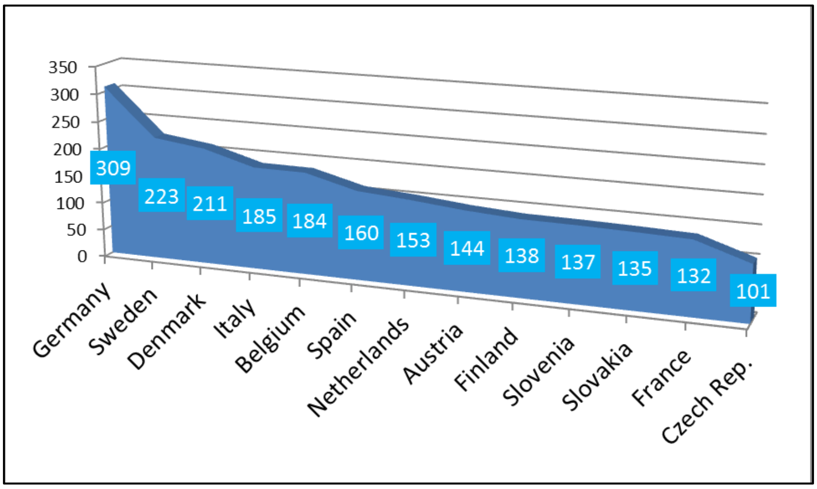
Figure 30 Market share of the five biggest user countries in terms of industrial robots sales



Source: JRC analysis with data from Industrial Robots, WR 2017 [195]

In terms of robotic density, or the number of industrial robots installed per 10 000 employees in the manufacturing industry, the EU countries are well above the average global threshold at 74 robots per 10 000 employees (Figure 31).

Figure 31 Number of industrial robots installed per 10 000 employees in the manufacturing industry in the EU in 2016

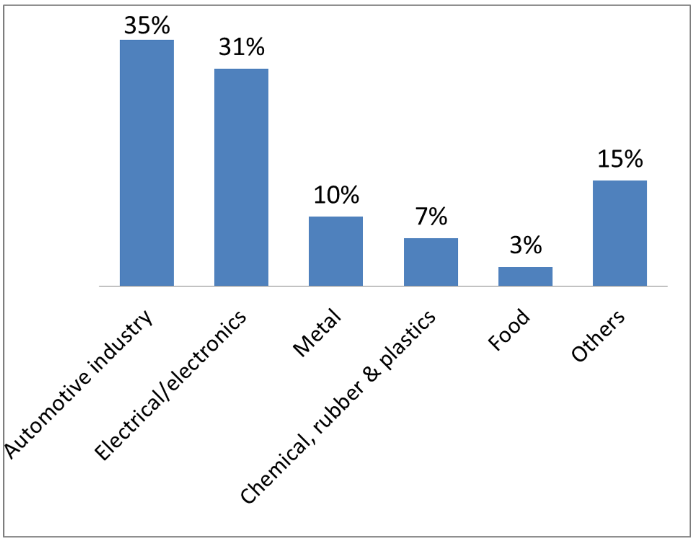


Source: JRC representation with data from IFR, World Robotics [197]

The main sectors taking advantage of robotics in 2016 are the automotive and electrical/electronics industries, followed by metals, chemical, rubber and plastics, and the food industry (Figure 32). [198]

[197] IFR, World Robotics, 2017
[198] https://www.statista.com/statistics/257080/new-installations-of-industrial-robots-worldwide-by-industry/

Figure 32 Main automated sectors globally



Source: JRC representation with data from Statista [198]

Robotics in defence

Robotics has enormous potential for **defence**. Robots can perform military operations considered too risky, complex or even impossible for humans. Military robots are autonomous or remote-controlled mobile robots designed for military applications, from transport to search & rescue and attack. Robots are used in the military on all three fronts – ground, water and sky - for rescue operations, disaster management, surveillance and security. Major tasks performed by robots include bomb disarmament, mine clearance, surveillance and help in search and rescue operations.

The use of robots in the military dates back to the 1930s, when the first remote controlled tank was made by the Soviet Union. Later during World War II, various versions of Goliath, a mobile landmine, were made. [199] Recently robotic devices have been used to move through rough terrain and detect and destroy bombs.[200] The next level in defence is expected to be robotics with artificial intelligence (AI). [201] More specifically robots can be used in the following applications: image interpretation for target identification and classification; diagnosis and maintenance of sophisticated weapon systems such as radars and missiles; support and carriage of ammunitions; a camera-equipped and shock-resistant platform to provide fire power remotely; missile target-range and trajectory analysis for evaluation of kill-zones and launch time and simulation to assist in qualifying missile performance in various environment.

Requirements for military use: military environments are more demanding than many (but not all) civil environments. There are many drivers for the use of robotics in support of military land operations. Situation awareness can be increased and the surveillance (and cognitive) burden on soldiers decreased by using automated remote sensors, for example. The physical workload of soldiers can be alleviated byreducing the equipment dismounted forces have to carry. Communication connectivity can be improved in hazardous situations. High tempo operations can be sustained with improved logistics such as automated resupply. Freedom of manoeuvre can be increased and forces better protected, with military personnel kept out of harms' way. Soldiers can be supported in the face of increasing demand to perform a wide range of missions.

[199] http://www.armyofrobots.com/an-insight-into-the-history-of.html
[200] https://www.azorobotics.com/Article.aspx?ArticleID=199
[201] http://www.defproac.com/?p=6000

Mobile ground robots are of particular use in the military as explosive ordnance disposal (EOD) robots, used to inspect, manipulate and render harmless suspected parcels, bombs, landmines, improvised explosive devices (IEDs) and unexploded Ordnance (UXO). For these robotic tools, it is essential for military operations that the vehicles can work in tough conditions. The main differences between these robot systems and their civilian counterpart are mostly related **to water**-, **dust-** and **shock-proofing**. Another essential requirement for military use is the **non-traceability of devices** and that the enemy cannot make use of any data collected by them. Securing the data link is therefore crucial, along with issues like **tempest shielding**. Next to these issues, there are also **(quick) deployment aspects** which are more important in the military context than in civil use. Examples include the choice of battery pack, which needs to be optimised for **longest possible operation time**, **robust and safe operation under very low and high temperatures**, **resistance to shocks**, **safe air transportability** and**low maintenance**. As well as the batteries, fast deployment requirements also affect the design of the robotic tool itself; such tools are often transported using standardised pallet sizes, which need to be taken into account during the design process.

Exoskeletons currently represent a small share of the global robotics market. However, their use in both the civil healthcare and military sectors is expected to increase steadily in future. It is a continuously evolving field. The use of exoskeleton suits for military personnel could vastly improve the safety and strength of soldiers. While the development of military exoskeletons appears to be vital, the development of exoskeletons for the medical world is also making great strides and has the potential to change the future of medicine. Due to the broad nature of the medical field, an exoskeleton could be used to help patients, doctors, and nurses alike. [202] Therefore special attention has been given to this particular technology in this study.

The first wearable exoskeleton was developed in 1965. The suit weighed almost 680 kg, making it too heavy and complex to warrant further funding. [203] Since then, significant progress has been made in sensors, power supplies, batteries, and other technologies bringing vast potential to the field. Exoskeletons are already used in rehabilitation and healthcare services. Wearable robotics for soldiers is a dynamic segment of the exoskeleton industry. Military exoskeletons are being developed by the military in the USA, China, South Korea, France, UK and Russia. [204] However, the take-up of military wearable exoskeletons in these countries remains low.

Military exoskeletons: In general, the defence industry needs cheaper and lighter exoskeletons, with longer battery life, which would give a clear advantage to the troops. Military exoskeletons face many of the same challenges as their civil counterparts: being comfortable to wear for many hours and integration with established military equipment and standards. Military exoskeletons have to be universal, yet comfortable and fully integrated with the soldier while operating on the battlefield. Furthermore, the exoskeletons should be reliable and very durable, working under harsh conditions such as humidity, pressure, impact and extreme temperatures. Further requirements specific to the military include high survivability, to protect personnel against bullets and blasts;, increased strength and endurance in demanding environments, to reduce soldier loads and enable them to maintain peak performance for longer; increased weapons effectiveness; high situational awareness; and high team effectiveness, including good communications, reliability and safety. [205]

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[202] http://blog.fieldtexcases.com/medical-military-applications-exoskeleton-suits/
[203] Jeff Kerns, 2015 The Rise of the Exoskeletons, Machine design, http://www.machinedesign.com/motion-control/rise-exoskeletons
[204] https://exoskeletonreport.com/2016/10/military-wearable-exoskeleton-research/
[205] NSRDEC Public Affairs, DOD Exoskeleton Technical Interchange Meeting focuses on reducing warfighter's load, June 6 2018.

4.3 Materials used in robotics

The raw materials for robots and robotics components are chosen according to the requirements of machining, flexibility, stability, shaping and compatibility. There are two main types of raw material: basic materials including **steel**, **iron** and **aluminium** and **composite materials**, including **alloys of carbon**, **aluminium**, **silicone**, **graphite** and **resin**. Basic materials used in exoskeletons include **carbon (high-strength steel)**, **chromoly** (chrome molybdenum steel), **aluminium**, **titanium**, **carbon fibre composites**, **polycarbonate plastic**, **glass fibre**, **nickel alloys**, **polysterene**, **magnesium-reinforced polycarbonate** and **polyethylene.** [206,207]

The trick is to use the lightest material of sufficient strength for each component. Robots for defence, rescue and security applications require particular materials since they need to survive and operate in harsh conditions. Different magnesium, aluminium, titanium and special steels are used such as: AZ31B-H24 alloy, ZK60A-T5 alloy, 6061-T6 alloy, 2024-T3 alloy, 7075-T6 alloy, TI-6AL-4V alloy, 1018 steel, 4130 steel, and AerMet 100 steel. [208]

Materials required for the manufacture of medical and surgical robots include ionic **polymer-metal composite**[209] and other types of composite. Such materials should satisfy medical regulations and meet human grade-standards.

Wearable robotics need to be strong, stiff and lightweight. To construct an exoskeleton, engineers will need lightweight materials that can withstand large forces. Materials like steel and aluminium have specific strengths of around 100 to 250 kNm/kg, while fibreglass is around 1300 kNm/kg. Carbon fibre offers specific strengths of over 2400 kNm/kg. New technologies, such as carbon nanotube, exceed 40 000 kNm/kg with a tensile strength of 62 GPa. However, much higher strengths might be possible as carbon nanotubes have a theoretical tensile strength of 300 GPa. New processes and technologies are focussing on cutting weight while increasing strength and mass production. [210] Carbon fibre composites were used early on by exoskeleton pioneer, Ekso Bionics, and are also touted for their light weight in Hyundai's HMEX and Cyberdyne's HAL for Labor Support. However, most exoskeleton products use very few composites, if any, relying mainly on metals and plastics. The future of composites in exoskeletons is debated. Exoskeleton manufacturers are far more likely to use them, it is believe, if the composites industry makes an effort to engage them with the latest developments in resins, fibres, processing and recycling. Polycarbonate, magnesium and aluminium alloys are likely to be used in future exoskeletons, with a good balance of cost and strength. [211]

Innovative materials are under development, e.g. vanadium dioxide, considered an ideal candidate for creating miniaturised, multi-functional motors and artificial muscles. [212]

Materials for military robotics

The preferred materials used in **military robots** are strong light metal alloys, such as **titanium** and **aluminium** alloys, normally used in partnership with **composites** (such as **kevlar)** for protection. [213]

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[206] https://www.mouser.com/applications/robotic-exoskeletons/
[207] https://www.compositesworld.com/blog/post/composites-in-exoskeletons
[208] http://battlekits.com/robot_materials.htm
[209] https://www.researchgate.net/publication/260423049_Manufacturing_process_for_patterned_IPMC_actuator_with_millimeter_thickness
[210] Jeff Kerns, 2015 The Rise of the Exoskeletons, Machine design, http://www.machinedesign.com/motion-control/rise-exoskeletons
[211] https://www.compositesworld.com/blog/post/composites-in-exoskeletons
[212] Robotics Business Review, https://www.roboticsbusinessreview.com/manufacturing/materials_science_muscles_into_robotics/

It is an important requirement for military systems (depending on the application) is that they can incorporate **signature reduction (stealth) technologies** including advanced materials to make them harder to detect.

Military signature control is based on an assessment of the threat systems which might detect and attack a vehicle (a robotic system for example), including the detection mechanisms (acoustic, optical, infra-red, radar etc). Signature control is just one part of the overall system design process which balances the mandatory and desired performance and cost characteristics to deliver a system meeting the military requirements. Signature control is a combination of design (shape and structure e.g. shielding high signature sources) and materials to control the acoustic, optical, infra-red and radar signatures. Information about the material composition of materials used in military applications is highly classified, as well as the military specifications for signatures to be achieved, and cannot be discussed here. However, basic principles and examples of approaches are discussed in the open literature and published research, and are summarised below for the **radar and infra-red signature** frequency domains.

Radar Absorbing Materials (RAM) and Radar Absorbing Structures (RAS) are designed to absorb radar waves and minimise or eliminate reflection, converting the absorbed energy to heat. Absorbers generally consist of a filler material inside a material matrix, with the filler constituents designed to absorb incoming radiation. The matrix material is chosen for its physical properties (temperature resistance etc.) while absorbers are characterised by their electric permittivity and magnetic permeability. The main forms of absorber are described below. [214]

Magnetic absorbers use a filler with ferromagnetic properties. This gives the absorber a high permeability and high magnetic loss. Advantages include the ability to greatly compress the wavelength due to the high permeability, enabling quarter wavelength resonant absorbers at a thickness that are a fraction of the free space wavelength. Disadvantages of magnetic absorbers include weight and cost. Magnetic absorbers come in several elastomer forms including silicone, urethane, nitrile and neoprene. The matrix material is generally chosen for its physical properties. Magnetic absorbers are also available in a rigid epoxy form. These absorbers are easy to machine and are generally used in load applications.

Dielectric absorbers have no magnetic properties. The loss mechanism is purely dielectric. Dielectric absorbers are usually made in a low-cost foam form but can also be used with elastomers. Advantages are low cost and weight. Disadvantages are higher conductivity, preventing usage in contact with electronic equipment and their lack of performance in most cavity resonance applications due to a lack of magnetic absorption.

Different types of RAM exist: [215]

- Foam absorbers –very lightweight conductive carbon-loaded sheet and shaped absorbers that provide high levels of loss at normal and off-normal angles of incidence, manufactured with a continuous gradient coating that produces broadband reflection loss performance.
- Surface wave absorbers –elastomers that are heavily magnetically loaded and are intended to be applied to a conductive or metal surface.
- Iron ball paint – tiny iron particles coated with carbonyl iron or ferrite. For the Lockheed-Martin F-117 Nighthawk and Lockheed SR-71 Blackbird [216], the surface

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[213] https://agmetalminer.com/2011/09/22/military-robots-spur-use-of-light-metals-and-composite-combinations/

[214] Emerson and Cuming, Tech Notes, Theory and Application of RF/ Microwave Absorbers.

[215] https://www.globalspec.com/learnmore/materials_chemicals_adhesives/electrical_optical_specialty_materials/radar_absorbing_materials_structures_ram_ras

was painted with tiny metallic spheres coated with ferrite: incident radar waves caused molecular oscillations in the spheres, causing the incident radar energy to be dispersed as heat.

- Low frequency absorbers – demonstrate high losses at sub-microwave frequencies, and are designed with shaped magnetic particles with high permeability.
- Jaumann absorbers, or Jaumann layers – radar-absorbing materials and structures that use wave-interfering techniques to cancel the reflected waves.
- Tuned frequency absorbers, or resonant frequency absorbers – have pronounced reflection loss at specific frequencies. The frequency selective surface for example, a periodic structure that typically consists of an array of patterned conductors (backed by a thin dielectric sheet), selectively scatters incident EM radiation according to its frequency.
- Cavity resonance absorbers – specifically designed to have high loss within a microwave cavity. In the enclosed space, there are no propagating waves, only standing waves. Material thickness is not as crucial as it is with free space absorbers since material resonance is not the goal. In cavity resonance damping, the absorber is a high permittivity/permeability material that will attract the energy and absorb it.

The **infrared signature** of a target is its appearance to IR sensors set against its background, and depends on the target (factors include the shape, size, temperature and emissivity), the spectral characteristics of the sensor, and the target's environment. The goal of signature control is for the target to appear similar to the background, in terms of temperature, emissivity and space, but any measures must be consistent with overall system requirements (for example external durability and cost). The aim is to conceal spontaneous emission of objects over a broadband range of the IR spectrum. The most important IR wavelengths for military applications are 1–15 microns (μm), set by windows of IR-transparency of the atmosphere (in particular short wave infra-red 0.9-1.7 μm, mid wave infra-red 3–5 μm and Long Wave Infra-Red 8–14 μm), within which the IR radiation easily passes through the atmosphere. Design measures are key (e.g. to reduce vehicle exhaust signatures). Mechanisms considered include thermal insulation, metallic reflectors, and low-emissivity structures, but face challenges such as heat build-up. Low emissivity paints for vehicles have been developed to reduce emissivity in the IR spectral band (e.g., 8–12 μm).[217] Multispectral patterned textile netting, for example the Saab Mobile Camouflage System (MCS) which is fitted to Australian M1A1 Abrams tanks, has been designed to provide visual camouflage and to mitigate and reduce thermal signatures and near-infrared signatures (providing protection against thermal imagers and other related threats such as heat-seeking missiles). The MCS system is also designed to provide control of radar signatures (to provide protection against radar reconnaissance and homing missiles in the range of 1 to 100 GHz).

Electronics

More broadly, robotics technology includes affiliated systems, such as related sensors, algorithms for processing data, graphics processing units (GPU) and so on. [218] The electronics and semiconductor industry has emerged as an important sector for robotics

[216] Arnab Chatterjee, Stealth Aircraft, Science Reporter July 2014.
[217] Daniel Sheehan University of San Diego Department of Physics; Infrared Cloaking, Stealth, and the Second Law of Thermodynamics; Entropy 2012, 14, 1915-1938; October 2012.
[218] Riek, L.D. The social co-robotics problem space: Six key challenges. Robotics challenges and vision. In Proceedings of the Workshop at Robotics: Science and Systems, 2013.

- the trend for electronics parts is for them to become smaller, more powerful, faster and more precise. [219]

Various metals (**copper, nickel, chromium, aluminium, lead, silver, gold, tantalum, palladium, platinum, zinc, tin**), plastics and other petroleum-based materials (polystyrene, polyethylene terephthalate (PET) and polyvinylchlorate (PVC)), minerals and non-metallic or semi-metallic materials, such as **silicon, antimony, bismuth, cobalt, fluorite (also called fluorspar), magnesium**, as well as ceramics, certain clays, glasses, resins, **calcium (in various forms) and carbon (in various forms)** are used as conductors, semiconductors and insulators in a variety of conventional electronics components such as resistors, capacitors, transducers, thermistors and microchips. [220]

For robotics (including UAVs), there is high EU dependence for semiconductors on the USA, supplemented by South Korea. Leading semiconductor materials are silicon, germanium, and gallium. The USA identifies germanium (used in optical components for fibre-optics and night vision applications), arsenic (used in semiconductors and other applications) and gallium (used for integrated circuits and optical devices like LEDs) as three of the 35 critical minerals where dependence on foreign sources creates a strategic vulnerability for the USA economy and military. [221] Hetero-epitaxial materials consisting of a 'substrate' with stacked epitaxially grown multiple layers of silicon, germanium, or compounds of gallium or indium are affected by USA Export Administration Regulations (EAR). [222]

Important semiconductors with military relevance are **silicon-germanium**, **gallium arsenide**, and **gallium nitride**, with gallium nitride growing rapidly in importance in both military and civil domains:

Silicon-germanium is used in integrated circuits (ICs) for the fabrication of heterojunction bipolar transistors and strained silicon metal–oxide–semiconductor (MOS) transistors for advanced complementary metal—oxide–semiconductor (CMOS) technologies. Silicon-germanium technology was initially industrialised by IBM in the early 1990s and used to develop low-cost, lightweight communications devices, and automobile collision avoidance systems. Silicon-germanium technology is applied in telecommunications, computers, consumer electronics, automotive, and military and aerospace. There are future growth opportunities in the internet, mobile communications and autonomous vehicles, and companies including NXP Semiconductors, IBM, Infineon Technologies, Tower-Jazz and GlobalFoundries are investing in this technology. [223]

Gallium arsenide: leading market applications are wireless communication networks, mobile devices, and aerospace and defence systems. Military applications include gallium-arsenide based power amplifiers in communication terminals and electronically-scanned radars (used in fighters such as Eurofighter and ships). The mobile devices segment will continue to dominate the gallium-arsenide market for the next five years due to rising demand for high-frequency amplifiers in smartphones. [224] Leading companies include Advanced Wireless Semiconductor, AXT, DOWA Electronics Materials, Global Communication Semiconductors, IQE and WIN Semiconductors.

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[219] https://www.robotics.org/content-detail.cfm/Industrial-Robotics-Industry-Insights/What-s-New-with-Robots-in-Electronics-and-Semiconductors/content_id/2254

[220] https://sciencing.com/raw-used-manufacture-electronic-components-8053265.html

[221] US Department of the Interior, Final List of Critical Materials 2018, May 2018.

[222] University of Puerto Rico, EXPORT CONTROLS AND OTHER COMPLIANCES, September 2014.

[223] BIS Research, Global Silicon Germanium Materials & Devices Market: Focus on Material Type (Source, Substrate & Epitaxial Wafer), Device Type (Wireless, Radio, FOT) & End-User (Telecommunication, Consumer Electronics, Automotive) - Analysis & Forecast 2017-2021, April 2018.

[224] Global GaAs Wafers Market 2018-2022: Emerging Concept of the Internet of Things to Drive Growth, Technavio, September 2018.

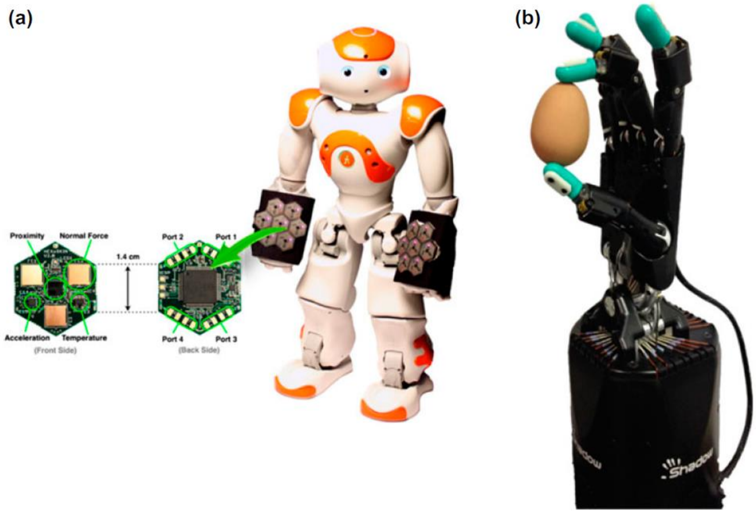
Gallium nitride: The military adoption of gallium-nitride (GaN) has expanded rapidly over the last five years with applications in radar, electronic warfare (e.g. counter-IED jammers), base stations and satellite communications. For example, GaN on silicon carbide is being applied in broadband electronic jammers and radar systems, and GaN on silicon has been deployed successfully in communication systems. [225] Some gallium nitride applications are subject to USA ITAR control (e.g. low noise amplifiers). Gallium-nitride components are expected to replace gallium-arsenide components in military applications such as radars during in-service upgrades, where the potential performance improvements are seen as cost effective. The Global GaN RF devices market is expected to grow at a CAGR of more than 15 % by 2022 [226], with applications in cellular infrastructure (the largest market), defence and TV. Companies in this market include Cree, Infineon Technologies, MACOM and NXP Semiconductors.

The strategic importance to Europe of gallium-nitride is shown by the European Defence Agency (EDA) Components work strand aimed, set up to establish a European supply chain for next generation defence applications for radars, communications and electronic warfare (EW) technologies, using gallium- nitride-on-silicon-carbide (GaN-on-SiC) semiconductor technology. [227] There have been four consecutive projects (KORRIGAN, MANGA, MAGNUS, and EUGANIC) and related activities. MANGA has successfully developed know-how and production processes for 100 mm SiC wafer production and GaN-on-SiC epitaxy. The EuGaNIC project will bring the technology to full industrial maturity in Europe. MAGNUS has designed and developed multiple applications and demonstrators of enabling technologies such as monolithic microwave integrated circuits (MMICs) and highly integrable transmit and receive modules for phased array antennas to be used in radars, communications and EW systems from 2-18 GHz. The new MUSTANG project, currently in preparation, will extend the use of GaN technology in frequency terms. [228]

New materials and advances in **electronic skin for interactive robots** are under development. **Flexible electronics** has huge potential to revolutionise robotics and prosthetics by changing the way in which machines interact with humans, real-world objects and the environment. For example, the conformable electronic or tactile skin on a robot's body, enabled by advances in flexible electronics, will allow safe robotic interaction during physical contact with various objects. The current research focus in this direction is marked by the use of novel materials and by the smart engineering of traditional materials to develop new sensors, electronics on substrates that can be wrapped around curved surfaces. Attempts are being made to achieve flexibility/ stretchability in e-skin while retaining reliable operation (Figure 33).

[225] International Defence Security and Technology; Gallium Nitride Technology continues to be a game changer for Military Radar, Electronic Warfare and Communications applications; November 2018.
[226] Global GaN RF Devices Market 2018-2022, Technavio, March 2018.
[227] European Defence Agency, Towards Enhanced European Future Military Capabilities, European Defence Agency Role in Research and Technology 2016.
[228] https://www.eda.europa.eu/what-we-do/activities/activities-search/captech-components 5th February 2019.

Figure 33 Robots equipped with e-skin; a) humanoid robot with multi-modal artificial skin at the Institute for Cognitive Systems, TUM-Germany; b) the Shadow Robotic Hand with BioTac sensors on fingertips at Shadow Robot Company UK.



Source: (*N. Yogeswaran et al., 2015*) *http://eprints.gla.ac.uk/110827/1/110827.pdf* [229]

Stretchable electronics are realised with a synthesis of novel materials such as composites of soft materials with conductive fillers or with smart structural engineering and designs such as serpentine-like structures for interconnects or wires. Among various polymers, elastomers like polydimethylsiloxane (PDMS) have received significant attention due to their biocompatibility, chemical inertness and mechanical strength. Other materials such as Ecoflex, polyimide, polyurethane, polyethylene naphthalate, TiO_2, $BaTiO_3$, Al_2O_3, Ta_2O_5/SiO_2, ZnO, ion gels, Ge, GaAs , InAs, Si, carbon-based materials (graphene and carbon nanotubes), organic materials ((3,4-ethylene dioxythiophene):polystyrene sulfonate (PEDOT:PSS), poly (3-hexylthiophene 2,5-diyl) (P3HT), polypyrrole and polyaniline (PANI), pentacene and rubrene have been investigated as suitable substrate, dielectric and active materials for flexible electronics applications. In smart engineering, ultra-thin silicon chips seem to be a promising solution.

Printed liquid metal, **liquid silicone rubber** and **metallic glass** are seen as potential game changers in the field of **soft robotics**. Soft robots will not look like anything that we associate with robotics. They will walk across the surface of alien planets. They will make discoveries in places that no human could ever hope to survive. They have the potential to change robotic medicine and improve the efficacy of robot-assisted surgery. Soft robots could squeeze into the smallest cracks to find survivors trapped under rubble, burrow through loose soil to find landmines, to keep soldiers or civilians safe or swim to the depths of the ocean to find what we have yet to discover. [230]

Fully functional human robots will also need numerous sensors to simulate a variety of human and beyond human capabilities. Vision and proximity sensors can be similar to the sensor types required for self-driving vehicles including camera, infrared, sonar, ultrasound, radar and LiDAR. The combination of these sensors allows the robot to identify an object and determine its size and its distance. Radio-frequency identification (RFID) sensing can provide identification codes and allow an authorised robot to acquire other information. Force or tactile sensing allows the robot to pick up objects of different types without crushing or dropping them, or to activate external touch-controlled

[229] N. Yogeswaran et al., 2015; http://eprints.gla.ac.uk/110827/1/110827.pdf
[230] https://interestingengineering.com/soft-robotics-and-the-materials-that-could-revolutionize-the-field

switches. Torque sensors enable the robot to measure and control rotational forces. Acoustical sensors help it to receive voice commands and identify unusual sounds in a familiar environment. With the addition of piezoelectric sensors, vibration caused noise can be identified and eliminated to avoid the misinterpretation of voice commands. Advanced algorithms can even allow the robot to interpret the emotions of the speaker. Temperature sensing is part of the robot's self-diagnostics and can be used to determine its environment and to avoid potentially harmful heat sources. Pressure, chemical, light and colour sensors enable the robot to evaluate, adjust and detect problems with its environment.

Software: Robotics tools depend largely on software, as these systems perform more and more intelligent tasks and are equipped with more and more sensors, making the intelligent on-board data fusion and decision-making more important. To this end, multiple (standardised) software architectures have been developed for robotic tools, for industrial and mobile robots [231], aerial robots [232], unmanned maritime systems [233], other unmanned systems [234] and more. These architectures are generally open source, so there is no direct supply chain problem.

4.4 Trends in robotics

For several decades robotics, which is now a multi-million-euro industry, has been a central pillar in the manufacturing industry. Growth in the robotics industry continues to be explosive. It is no longer just a manufacturing technology, but has evolved to address a much wider range of applications and domains where a variety of services is provided to different end users.

The global robotics market is expected to reach c. USD 126 billion (more than 3 million units to be sold) by 2025 and USD 494.7 billion by 2040, accounting for more than 28 million units.[235] Although the market for industrial robots is expected to experience slower growth in the automobile industry, the rising demand for automation in other manufacturing industries is creating a strong push for industrial robot manufacturers to diversify their portfolio further. A moderate growth of <8 % CAGR is expected in the industrial robotics sector. [236]

An overall increase of about 10 % CAGR is projected in the coming years for the robotics market in general.[236] According to robotics industry representatives, there is huge potential for growth in the service robots market, in contrast with to the more mature industrial robots industry, which has more competitors, less profit differentiation and tighter profit margins. The most rapidly growing robotic sectors will be consumer (>20 %) and commercial robotics (>13 %). For specific service fields such as medical robots, a growth of >20 % is anticipated.[237] A growth of 7.7 % is expected for the military robotics market. [236]

Companies developing exoskeletons no longer find it difficult to secure funding. Investors recognise that this technology has many potentially profitable applications. The market for exoskeletons is expected to grow significantly at a CAGR of 40-50 % by 2025. [238] Lower body exoskeletons used as rehabilitation tools or to improve quality of life are the current market leaders, but commercial systems that augment human

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[231] ROS: http://www.ros.org/
[232] https://en.wikipedia.org/wiki/MAVLink
[233] http://www.robots.ox.ac.uk/~mobile/MOOS/wiki/pmwiki.php/Main/HomePage
[234] https://en.wikipedia.org/wiki/JAUS
[235] Robotics Market and Supply Chain Long Term Assessment for the EU Market, The business Research Company, 2018.
[236] https://www.statista.com/statistics/257163/projected-revenue-growth-of-the-global-robotics-market/
[237] https://www.marketwatch.com/press-release/medical-robotics-market-highest-cagr-of-208-with-growth-rate-in-robotic-industry-size-share-future-predication-by-2023-2019-04-01
[238] https://www.compositesworld.com/blog/post/composites-in-exoskeletons

capabilities will show the strongest growth in future. An estimated 20 % of the world's population experiences difficulties with physical, cognitive, or sensory functioning, mental health, or behavioural health.[239] These experiences may be temporary or permanent, acute or chronic, and may change throughout one's lifespan. Of these individuals, 190 million experience severe difficulties with day-to-day tasks. The world's population is also rapidly aging, which will further increase the number of people who may need help. In addition, there is a substantial healthcare labour shortage- there are far more people who need care than healthcare workers available to provide it. Robotics technology offers sizeable opportunity to help fill these care gaps and support healthcare workers.[240]

In summary, applications for exoskeletons range from construction and agriculture to transportation and healthcare. Demand for these wearable robots is predicted to be on a par with the industrial robots now used widely in manufacturing.[241] Logistics and supply chain automation is one of the fastest-growing applications for mobile robots and manipulators. E-commerce order fulfilment, more flexible warehouses, and drone delivery are among the benefits of robots and AI in supply chains.[242]

Recycling is an important future application for robots. When robotics and recycling are found in one sentence, it is mostly related to the benefits of using robotics and AI in materials recovery facilities. Benefits include heavy lifting, no deviations due to fatigue, continuously high levels of concentration, purity rates and accurate identification of products, maximal operating time, reproductivity of results, reduced labour and training and lower operating costs. Robots have a compact footprint; they can be installed with little or no retrofit to the overall system. They can also work alongside human sorters. With cloud connectivity, pieces of equipment can 'talk' to one another.

Some companies are already looking at the environmental impact reducing waste, recycling/recycled materials and improved sustainability for their robotic devices.[243] Companies including Europe-based TOMRA Sorting Recycling; Eugene, Oregon-based Bulk Handling Systems (BHS); Canada-based Machinex; and Finland-based ZenRobotics are among those focusing on tying machine learning into devices and systems to offer thorough automated sorting options for recyclers.[244] Apple has also recently announced that it has started using robots to take apart iPhones in California and the Netherlands. Compared with traditional methods like shredding, robots have proven much more effective at preserving resources, according to the company.[245] AI and robotics will also revolutionise the defence industry. Demand for AI & robotics defence systems is expected to be driven by massive investment in countries like the USA, China, Russia, Israel.[246] Robots are also changing the nature of search and rescue operations relating to hurricanes, mudslides, earthquakes and terror attacks.

It is important to stress the significant change that robotic and autonomous systems are likely to make to military operations in the 2021-2040 timeframe. The USA DOD Budget for FY19/20 doubled the funding for Robotics and Autonomous Systems (RAS) between 2018-2023[247] and the main factors driving USA development of robotic and autonomous systems also apply to Europe. The trends are highlighted by the goals of the USA Army

[239] https://cacm.acm.org/magazines/2017/11/222171-healthcare-robotics/fulltext
[240] https://arxiv.org/pdf/1704.03931.pdf
[241] https://www.roboticsbusinessreview.com/category/service
[242] https://www.roboticsbusinessreview.com/category/supply-chain
[243] https://assets.ossur.com/library/38757
[244] https://www.recyclingtoday.com/article/recycling-robots-ai-sorting/
[245] https://www.richardvanhooijdonk.com/en/blog/will-recycling-robots-soon-be-doing-all-our-dirty-difficult-and-dangerous-work/
[246] https://www.prnewswire.com/news-releases/ai--robotics-to-dominate-the-defense-industry-300600748.html
[247] Department of Defense, Fiscal Year (FY) 2019 Budget Estimates, February 2018.

Robotics and Autonomous Systems Strategy.[248] Short-term objectives (2017-2020) include mature concepts and programmes to increase situational awareness, lighten the soldier load, improve soldier sustainment, enhance freedom of manoeuvre and augment force protection. Medium-term objectives (2021-2030) include improvements in situational awareness, soldier load reduction, sustainment and manoeuvre using developments in autonomy, machine learning, AI, power management, and common control to achieve more capable UGS and UAS. There will be increased use of mixed manned and unmanned teams. Longer-term objectives (2031-2040) include new autonomous ground and air systems to be fully integrated into military force structures, which will allow soldiers and commanders to focus on the execution of the mission rather than the manipulation and direct control of robots. This will reduce human exposure to hazards and give commanders more options. Human-machine teams will operate for extended durations. Soldier exoskeleton technology should incorporate integrated displays that provide a common operating picture, intelligence updates, and integrated indirect and direct fire weapons systems. Achieving such robotics objectives (for ground and air vehicles) will require significant advances in autonomy, AI and common control (software that allows control of multiple ground and air systems by a single human with one controller to reduce cognitive and physical burdens). The USA Army aims to create a common operating environment (COE) using common standards and technologies to integrate robotic systems into the command and control network.

Robotics legislation and regulation in the EU

There is no harmonised EU legislative framework for robotics yet, but the EU is working on it.[249] Some laws do exist or are currently in preparation. These are mostly concerned with forbidding the development of autonomous robots with lethal force.[250] The European parliament has even proposed the creation of a specific legal status for robots.[251] This is, however, drawing objections from experts.[252] It is considered a dangerous avenue, as it opens the door for a transfer of liability from humans to robots. More generally, in the light of the new EU General Data Protection Regulation, every organization involved in robotics and AI would do well to identify any links they have with European individuals and review their data protocols.[253]

In terms of standardisation, ISO/TC 299 aims to develop high quality standards for the safety of industrial robots and service robots to enable innovative robotic products to be brought onto the market. In addition, it aims to foster the growth of the robotics market by introducing standards in fields like terminology, performance measurement and modularity. The scope of ISO/TC 299 reads 'Standardization in the field of robotics, excluding toys and military applications'.[254] At the moment there are 18 ISO TC 299 standards published and 12 under developments.[255] The USA National Institute of Standards and Technology has developed a whole range of standardised test methodologies, mostly geared towards explosive ordnance disposal (EOD) and response robots.[256, 257] Asian countries such as China and Japan have less stringent safety regulations and standards than the USA and Europe.

[248] US Army Training and Doctrine Command, Robotics and Autonomous Systems Strategy, 2017.
[249] http://www.europarl.europa.eu/oeil/spdoc.do?i=28110&j=0&l=en
[250] https://www.stopkillerrobots.org/2018/07/parliaments-2/
[251] http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-%2f%2fEP%2f%2fTEXT%2bREPORT%2bA8-2017-0005%2b0%2bDOC%2bXML%2bV0%2f%2fEN&language=EN .
[252] https://gizmodo.com/experts-sign-open-letter-slamming-europe-s-proposal-to-1825240003
[253] https://www.roboticsbusinessreview.com/legal/gdpr-tighten-european-personal-data-protection-globally-robots/
[254] https://committee.iso.org/home/tc299
[255] https://www.iso.org/committee/5915511/x/catalogue
[256] https://www.nist.gov/el/intelligent-systems-division-73500/response-robots

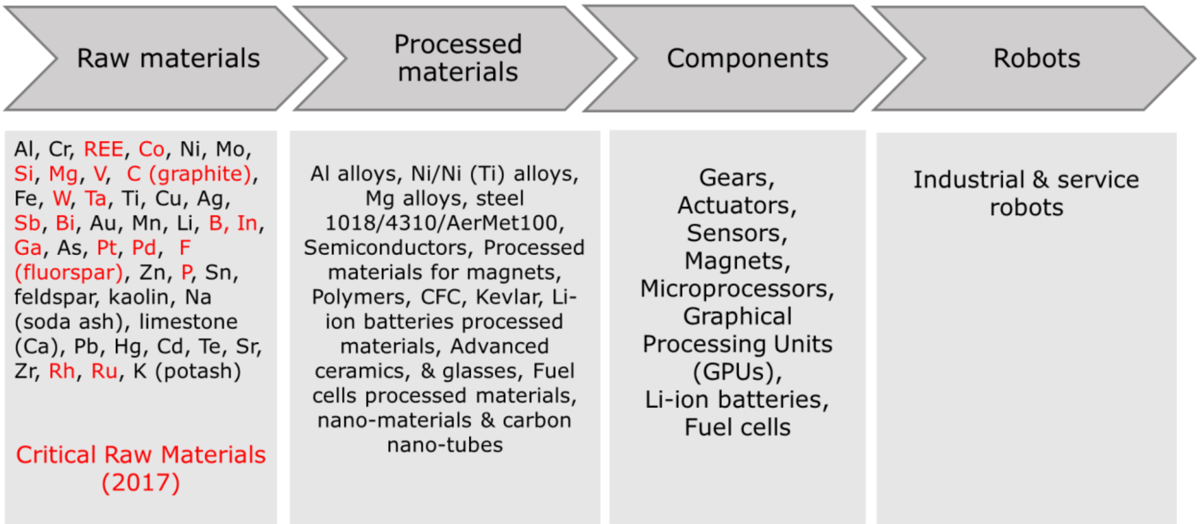
4.5 Materials supply chain in robotics

4.5.1 Main steps of the robotics supply chain

The manufacturing process for robots generally includes the following key participants in the supply chain: raw/processed materials suppliers, robotic component manufacturers, software developers, robot manufacturers, system integrators and customers. Manufacturers of robots and robot components usually obtain the appropriate materials from their suppliers and procure software and codes from a software provider. Most large robot manufacturers produce their own components and software systems, thus safeguarding their technology and software codes. Alternatively, components can be manufactured by the parent robotic manufacturers or can be outsourced to robotic component manufacturers. The robot manufacturers assemble the robotic components with the software and develop the robots. Industrial robots are further integrated into the customers' facility – a service normally provided by an integrator. Service robots can be sold directly to the customer/end user. System integrators, customers and software developers are not included in the analysis since they are not directly related to the question of materials.

The main elements of the robotics supply chain covered in this analysis are raw materials, processed materials, components and systems (robots) (Figure 34).

Figure 34 Robotics: an overview of raw materials, processed materials and components considered in the analysis



Source: JRC

Step 1: Raw materials

In total 44 raw materials (REE counts as a single material) have been identified as relevant to robotics. Many of them - 19 materials are flagged as critical in the 2017 Critical Raw Materials (CRM) list, namely: Pt, Pd, Rh, Ru, Co, Si, C, Mg, V, Bi, REE, B, In, Sb, Ga, F, P, W and Ta.

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257 https://www.nist.gov/sites/default/files/documents/el/isd/ks/DHS_NIST_ASTM_Robot_Test_Methods-2.pdf

Step 2: Processed materials

The main materials used in robotics are standard materials such as steel and aluminium alloys and speciality materials such as different types of composite, polymer and ceramic. Nowadays, EU robotics manufacturers make 50:50 use of standard materials and composites. Materials account for approximately 30 % to 40 % of the cost breakdown of a robot, including steel, casted and machined materials. [194] Since the main goal of robotics manufacturers is to produce cheaper, light-weight robots which consume less energy, the push is to reduce the amount of steel and metal (heavy metals) in general and use more plastic, aluminium and composites. The relatively high cost of the composites – around 20 times higher than steel- might be an issue for their use in higher payload work: a cost versus performance issue. The use of composite materials can increase significantly as soon as composites become cheaper. However, more and more OEMs are looking to alternative materials to produce lighter cars to meet stringent fuel standards. [258] Less expensive carbon fibre would allow manufacturers to drop their costs significantly while decreasing the fuel consumption of their cars and therefore cutting down on CO_2 emissions. Composites also look to be promising for the aeronautics sector. [259]

In total, 28 processed materials have been identified and considered in the analysis, namely special Al alloys, Ni alloys, Ni/Ti alloys, Mg alloys, specific steels-1018/4310/AerMet100 - carbon fibre composites, kevlar fibres, carbon nano-tubes, nano-materials, polymers, semiconductors, advanced ceramics, glasses & refractories, as well as the processed materials required for Li-ion batteries and fuel cells. To narrow the search of companies, specific Al alloys and steels have been selected. [260]

To calculate the market shares for all processed materials variety of data sources was used, from statistical data (e.g. Statista), to public databases (e.g. Europages) to companies' websites, blogs and other internet open sources. For some materials, the market shares for the key country suppliers were determined based on their manufacturing/production capacity (e.g. carbon fibres [261]). When no information on production capacity was available, sales revenues (polymers [262], advanced ceramics glasses & refractories [263], semiconductors [264]) or the number of companies per country (carbon nanotubes & nanomaterials [265], Mg alloys, Al alloys, Ni-alloys, Ni/Ti alloys, special steels, Kevlar [266]) were used to estimate the shares. Information on data sources for processed materials used in Li-ion batteries and fuel cells is available in the relevant chapters. Companies considered in the analysis providing polymers, semiconductors, advanced ceramics , glasses & refractories and aramid (Kevlar) fibre are listed in Annex 2 Table 41, Table 42, Table 43, and Table 44.

Step 3: Robotics components

A robot can contain more than 2000 individual parts such as motors, gears, bearings, pistons, grippers (end-effectors), axles, wheels, controllers, power units and supporting structures. The components also include application processors, multi-point controllers, sensors and sensor hubs. The control unit, or the CPU, forms the main part of the robot. It may also have an end-effector, which allows the robot to work. Software is an

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[258] http://compositesmanufacturingmagazine.com/2014/10/carbon-fiber-prices-drop-much-90-percent/
[259] https://www.nlr.org/article/composite-manufacturing-getting-ready-aircraft-future/
[260] http://battlekits.com/robot_materials.htm
[261] https://www.statista.com/statistics/380549/leading-countries-by-carbon-fiber-production-capacity/
[262] http://polymerdatabase.com/Polymer%20Brands/Plastic%20Manufacturers.html
[263]https://www.statista.com/statistics/609908/top-manufacturers-of-glass-advanced-ceramics-and-refractories-by-revenue-globally/
[264] https://www.statista.com/statistics/791081/worldwide-top-semiconductor-supplier/
[265] https://www.nanowerk.com/nanotechnology/nanomaterial/suppliers_plist.php?subcat1=cnt
[266] https://www.europages.co.uk

essential part of a robot – it adds intelligence to the machine. Software is required for the robot to perform autonomous tasks; it is usually specific to the robot. The complexity of the intelligence of a robot can be increased by adding more sensors and microprocessors.

For simplicity, the following main components are considered in the analysis: mechanical parts (gears in particular), actuators, sensors, controllers and power supply units – Li-ion batteries and fuel cells. Mechanical parts include, in general, pistons, grippers, wheels, and gears that make the robot move, grab, turn and lift. An actuator is a common robot part: an electromechanical device which converts energy into mechanical work. The most popular actuators are electric motors. The controller, also known as the 'brain' is run by a computer programme, and sensors tell the robot about its surroundings.

Gears are put in the spotlight since they have been identified as a potentially critical component by European robot manufacturers. [194] Two factors make them critical: they are not a standard element and there are only a few manufacturers globally with a highly concentrated supply – a Japanese oligopoly held by international giants like Nabtesco, Harmonic Drive and Sumitomo Heavy Industries. Nabtesco has around 60% market share in gears for industrial robotics. Nabtesco Precision Europe GmbH in Germany is part of Nabtesco Group, which also supplies also gears. Harmonic Drive AG has its European headquarters and manufacturing in Limburg/Lahn, Germany. The shares for 'gears' were determined based on companies' market shares. [267, 268] Companies supplying gears are listed in Annex 2 Table 45.

As for bearings and other basic (standard) mechanical parts, there are many suppliers so they are not deemed critical by the European robotics industry.

Actuators: actuation systems are an enabling technology for robotics application. The present market of actuators for robotics application is interrelated to the more generic robotics market - mainly industrial robots. As for mobile robots and human-robot interaction applications, robots must be fast, safe, low-cost and reliable. This necessitates new actuators and transmissions that have high torque-to-weight and power-to-weight, are safe interacting with people, are impact-resistant, have appropriate impedance for interactive tasks, and are reasonably fast and efficient.

The following segments of the world robot market are expected to grow rapidly if the necessary actuator technologies are developed: physical assistance of humans by robots, micro-mobile sensor nodes for security (requiring miniature high performance actuators, such as for microflight), power-suits and prosthetics (requiring high power, high torque, high efficiency actuators) and domestic robots (require safe, low cost, low inertia actuators for mobility and manipulation). The shares of 'actuator' suppliers were estimated based on the number of supplier companies per country. [269] Companies supplying actuators are listed in Annex 2 Table 46.

Sensors: a large variety of sensors is used in robots: chemical/gas sensors, gas identification sensors, force/load/torque/strain sensors, heat sensors, humidity/moisture sensors, motion/velocity/displacement/position sensors, presence/proximity sensors, pressure sensors, transducers, temperature sensors, tilt switches, vibration & shock sensors and more. Sensors give the robot controller information about its surroundings. One of the more exciting areas of sensor development is occurring in the field of computer vision and object recognition. Robot sensors can detect infrared radiation to 'see' in the dark. For this analysis, internet of things (IoT) sensor manufacturers are

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267 https://www.nabtesco.com/en/products/robot.html
268 https://www.prnewswire.com/news-releases/global-and-china-industrial-robot-speed-reducer-industry-report-2013-2016-300045487.html
269 http://www.unmannedsystemstechnology.com/category/supplier-directory/hydraulic-pneumatic-systems/actuators-actuation-systems/

used. IoT sensors include light, HVAC, magnetic, seismic, imaging, thermal, acoustic, chemical, humidity and location. In addition to IoT sensors, hyperspectral/CMOS (complementary metal oxide semiconductor) imaging sensors, as well as infrared (IR) cameras are also included.

The shares are determined based on the number of companies supplying such sensors.[270, 271, 272, 273, 274] For CMOS sensors the 2016 market shares of different companies were used[275]. Companies manufacturing IoT sensors, hyperspectral and CMOS sensors are listed in Annex 2 Table 48, Table 49 and Table 50.

A wide variety of materials can be used in sensors, such as Si, Mn, Ti, Bi, Zr, Pb, Zn, In, Ga, Ba, As, Hg, Cd, Te, Pd, Ca, Y, Pr, Nd, Yb, Eu, Dy, Al, Ho, Er, Tm, Sm, as well as polymers and carbon ceramics. REEs such as Y, Pr, Nd, Eu, Dy, Ho, Er, Tm and Sm are used for temperature sensing in particular. [276, 277]

Although there are various sensor-producing companies in the EU, there are no strong EU sensor providers. European robotics companies are often unable to access the best sensor technology available, often from the USA or Israel, due to export restrictions. A specific **defence supply chain issue** is the use of sensor systems under export license (typically IR cameras).

Controllers: in a broad sense, a robot controller is a combination of hardware and software to programme and control a single or multiple robots. Every robot is connected to a computer controller, which regulates the components of the arm and keeps them working together. The controller also allows the robot to be networked to other systems, so that it can work together with other machines, processes or robots. Almost all robots are pre-programmed using 'teaching' devices or offline software programmes. In the future, controllers with artificial intelligence (AI) could allow robots to think on their own, or even programme themselves. This could make robots more self-reliant and independent. Shares on controllers were taken from Statista. [278] Companies supplying microprocessors are listed in Annex 2 Table 47.

Graphics processing units (GPUs) are widely used in PCs to perform graphics operations. They provide a number of basic operations to the CPU, such as rendering an image in memory and then displaying that image onto the screen. As regardsmaterials, GPUs rely on silicon, tantalum, palladium and gold. GPUs are mainly produced by two USA companies: nVIDIA and AMD. A supply share of 95 % was assumed for the analysis. More details can be found in the unmanned vehicles chapter. Companies supplying GPUs are listed in Annex 2 Table 60.

The use of a **magnetic gripper** on robot arms replaces the traditional vacuum technique. A disadvantage of vacuum grippers is that they are susceptible to malfunction and subject to wear. Electromagnets can be also used in robots. However, they are so heavy that the lifting capacity is reduced. A magnetic gripper with permanent magnets is considerably lighter. Moreover, the gripper does not wear and has a longer service life

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270 https://www.reuters.com/brandfeatures/venture-capital/article?id=23044
271 http://orbisresearch.com/reports/index/china-iot-sensors-market-2017-industry-trend-and-forecast-2021
272 https://businessanalyst24.com/148696/global-iot-sensors-market-by-industry-chain-manufacturing-process-cost-structure-2018-2023/
273 https://www.photonics.com/Category.aspx?CatID=13925
274 https://www.europages.co.uk/companies/infrared%20cameras.html
275 https://www.vision-systems.com/articles/print/volume-23/issue-5/features/image-sensors-expand-machine-vision-applications.html
276 https://www.electrochem.org/dl/interface/spr/spr06/spr06_p66-69.pdf
277 http://www.mdpi.com/journal/sensors/special_issues/IC-MAST
278 https://www.statista.com/statistics/263189/global-market-share-of-microprocessor-vendors/

than vacuum gripper. [279] Therefore rare-earth permanent magnets have been considered in the analysis.

Information on the **power units** used in robotics, namely Li-ion batteries or fuel cells, is given in the relevant chapters.

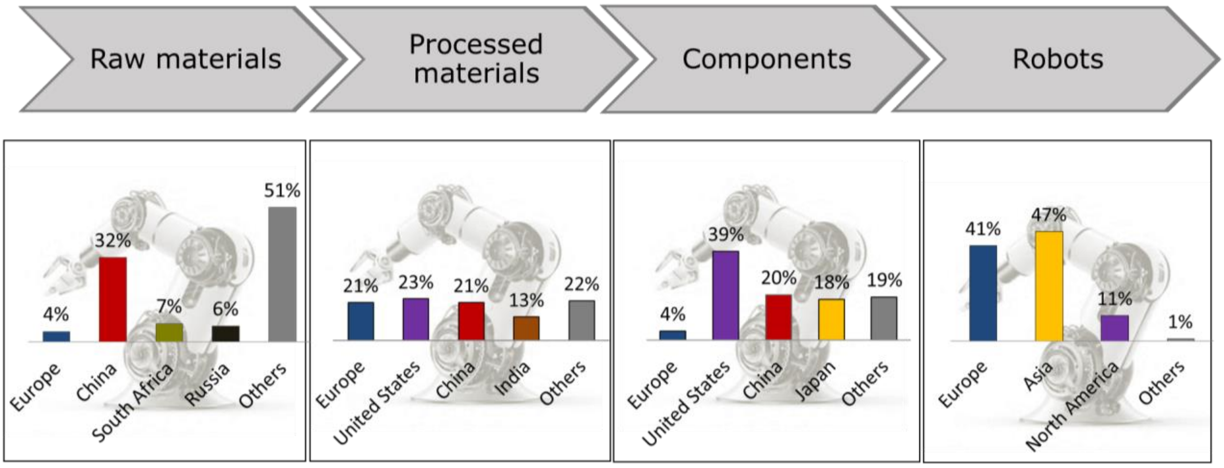
Step 4: Robots

Both industrial robots, having a market share of 80 %, and service robots (20 % market share) are considered at this step. Exoskeletons, although part of this chapter, are also analysed separately due to their specificities.

4.5.2 Key players and market share along the robotics value chain

The key country suppliers along the identified supply chain steps for industrial and service robotics are shown in Figure 35.

Figure 35 Robotics: key players in the supply chain



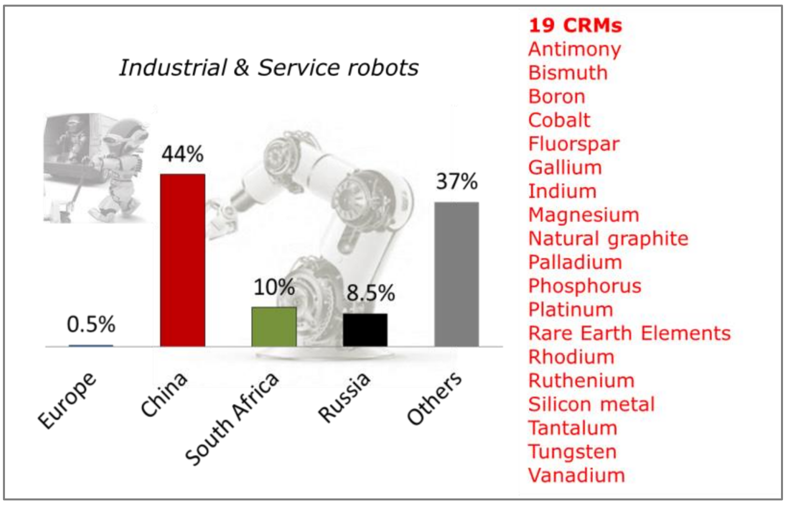
Source: JRC

China is the major supplier of more than one third of the **raw materials** required in robotics. China is the biggest supplier of 23 out of the 44 raw materials used in robotics. Of the 19 CRMs identified for robotics, 12 are supplied predominantly by China. In view of CRMs only, China supplies more than 40 %, followed by South Africa and Russia. The supply of CRMs from European countries is negligible (<1 %) (Figure 36).

In view of the supply of **processed materials** for robotics, Europe is strongly positioned, delivering more than 20 % of the materials. Europe is strong in production of Ni/Ni(Ti) alloys, Mg alloys, polymers, advanced ceramics and glasses as well as processed materials for fuel cells. There is some CFC and nano-material production in Europe, though proportions are relatively small. Other key countries supplying processed materials are the USA, China and India. Europe is highly reliant on external supply of the selected Al alloys (main suppliers India & USA), selected steels (main supplier India), kevlar fibre and semiconductors (main supplier USA) and LIB processed materials (main supplier China).

[279] https://www.roboticstomorrow.com/news/2018/12/04/magnetic-gripper-for-robot-applications-/12898/

Figure 36 Supply of CRMs for robotics: key players



Source: European Commission, 2017, Study on the review of the list of critical raw materials

The **components** for robotics are delivered mostly by the USA (c. 40%), China (20%) and Japan (18%). Europe also has some limited domestic capacity for components manufacturing with Siemens, Porsche and Continental providing parts. The quality of the components supplied from outside Europe is often a concern for robotics manufacturers.

Although EU Industry believes that access to global supply chains will meet their chip and processing needs, there are concerns around security of supply for military applications in terms of trustworthiness. Defence ministries have limited market influence as their market needs are small compared with civil applications, and complex global supply chains make it difficult for them to assure parts placed into military systems. However, as robotics systems develop increasing levels of autonomy, with AI and software integration, which will be implemented by using increasingly complex programmable electronics, their exposure to cyber physical security risks will grow. Modifications after in-service introduction, including electronics and software modifications to improve performance, may actually increase the 'attack surface'. There are concerns that potential adversaries might tamper with COTS electronics and with associated software to affect the functionality of military equipment during procurement or in-service updates, and the USA is already taking action to try to mitigate these risks.[280] The existence of counterfeit electronics in the supply chain demonstrates the potential for such attacks.

According to EU robot manufacturers, there are some European players for robotics components but only for smaller products; not for medium or large components. The volumes currently required are small, so Europe cannot compete with other established suppliers. Some European players are starting to invest, but the process is still in its early days. Other big robotics company representatives claim that there could be an advantage in supplying materials and components from within Europe since it would cut out huge transportation costs.

European companies providing robotics parts are Siemens, Porsche and Continental. Representatives of robotic companies in Europe say that producing all raw materials and parts in Europe will reduce their competitiveness, mainly due to higher prices. They believe that the ratio of domestic versus non-EU production should be 50:50. There is also the issue of market growth: most suppliers tend to be located close to rising markets. Asia is a rapidly growing market and it is therefore to be expected that the

[280] US Defense Science Board, Final Report of the Defense Science Board Task Force on Cyber Supply Chain, February 2017

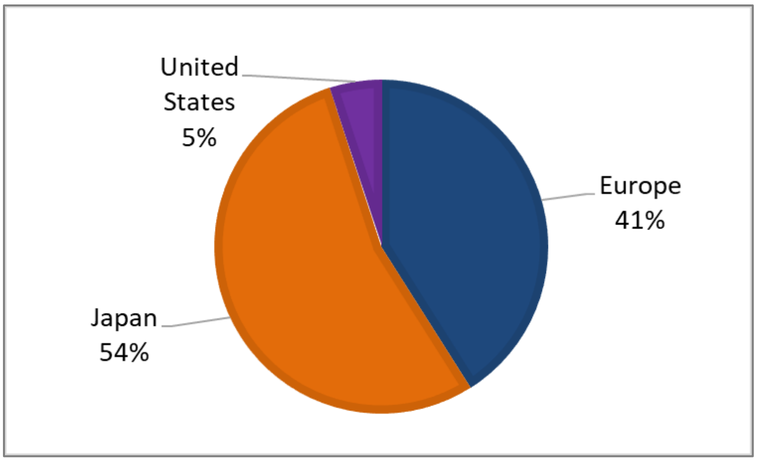
majority of suppliers will be located there. Close cooperation with Asia rather than competing with it is believed to be a sensible strategy – European companies are building manufacturing facilities outside Europe, closer to the market – customer-centric organisations. Although leading European robotic companies see the advantage of sourcing their supplies from inside Europe, they do not see the sense in restricting all production to Europe, in what is clearly a global business.

Europe is a very strong player in **industrial and service robotics**, producing > 40 % of all robots employed globally. The market leader, however, is Asia (mainly represented by Japan), satisfying about half of the present market. The rest of global demand is met by North America (mainly USA).

The present industrial robotics market is dominated by players such as FANUC Corporation (Japan), ABB Ltd. (Switzerland), Mitsubishi Electric (Japan), Yaskawa Electric Corporation (Japan), Kawasaki Heavy Industries Ltd. (Japan), Kuka AG (Germany), Denso Corporation (Japan) and Panasonic Corporation (Japan). [194] It should be noted though that ABB also produces robots in China and the USA. ABB is still a Swiss-Swedish company; the largest share is owned by the Wahlberg family (10%), but ABB also invests in China. According to the chief executive of the automation giant [281], China already dominates the robotics market. The industrial giant, Kuka, is registered in Germany, but 75% [282] of its shares are in Chinese hands and Kuka is focusing on growing its business there. [283] Other industrial robotics companies reflected in Figure 37 are listed in Annex 2 Table 52.

In terms of revenues, European industrial robotics companies hold around 40 % of the industrial robotics market. Japan is the leader with more than 50 % (Figure 37). The revenues of 21 leading industrial companies are taken into account for shares calculation. [284]

Figure 37 Country production shares based on major industrial robotics companies globally



Source: Technavio [284]

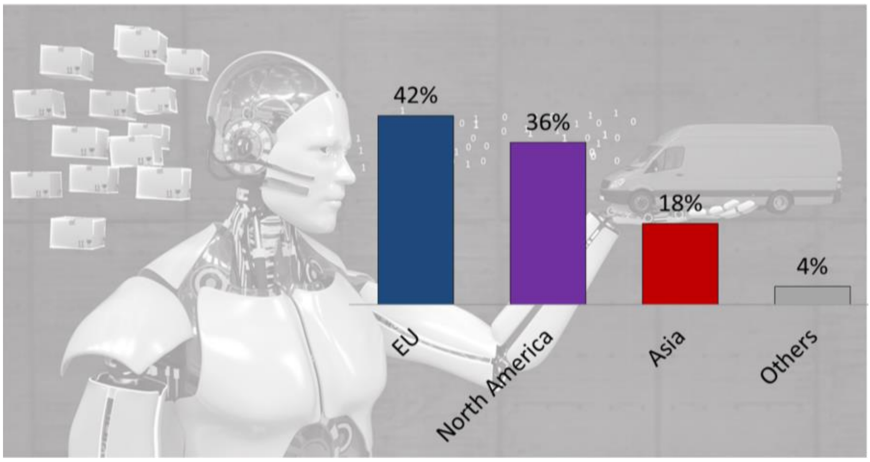
While Japan is heading the industrial market, USA leads in non-industrial robotics, unmanned vehicles and drones, and artificial intelligence: Intuitive Surgical (USA), AeroVironment (USA) and Faro Technologies Inc. (USA) are leading companies in these

[281] https://www.cnbc.com/2017/10/26/china-is-the-largest-market-for-robots-in-the-world-right-now-abb-ceo.html
[282] https://www.statista.com/statistics/317178/leading-industrial-robot-companies-globally-by-revenue/
[283] https://global.handelsblatt.com/companies/robot-maker-kuka-feels-the-squeeze-861702
[284] https://www.technavio.com/blog/top-21-companies-in-the-industrial-robotics-market

applications. [285] Of the 10 most innovative robotic companies for 2018, eight are USA companies, and the remaining two are Japanese [286] (Annex 2 Table 53).

As for **service robots**, representing around 20 % of the current robotics market, the EU is the market leader (42 %), followed closely by North America (36 %) and Asia (18 %) [287] (Figure 38). The shares are based on number of companies per country.

Figure 38 Country production shares of service robots



Source: RockEU2[287]

The shares in Figure 35 are calculated by combining data from Figure 37 and Figure 38, taking into account an 80 % market share for industrial robotics and 20 % market share for service robotics.

Exoskeletons

As discussed above, **exoskeletons** are treated separately due to their specificities: they are perceived partly as a medical tool and partly as robot.

Materials and components for exoskeletons

While metal is the main raw material used in robots, plastic is the fundamental material for exoskeletons, making them lighter and wearable. Single parts for exoskeletons are simple, like plastic or plastic foaming, and are developed in Europe. Small gears, electrical equipment and batteries are harder to source. CFCs are also used to a certain extent in exoskeletons, though their use is still very limited. Magnesium-reinforced polycarbonate, aluminium and magnesium alloys have the potential to strike the balance between cost and strength which is crucial for exoskeletons. [288]

Flexible carbon nanotube composite coatings applied on a wide range of fibres, including cotton, nylon and wool, are used to create smart textiles. [289] Fabric coated with electrically conductive carbon nanotube composite technology could be used in future smart garments that measure human motion with the sensing capabilities of nanotubes.

According to a robotics business representative interviewed for this report, the critical components for exoskeletons are electric motors, transmissions, power cords, batteries, sensors and software.

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[285] https://www.globalxfunds.com/leading-companies-in-the-development-of-robotics-and-ai/
[286] https://www.fastcompany.com/most-innovative-companies/2018/sectors/robotics
[287] https://www.eu-robotics.net/cms/upload/about/RockEU2Deliverables/D1.7.pdf
[288] https://www.compositesworld.com/blog/post/composites-in-exoskeletons
[289] https://www.compositesworld.com/news/carbon-nanotube-composite-coatings-used-to-create-smart-textiles

The **software** can be made by EU companies.

Motors are supplied from Germany, Switzerland and America. Increasingly, motor components are assembled in the EU; the parts of the motor, such as magnets and wirings, are not perceived as critical, unlike the motor design itself, which is executed in the EU.

Transmission is critical – the motors turn rapidly for a transmission ratio of 1:20. To achieve more strength and less velocity there is a gearbox at the exit of the motor. These are supplied mainly by Japanese manufacturers (Nabtesco and Harmonic Drive). Japanese Nidec Corporation is also investing heavily in German robotics companies for the production of speed-reducing gearboxes to propel the joints of robot arms.[290] While the German players sell mostly within Europe, they also supply manufacturers in Asia. Demand in Asia is expected to rise, particularly as Beijing works to upgrade its industries under the 'Made in China 2025' initiative.

Gear-boxes can be a real bottleneck in exoskeletons. Companies are starting to design gearboxes and will probably make them in Europe. The lead time will be shorter than importing them from Asia.

Batteries are of medium criticality.

Sensors can be another critical component. Subcomponents for sensors are made in Asia, but integration can be carried out by many companies; a Swiss company for instance is one supplier of sensors.

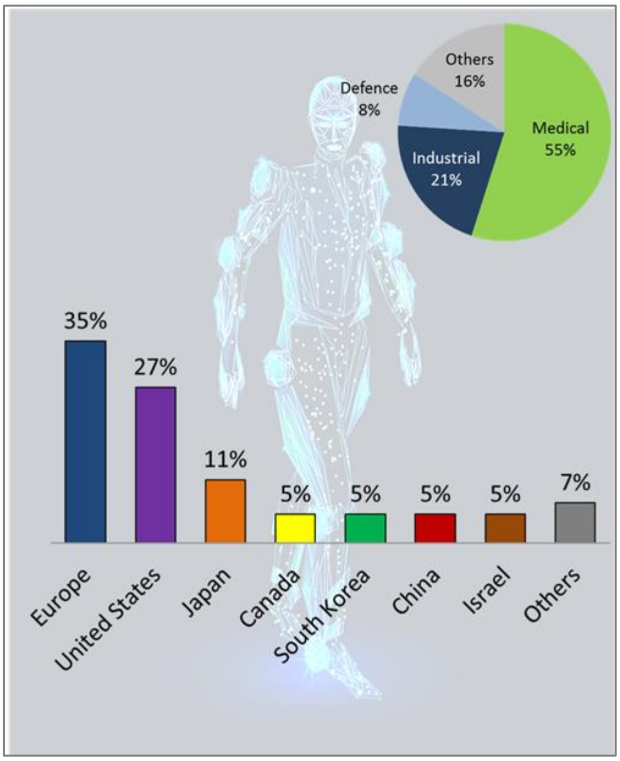
As for the electronics in exoskeletons, the situation is similar to that in robots. Although there are a few big players in electronics in Europe that can supply to robotics industry, some exoskeleton companies opt to import components from the USA due to a combination of good quality and lower price. There are plenty smaller companies in America providing high quality electronics. The **electronic card** is supplied mainly from China and also Taiwan. Intel **processors** are mounted on Chinese-made chipsets. The electronics for an exoskeleton are very close to a PC card.

European companies prefer to source materials and components from inside Europe for several reasons: shorter lead times; customs costs, which can be significant; and the risk of being copied by Chinese industry. It can be cheaper to manufacture metal structures, aluminium parts and gearboxes in China but long lead-times are of critical inconvenience. Trade agreements with third countries can also lead to significant customs charges on goods imported from outside the EU.

Europe holds around one third of the exoskeleton market (in terms of production), followed by the USA and Japan (Figure 39). Shares are calculated based on the number of companies per country. [291] Four of the nine publicly traded exoskeleton companies in advanced stages of development and marketing are based in the USA, and three are Japanese. [292] Companies considered here as exoskeleton producers are listed in Annex 2 Table 51.

[290] https://industryeurope.com/nidec-corporation-to-buy-5-german-robotics-companies/
[291] https://exoskeletonreport.com/2015/10/map-of-exoskeleton-companies/
[292] https://www.nanalyze.com/2017/02/9-robotic-exoskeleton-stocks/

Figure 39 Country production shares of exoskeletons



Source: Exoskeleton Report (2015) [291] and Exoskeleton Report catalogue [293]

Most existing exoskeleton companies serve the medical (health-care) sector (55 %), followed by the industrial sector (21 %).[293] The Medical sector, for the purpose of analysis, is taken to include rehabilitation, nurse support, care support and living support as well as elderly support. The main four exoskeleton players in the health care market are ReWalk (USA), Ekso Bionics (USA), Cyberdine (Japan) and Indego (USA). Around 8 % of the exoskeleton companies in the analysis have declared defence relevance, of which 70 % are located in the USA. Since 2010, Ekso Bionics, Lockheed Martin and Sarcos/Raytheon are the leading American companies in defence exoskeletons.

4.5.3 Supply chain of civil versus military robotics applications

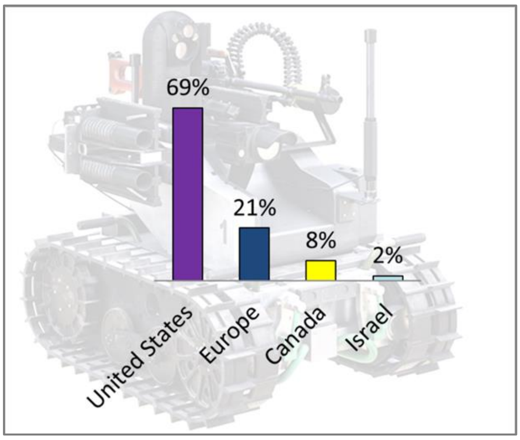
Military robots are one of the main end uses of the service robot category, along with robots for disaster management, healthcare, consumer and logistics robots. It is believed that military robots will be developed by new players rather than by the established industrial robotics players for two reasons: it is difficult to justify this type of activity (due to image/moral issues) and companies need to meet the specific requirements of the defence market in order to be competitive. Industrial users are normally reluctant to enter the defence market because of its complexity and specificity. The industrial players are unlikely, therefore, to become the new defence players. New and existing small robotic companies should get support and access to funds to develop military robots. The perception of existing robotics companies in Europe is that the bureaucratic process, related to national and EU legislation is too complex, as is the certification of new robots. While there is no EU regulatory framework dedicated specifically to robots, there is a host of existing regulations to comply with, covering, for example, machinery, medical devices, work equipment, etc. [294]

[293] https://exoskeletonreport.com/product-category/exoskeleton-catalog/
[294] https://www.b2match.eu/system/eu-taiwan-2017/files/Felicia_STOICA_-_EU_regulatory_framework_for_robots.pdf?1499334449

Key players in robotics for defence

The USA holds the current lead in robotics for military purposes (Figure 40). [295] Of around 30 companies providing robotic systems for military applications in 2013, 19 were in the USA, accounting for >60 % of the military market; seven were European companies (UK, France and Italy) and Canada and Israel held the rest of the market. [296] Six of the top 10 robotics companies considered to be disrupting the defence industry are USA companies, three are European (MRX Technologies (UK), Qinetiq (UK) and M-Tecks Robotics (France) and one is Canadian. [297] Important players in the military robotic sector are Telerob Gesellschaft für Fernhantierungstechnik mbH (Germany), Allen-Vanguard Corporation (Canada), Cobham PLC (UK), Security Defence Systems (India), QinetiQ (UK), BROKK AB (France), MED-ENG (Canada), Endeavor Robotics (USA), AB Precision (UK) and ICOR Technology (Canada).

Figure 40 Country production shares of military robots



Source: Venture Radar [298] and Disruptor [297]

The USA is an established leader in military robotics. Leading organisations actively supporting development of military exoskeletons are the USA Army, Defense Advanced Research Projects Agency, USA Marine Corps, USA Special Operations Command, USA Air Force Air Mobility Command and USA Department of Veterans Affairs, illustrating the wide range of military interests from war-fighting to supply handling and helping wounded soldiers to rehabilitate. In addition, several leading USA universities and research organisations are involved in exoskeleton for both military and civil purposes, namely Massachusetts Institute of Technology, University of Florida, Georgia Institute of Technology, Harvard University, University of California, Berkeley, Arizona State University, United States Military Academy at West Point and the Defense Advanced Research Projects Agency. [299],[300]

China is predicted to become an important player in the military landscape of robotics. It has put strong initiatives in place to make it world leader in industrial automation and military robotics. Indeed, 2016 was a bellwether year for Chinese robots, and the security sector was no exception. [301] China is investing heavily in exoskeletons and has

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[295] Shares based on number of companies per country

[296] http://www.everything-robotic.com/2013/03/which-companies-provide-robotic-systems.html

[297] https://www.disruptordaily.com/top-10-robotics-companies-disrupting-defense-industry/

[298] https://www.ventureradar.com/keyword/Military%20Robotics

[299] https://exoskeletonreport.com/2016/07/military-exoskeletons/

[300] http://www.statepress.com/article/2018/04/spscience-asu-engineering-the-future-in-wearable-robotics

[301] https://www.roboticsbusinessreview.com/manufacturing/top-5-chinese-robots-advancing-military-uses-2016/

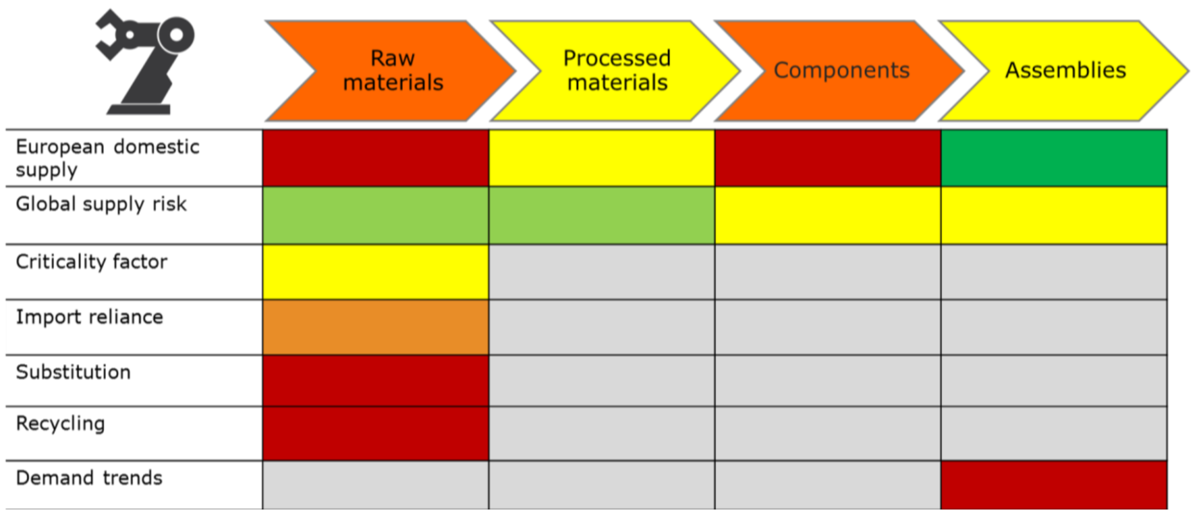
unveiled a number of different types. [302,303] State-owned company, Norinco, supplies the Chinese state with combat vehicles and is spearheading the development of military exoskeletons. Besides Norinco, the China Shipbuilding Industry Corporation has also revealed an exoskeleton suit to be used by shipyard workers, who often have to carry heavy loads. Nanjing Military Hospital has unveiled an exoskeleton capable of lifting just over 36 kilograms and military engineers at EEAE have developed the exoskeleton suit, 'model L-70'.

Another country with serious ambitions in military robotics is Russia. [304] The Russian government wants unmanned vehicles and robots to play a key role in its future military arsenal. With a number of ambitious projects in development, Russia intends to make everything from unmanned vehicles to fully autonomous artificial intelligence integral to its armed forces. More companies supplying robots for military applications and considered for the country shares in Figure 40 are listed in Annex 2 Table 54 and Table 55.

4.5.4 Overview of the supply risks for the robotics supply chain

An overview of the various supply risks and bottlenecks for robotics are visualised in Figure 41. The performed bottleneck assessment has shown potential high supply risk for raw materials and components and medium supply risk for processed materials and assemblies. Though Europe is one of the major producers of industrial and service robots, the highly concentrated supply and expected rapid demand growth are factors contributing to the medium supply risk assessed for the last step of the supply chain. Moreover, the lack of raw materials and components, lack of enough skilled work force in Europe and increasing competition from China (acquisition of leading European robotics companies by Chinese companies) are additional factors that can challenge the competitive position of Europe on the global market.

Figure 41 Overview of supply risks and bottlenecks in the supply chain of robotics



Source: JRC

[302] https://www.popsci.com/chinas-new-exoskeletons-not-just-call-duty-or-tom-cruise-anymore
[303] http://www.illustratedcuriosity.com/technology/technology-robotics/china-is-investing-heavily-in-exoskeletons/
[304]https://www.businessinsider.com/russia-has-serious-ambitions-for-military-robotics-2017-11?international=true&r=US&IR=T

4.6 Opportunities for research and policy actions for robotics

4.6.1 Research opportunities

Robotic automation has been a revolutionary technology in the manufacturing sector in the recent years and is expected to transform the industry further over the next couple of years. Expected future trends which will dictate R&D needs in the robotics field include: **industrial internet of things (IIoT) technology, including smart sensors to collect data for the manufacturers; big data analysis; producing standards and open documentation to make robotic integration easier; new business models to lessen upfront costs** (known as robots-as-a-service or robot rental models)**; and customisable modular robots** (able to change their parts as tasks change).

Collaborative robots and **autonomous vehicles** will become more evident. **Cloud robotics** is also expected to accelerate. Artificial intelligence (AI) and machine learning are the focus of research and development across the world. Robots empowered with this technology can improve on their own, learn new techniques, and adapt in many ways. Machine learning can also help manufacturers perform preventative maintenance, as the robot will be able to alert the proper personnel as soon as an issue arises.

Cybersecurity is often overlooked in current industrial/civilian robotics products. As these tools become increasingly connected to the web/cloud, the door is opened to tremendous security problems. It would be fairly easy to hack into present-day industrial robotics systems and cripple entire plants/industries or cause major accidents. With the use of robotics technology ever rising, and the technology more and more entangled with our everyday lives, this security aspect should subject to much more research. Cyber physical security of electronics systems (such as controllers) for military robotics applications is also a key issue as robotics systems develop increasing levels of autonomy, with AI and software integration, needing mitigation. The USA, for example, is concerned that potential adversaries might tamper with COTS electronics and with associated software to affect the functionality of military equipment during procurement or in-service updates, and is taking action to try to mitigate these risks. R&D investment will be required in methods to protect military systems (and critical civil infrastructure) against cyber supply chain attacks. Cybersecurity is therefore an area where civil-military synergies could arise.

In terms of materials research opportunities, the **development of innovative, light and high-strength structural and functional materials** is the main research focus for robotics, including exoskeletons (or wearable robotics). Materials with the potential to deliver superior performance (innovative light and high-strength alloys) are magnesium, aluminium, titanium alloys, special steels and composites (fibre reinforced), including combined polymer-metal composites. **Innovative materials for special applications (multi-functional motors and artificial muscles) are also under development, e.g. vanadium dioxide.**

New and promising trends in robotics include the **development of new materials and advances in making electronic skin for interactive robots and associated flexible or stretchable electronics; smart textiles based on flexible carbon nanotube composite coatings; and soft robotics using printed liquid metal, metallic glass and liquid silicon rubber.** Materials engineering is a powerful tool to design novel materials for specific forward-thinking applications.

Smaller, more powerful, high speed and precision electronics are essential to robotics development. Gallium nitride, in particular, is gaining rapid importance in both military and civil domains.

Robotics of the future, with advances in autonomy and AI, will depend more and more on **complex software architectures**. Cloud robotics is emerging as a solution to support an interconnected web of robots. Open challenges and problems in cloud robotics systems, which should be addressed for improving the performance of cloud-based robotic systems, are: efficient resource and task allocation over the cloud; reducing communication delays over the cloud; data inter-operability and scalability of operations between robots in the cloud; and privacy and security in cloud–robot systems.

Exoskeletons, composites, batteries and electric motors are critical elements that need to become cheaper and therefore more accessible. **The defence industry needs cheaper and lighter, but reliable and safe exoskeletons, with a longer battery life, which would give a clear advantage to troops.** Military exoskeletons also need to have increased strength and endurance in demanding environments, assuring high survivability. Based on these requirements, topics for further research in military exoskeletons could include: software to coordinate exoskeleton movements; vital sign and stress monitoring technologies; armour with high ballistic performance; improved helmet back-face deformation liner and retention systems for increased protection against bullets, blasts and shrapnel; visual augmentation system/operator-automated remote sensors for increasing situation awareness and reducing the surveillance (and cognitive) burden on soldiers; weapons interface; more efficient and smaller power units; and, improved thermal management and communications connectivity.

An **optimal battery pack, resistant to extreme temperatures and shocks, with safe air transportability, long operation time and low maintenance, is an important deployment aspect for military robots in general.** Besides batteries, the design of military robotic tools should take into account standardised pallet sizes for transportation.

In view of materials specific to the field of defence, the **development of advanced materials, including paints and textiles, to mitigate and reduce signatures**, is an important field. Nanotechnologies seem to offer a cutting-edge solution, such as composite nanostructures-nanoparticles or nanowires with specific properties incorporated into a host substrate. Metamaterials - artificial material composites such as metal-insulator-metal - offer another potential solution.

4.6.2 Opportunities for policy actions

The market is small and therefore remains challenging. Although the number of vendors is increasing, customer demand is very much fragmented and diverse, making the market even more difficult.

Though the European robotics market is one of the largest and most technologically advanced, manufacturers are facing increasing competition from Asia, especially Japan and growing economies such as China. In order to survive and grow in the global robotics market, Europe needs to take certain.

The robotics industry in Europe has suffers from a long and complex approval procedure. According to industry sources, there is a strong need to **streamline the approval process** of new robots as well as stimulating R&D. The robotics industry is currently concentrated in Germany, France and Italy. **Functional collaboration should be facilitated among European countries and companies**. The European Commission could advocate further production of robots, strengthening the Europe’s position and discouraging companies from setting up factories in Asia, intensifying interest and awareness in Europe and increasing the supply of robotics components and raw materials. **More research and development should be also facilitated,** especially involving smaller service robotics companies. Both Horizon Europe and EFD are suitable instruments to grant such support.

Europe is believed to have reached saturation point in the robotics industry and to be hampered by high operational and human resource costs. The European Commission could **support the industry** in many ways, from **increasing awareness and incentives to encouraging companies, old and new, into advanced research and**

development. Funding robotics research into size, weight, technology, software, materials and application would make a considerable difference.

Emphasis could be put on **small and medium size enterprises (SMEs)**, **to grow the European robotics market**. Almost all major companies and factories in the region have been automated. The European Commission could promote the incentivisation of automatisation/robotisation of SMEs at Member State level.

In many segments of service robotics Europe has a head start on the rest of the world. The European Commission can capitalise on this and **counter increasing competition** from Asian and American companies, promoting support to small and specialised service robotics companies through development funds, investments, loans, subsidies and tax breaks for implementation at Member State level.

According to leading robotics companies in Europe, heavy safety standards and regulations are a major impediment. Growing companies already investing heavily in prototypes complain of excessive government emphasis on safety regulations. The same is true of exoskeletons – too long and heavy a certification process in Europe. Industry representatives would prefer a **framework to test safety through real life testing** rather than relying on analysis (documentary phase). The European Commission should promote improvement of the standardisation/certification process to make it shorter and lighter while complying with the highest safety standards.

To **attract and maintain technical expertise in Europe**, The EC could promote awareness and investments in the study of robotics, in the form of reduced tuition fees, increased employment opportunities, aid for university collaborations and the promotion of foreign exchange programmes, tailored to each Member State.

Europe lacks manufacturers of important robotics components. The dominance of foreign suppliers, specifically for some higher level components that are expected to be key for future technological development (e.g. GPU's), is seen as a threat by the robotics industry. **Therefore strengthening and investing in the local components manufacturing industry** would be profitable in general for robotics companies. It would increase production in Europe and discourage companies from setting up manufacturing plants in Asia. In addition, this would establish a new revenue stream for Europe through the sale of technologically advanced robotic components to robot manufacturers in other countries. The EC could invite Member States to define appropriate incentives to encourage local robotics components-related companies to invest in Europe, and to support the development of new businesses. Measures to discourage the inflow of components produced outside Europe could also be defined at Member State level.

Robotics, the growth of artificial intelligence, and the internet of things are rapidly changing the face of European manufacturing. To benefit from these technologies safely **cybersecurity** is the utmost importance. The cyber challenge needs to be addressed in various ways, from investing in security awareness training and cyber hygiene to instigating policies and legislation initiatives and adopting appropriate standards.[305]

Although in the current market scenario, the supply of raw materials is not seen by European robot manufacturers as a potential bottleneck, an **adequate supply of raw materials should be maintained**. A good strategy for this is believed to be the supply and close cooperation with Asia instead of competition.

Finally, **Europe should strengthen its local robotics market and seek ways to increase and sustain internal market demand,** actively involving robotics stakeholders through various initiatives.

305 https://www.enisa.europa.eu/publications/enisa-position-papers-and-opinions/enisa-input-to-the-css-review-b

As robotic automation gains widespread adoption, the need for **open automation architectures** grows. Large industry players should work with industry organisations to produce standards and open documentation that make robotic integration easier while improving product compatibility. [306]

Last but not least, advances in robotics and artificial intelligence will create the need for an adequately **high-skilled work force**. Robotics companies already perceive this as a big potential bottleneck for future development of the sector in Europe. Companies are looking to hire high-level maths software engineers and robotics postgraduates. China and India are highly competitive in terms of supplying skilled workforces. Business and academia should therefore be encouraged to identify skills gaps and shortages for the robotics sector. Tailored retraining and upskilling programmes will be an important follow-up, which the European Commission can support. It is also up to stakeholders (industry, academia etc.) to take advantage of relevant EU funding, such as Erasmus and European structural & investment funds.

The European Commission has already proposed an approach to AI and robotics. It deals with technological, ethical, legal and socio-economic aspects to boost EU research and industrial capacity and to put AI at the service of European citizens and the economy. [307]

4.7 Robotics: summary

Robotics is an emerging technology offering enormous potential for many civil and defence applications. A variety of issues ranging from cybersecurity to standards and regulations needs to be further addressed as the robotics sector develops. Materials engineering, design, electronics and software are some key areas in which research is needed.

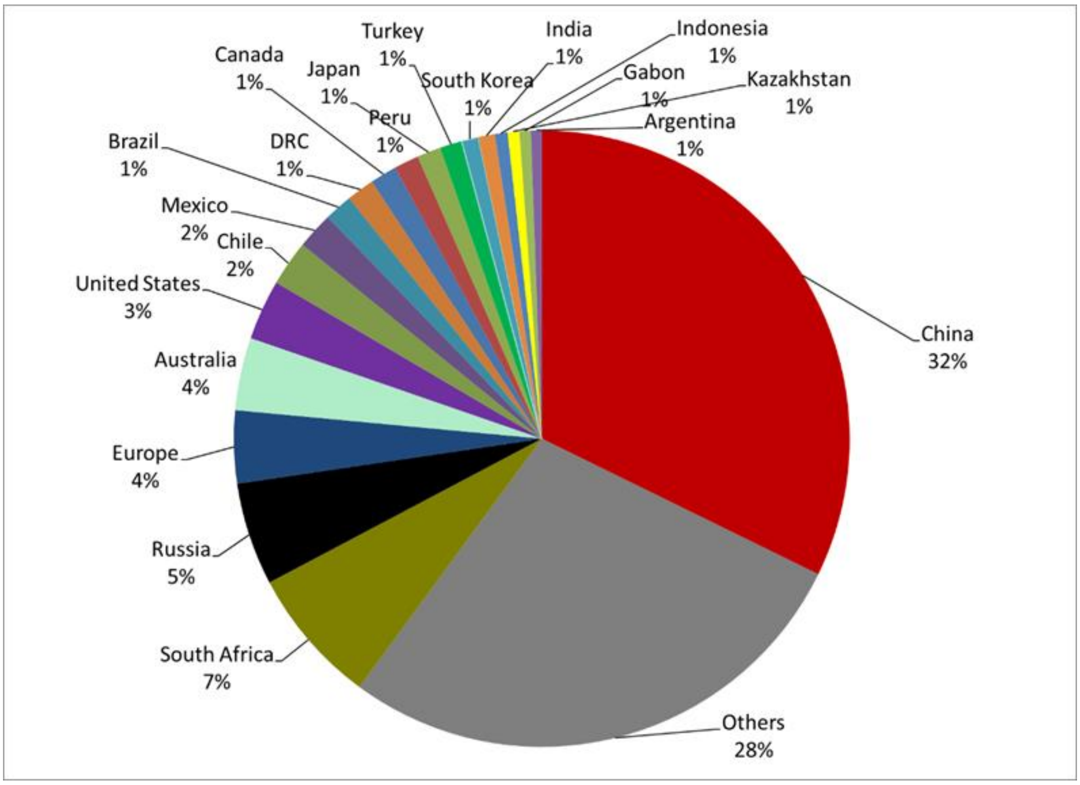
It is difficult to predict the growth rate in robotics due to the variety of sectors involved. The highest growth is expected in the service sectors – e.g. logistics robots - but a lower growth rate of between 10 % and >20 % is forecast for other branches of the industrial and service robotics market. Growth projections for exoskeletons, also used across various sectors, are even more optimistic, forecasting a CAGR of up to 40-50 % in the next few years.

In total, 44 raw materials and 29 processed materials were identified as relevant for robotics and analysed in this study. Out of the 44 raw, 19 materials are flagged as critical for the EU economy, namely Ta, W, P, F, Ru, Rh, Ga, In, B, Pd, Pt, REE, Bi, Sb, V, Mg, C, Si and Co. China is the major supplier of CRMs for robotics, delivering more than 40 % of CRMs, followed by South Africa (10 %) and Russia (9 %). The analysis shows that China is also the major supplier of more than one third of the raw materials required in robotics. Other suppliers are South Africa (7 %) and Russia (6 %) with many small suppliers having less than 6 % market share, which gives vast opportunities for supply diversification. An overview of the different raw materials suppliers for Robotics is shown in Figure 42. Europe delivers around 4 % of the raw materials for robots.

Europe is well positioned on the second supply chain step, supplying more than 20 % of the processed materials required in robotics. It should be noted, however, that Europe is fully dependent on supply of aramid (Kevlar) fibre and semiconductors, both materials predominantly supplied by the USA (Figure 43). The major supplier of processed materials is the USA with a 23 % share. Other key suppliers are China (21 %) and India (13 %).

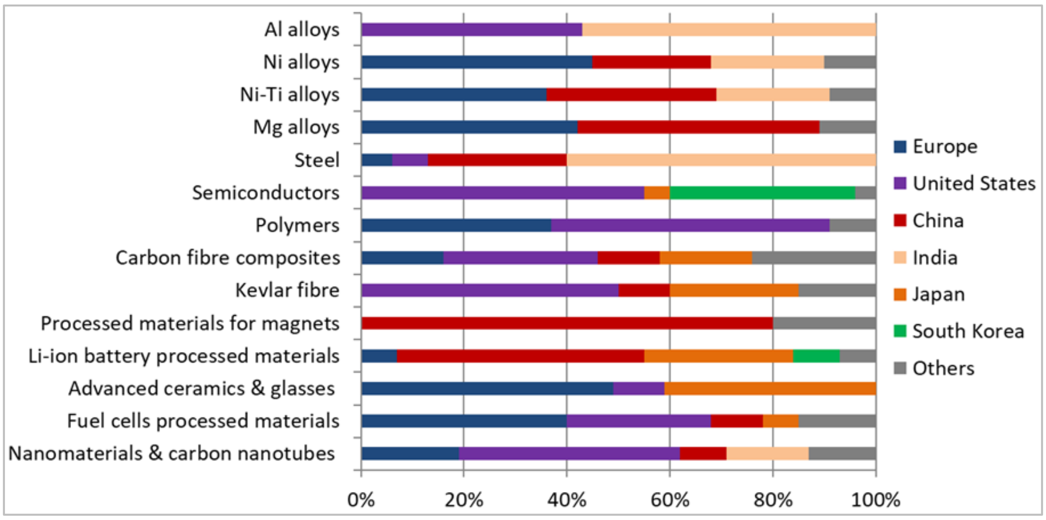
[306] https://www.robotics.org/blog-article.cfm/Top-6-Future-Trends-in-Robotic-Automation/101
[307] https://ec.europa.eu/digital-single-market/en/artificial-intelligence

Figure 42 Raw materials suppliers for robotics: overview



Source: European Commission, 2017, Study on the review of the list of critical raw materials

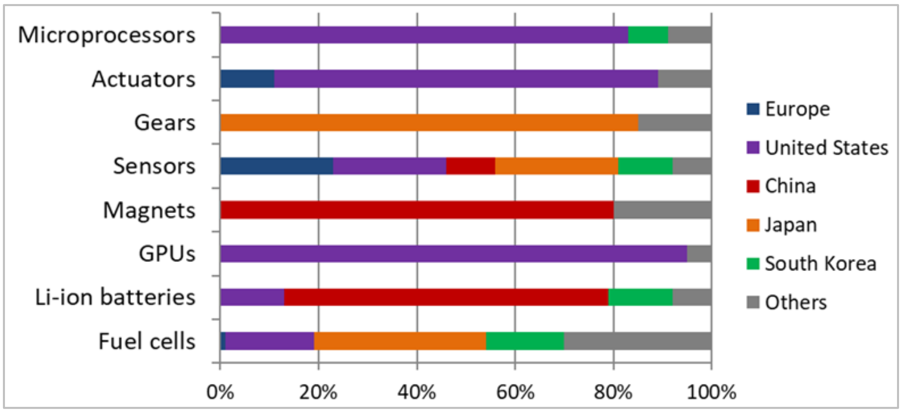
Figure 43 Country production shares of processed materials relevant to robotics



Source: JRC

The key supplier for components for robotics is the USA with a 39 % share, followed by China (20 %) and Japan (18 %). Europe has a marginal share of the supply of components – around 4 %. Around 20% of components are provided by a number of small players. More concretely, the USA is the major supplier of actuators, controllers (microprocessors) and GPUs, and one of the key suppliers of sensors and fuel cells. Japan is the key supplier of gears, sensors and fuel cells. China is the major supplier of Li-ion batteries. Other key suppliers are Israel (actuators), South Korea (microprocessors and FCs) and Canada (FCs). Europe is among the three major suppliers of sensors and actuators. However, Europe shows strong dependence on the supply of five out of the seven analysed components, namely gears, LIBs, microprocessors, FCs and GPUs. Electronic components and parts are typically supplied from Asia, while processors are mostly delivered from the USA. Chinese companies produce processors, but not the high level processors needed in robotics. However, it can be expected that in the future, China might also supply these. Although chips and processors are not produced in Europe, robotics company representatives do not see this as a potential bottleneck, believing that there will be enough supply globally. Batteries, on the contrary, are seen as an imminent bottleneck. In the future, batteries are expected to be solid state – solid state lithium, for instance, and graphene. The EU has introduced a very strong programme in graphene but the intermediate steps are also important and this could be semi-critical, according to experts. The country production shares for components used in robotics are shown in Figure 44. Components are listed arbitrary.

Figure 44 Country production shares of components relevant to robotics



Source: JRC

Asia, mainly represented by Japan with a 47 % production share, leads the industrial robotics market, followed by Europe (41 %), while North America (mainly the USA) performs better in non-industrial robots. The USA also has the biggest number of highly innovative robotics companies. The EU is a major player in the service robots market, followed by North America and Asia. Europe leads the exoskeletons market, followed by the USA, Japan and numerous smaller players. Exoskeletons are currently used predominantly by the medical sector. Defence represents only 8 % of the exoskeleton market. The key players in military exoskeletons are located in the USA.

The performed bottleneck assessment shows potential high supply risks for raw materials and components and a medium supply risk for processed materials and assemblies. Though robotics relies on a vast number of raw materials, half of them supplied by just three countries - China, South Africa and Russia, raw materials supply is not of particular concern for manufacturers in Europe. **The major concern of the European robotics industry is the lack of domestic component manufacturers**. Despite having technical expertise, Europe has failed to mark its presence in the robotics component market and the dominance of the Asian market will be difficult to compete with. **The lack of an adequate skilled workforce** along with long and **difficult certification processes** are also major concerns for European robotics manufacturers, affecting their competitiveness.

In short, there is a need to strengthen components production for robots in Europe; assure that EU legislation supports robot manufacturers rather than hampering their business; identify the skills needs of the robotics sector and take action to assure its availability in future; and last but not least, ensure materials advancements to meet the challenging robotics requirements of the future.

5 Unmanned vehicles

Unmanned Vehicles (UV) are powered vehicles without a human pilot on board, also called uncrewed vehicles. There are two basic types of control for UVs: those, which are controlled remotely and autonomous vehicles, which are capable of navigating on their own by means of sensing their environment. UVs are grouped according to their mode of locomotion and physical operating range, i.e. aerial vehicles and those moving on ground, on water, and underwater. The following types of UV are commonly distinguished:

- Unmanned Aerial Vehicles (UAVs) are aircraft that do not carry a human operator, use aerodynamic forces to provide vehicle lift, and can be expendable or recoverable (commonly known as drones);
- Unmanned Ground Vehicles (UGVs) include the autonomous car;
- Unmanned Maritime systems (UMSs) include:
  - Unmanned Surface Vehicles (USVs) which operate on the surface of the water;
  - Unmanned Underwater Vehicles (UUVs) which operate underwater;
- Unmanned spacecraft.

'Drones' is an umbrella term, whose exact scope differs depending on the context. It is frequently used interchangeably with 'UAVs', but can also be applied more widely, to cover certain types of UV listed above, or indeed, UVs in general. There are, for example, land-based drones and submarine drones (UUVs). The term does not generally refer to 'driverless trains', UGVs or USVs. This analysis focusses on UAVs, and to a lesser degree UGVs, due to the significant rise in the number of these and the pronounced heterogeneity of UAVs in comparison with other types of UV. There is also a lack of consistent, accessible data for the other vehicle types. Accordingly, unless otherwise noted, this chapter refers to UAVs, although the analysis often applies more widely to other types of UVs too. Additional information is given where useful.

In technological terms, unmanned vehicles fulfil the definition of robots with locomotive capabilities, or 'aerial robots'. In this respect, UAVs are essentially flying robots 'that can be remotely controlled or fly autonomously through software-controlled flight plans in their embedded systems, working in conjunction with on-board sensors and GPS.

The technologies, components and materials used for the various categories of robots are similar to, and partly overlap with, those used for UAVs. Due to specific requirements regarding capability and technical performance, the UVs in this study are analysed separately from industrial robots, which are typically without locomotive capabilities.

5.1 Description of unmanned vehicle technology and relevance to civil and defence sectors

The aeronautics industry, which includes the UAV industry, is considered one of the top five advanced technology sectors in Europe. To support its role as a global player, the EU invests massively in the European aviation sector, fostering research and innovation. The Single European Sky Air Traffic Management Research project (SESAR) has received EUR 430 million a year for the period 2016 to 2020. Together with the European aeronautics industry, the EC also set up the Clean Sky Joint Undertaking as a public-private partnership, to coordinate and fund research activities to enable quieter, more environmentally friendly air traffic. With more than EUR 4 billion for the period 2014-2020, the Clean Sky 2 programme was set up to maintain Europe's global leadership position in aeronautics. Although UAVs are not explicitly covered by these Joint Undertakings, the extent of funding made available to the aeronautical industry is a clear sign of its importance to Europe. UAVs are one of the key innovations within this sector, revolutionising the industry and providing enormous opportunities for small and medium-sized enterprises (SMEs) in particular. [308]

The various types of UV listed above are also used for military applications. For those UV types where military applications are common, distinct vehicle categories have become established, such as unmanned combat aerial vehicles (UCAVs). Military UAVs 'can carry a lethal or nonlethal payload. However, 'ballistic or semi-ballistic vehicles, cruise missiles, and artillery projectiles are not considered unmanned aerial vehicles'. [309]

The safe and efficient operation of an UAV in the national airspace system by the pilot in command requires additional elements, i.e. a ground-based controller (components that control the unmanned aircraft) and a related communications link (between the UAV and controller). The UAV, controller and system of communication form together an **unmanned aircraft system** (UAS). [310] UAVs can be grouped by the degree of their autonomy: either under remote control by a human operator – 'remotely piloted aircraft system' (RPAS) – or controlled autonomously by on-board computers. [311]

Unmanned aircraft have proved capable of providing environmental monitoring, control and security, as well as a fascinating variety of commercial services. UAVs can perform air operations that are difficult for manned aviation, and their use can bring evident economic savings and environmental benefits whilst reducing the risk to human life. They can be classified according to their main purpose (Table 13). Environmental requirements are often more demanding for military applications than for civil applications. For defence systems, operating temperatures typically range from below 0 °C (in certain cases down to -40 °C) and up to 60 °C. Requirements regarding maintainability and transport can also differ from civil applications.

Table 13 UAV classification by main applications (not exhaustive)

Civil and commercial applications	**Military applications**
Agriculture	Reconnaissance: providing battlefield and regional intelligence
Infrastructure inspection	Target and decoy: providing ground and aerial gunnery a target that simulates an enemy aircraft or missile
Monitoring and surveillance	Combat: providing attack capability for high-risk missions (often referred to as unmanned combat aerial vehicle, UCAV)
Data collection	Aerial remote sensing Electronic signal data collection CBRN sensing
Research and development	Pilot devices for advancing UAV technology
Logistics	Delivering cargo

Bottlenecks in the UAV sector need to be understood and tackled due to the increasingly important role that UAVs play in civil, military, and economic terms. In spite of the strong position of the European aeronautics industry and the rising importance of UAVs, there are serious concerns about European capacities and capabilities within this sector.

[308] Antony Gravili (2016): Innovation and Investment: Embracing a new era. In: Commission en direct, February 2016, Dossier Aviation Strategy.
[309] Free Dictionary (2018): "unmanned aerial vehicle", *TheFreeDictionary.com*, Retrieved 01.06.2018.
[310] The term RPAS increasingly replaces the term UAV.
[311] International Civil Aviation Organization (ICAO)(2016): Unmanned Aircraft Systems (UAS). ICAO's circular 328 AN/190.

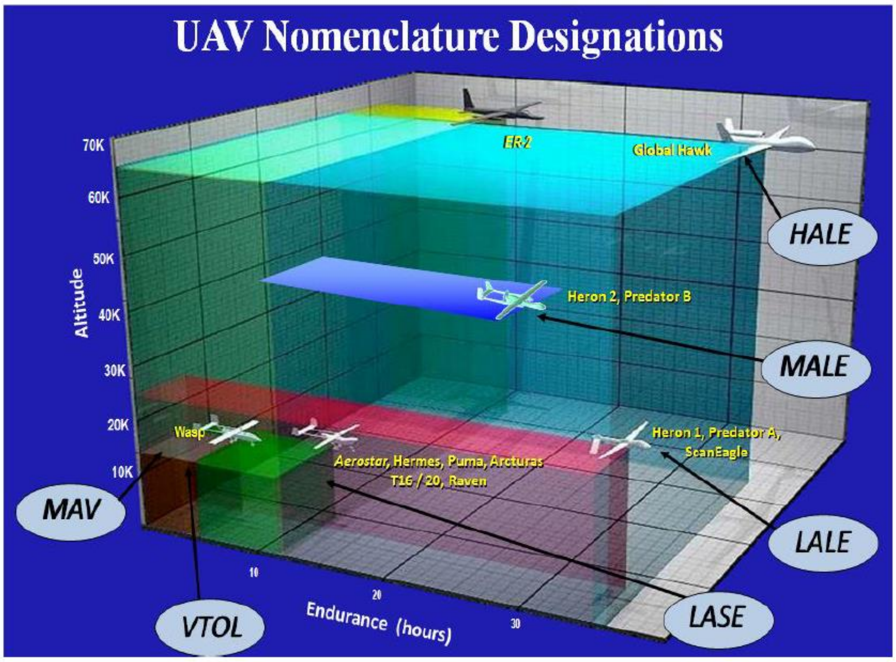
A 3C assessment [312] in the context of the development of a European Defence Technological and Industrial Base (EDTIB) revealed that capacities for producing UAVs are not sufficient and that there is a serious capability gap. The results of the EDTIB assessment suggest that competences in the UAV sector require additional efforts in technology development to catch up with those of global competitors. [313]

It is important to stress that the following analysis focuses on the production of the UAV as a vehicle (hardware), and that the UAV's wider infrastructure does not fall within the scope of this study. In fact, the UAV vehicle itself is only one part of the relatively high operational effort related to its usage. Although support services like ground stations are critical components, there are no known significant issues with them as regards bottlenecks in the supply of raw materials, even though most of them are produced in Asia. In contrast, a general analysis of the UAV service, without a focus on raw materials, would need to consider a number of further supra-UAV bottlenecks, e.g. pilot and operator training, integration into airspace (UTM systems) and secure authentication.

UAV Typology

UAVs extend from large aircraft, similar in size and complexity to manned aircraft, to small, consumer electronics aircraft. Accordingly, they cover a wide range of application fields, capabilities and vehicle sizes. In general, both military UAVs and civil UAVs (hobby, commercial) comprise a wide range of sizes, while the larger UAVs are more commonly used by the military. To show the wide range of UAV capabilities, Figure 45 illustrates a class nomenclature that is commonly applied in the military realm by depicting maximum altitude versus endurance. [314]

Figure 45 Class nomenclature in the military realm



Source: Watts, A.C et.al [314]

[312] 3C assessment is an assessment of capacities, competences, and competitiveness.
[313] European Parliament (2013): The development of a European Defence Technological and Industrial Base (EDTIB). DIRECTORATE-GENERAL FOR EXTERNAL POLICIES OF THE UNION, DIRECTORATE B.
[314] Watts, A.C., Ambrosia, V.G., Hinkley, E.A. (2012): Unmanned Aircraft Systems in Remote Sensing and Scientific Research: Classification and Considerations of Use. *Remote Sens.* (4): 1671-1692; doi:10.3390/rs4061671.

Most UAVs, however, are small, with short endurances and rather low altitudes. In the civil sector, including professional applications, most UAVs weigh less than 25 kg due to regulation constraints, and a large majority weigh less than 10 kg. Experts estimate that 95 % of civil UAVs weigh less than 15 kg, and that at least 95 % of UAVs in the professional market weigh less than 10 kg. This tendency is expected to continue for at least the next 10 years. The dominance of smaller UAVs is illustrated by the array of products of Da-Jiang Innovations (DJI), which controls 74 % [315] of the overall professional UAV market with only two UAV models weighing more than 10 kg (these are relatively niche products in the company's portfolio).

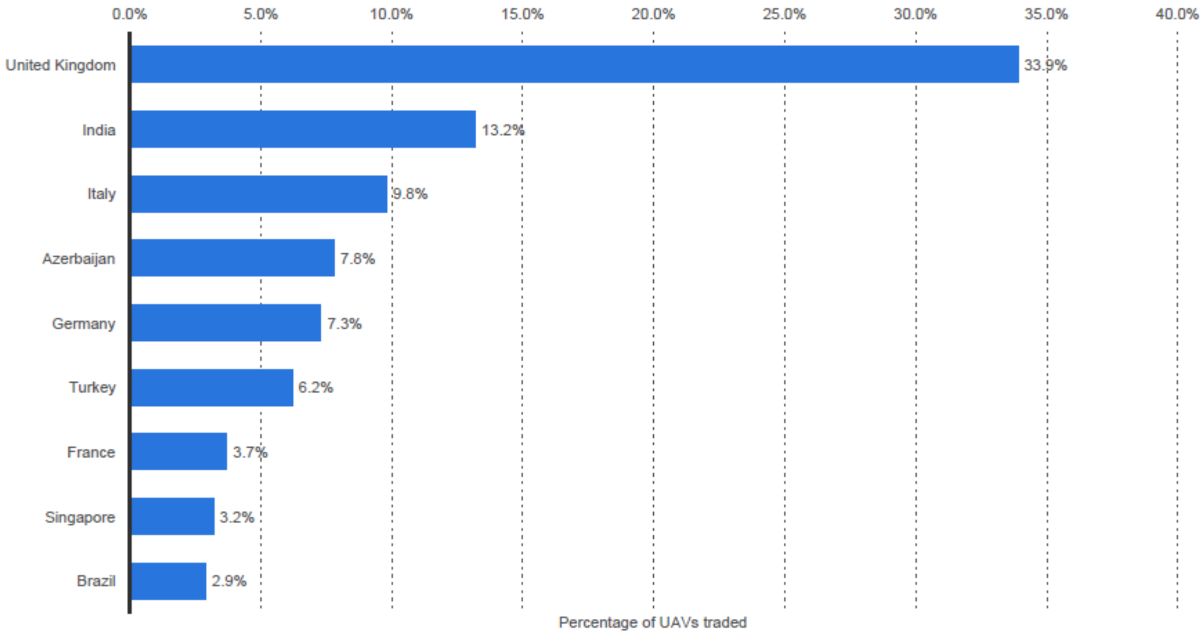
UAV market development

UAVs were initially used in environmental and other conditions that prohibited the use of manned aircraft, thus extending their operating range. They were therefore used predominantly in military applications, with the Predator and Global Hawk drone programmes making breakthroughs. [316] Civil applications gained ground from the 1970s, and now dominate the market in terms of the number of units sold. Over a million drones were sold for civil use by 2015, in a wide range of fields such as agriculture, scientific data provision, logistics and commerce. However, the market size in terms of value is still dominated (over 50 %) by military applications, followed by commercial and hobby uses. [317]

Within the EU, demand for UAVs is dominated by certain Member States: France, Spain, the Benelux countries, Germany and the UK. [318] The UK has been an early adopter of drones for public safety, and a wider rollout was expected in 2018. For example, the UK's first permanent police drone unit was launched in 2017, covering Devon, Cornwall and Dorset. The unit's drones have been used to find missing people and gather evidence to secure court convictions, and can be used to track suspects in firearm incidents and counter-terrorism operations. [319] In contrast, the usage of drones in France has been more diverse, with a focus on inspection and construction. German drone use is similar to that of France, but its high penetration of renewable energy means that the inspection of solar and wind farms is expected to represent an attractive additional segment in the future. As the aforementioned countries are main players on the demand side, the European Union is a leading importer of drones. The UK leads, with more than a third of global imports of UAVs, followed by Italy, Germany and France (Figure 46). A rise has been documented in the number of drones in the EU; the smaller ones in particular.

[315] https://dronelife.com/2018/09/18/new-report-unveils-drone-industry-market-share-figures/
[316] Kindervater, K.H. 2016. The emergence of lethal surveillance: watching and killing in the history of drone technology. *Security Dialogue*, 47 (Jan.): 223- 238.
[317] *Statista Dossier "Commercial UAVs"*
[318] https://www.expouav.com/news/latest/commercial-drone-market-europe-look-like-2018/.
[319] BBC, First UK police drone unit launched in Devon, Cornwall and Dorset, https://www.bbc.co.uk/news/uk-england-devon-40595540, 14 July 2017

Figure 46 Major UAV-importing countries between 2010 and 2014



Source: Statista Dossier 'Military drones'

Regulatory framework for UAVs in Europe

Civil and military UAVs are subject to distinctly different legislation and regulations. The civil regulations are discussed here first.

The development of unmanned aircraft has received increasing support from public policymakers in Europe, who are aware of the wide range of potential societal benefits. In 2013, the SESAR Joint Undertaking developed a European RPAS [320] Roadmap. The Riga Declaration went on to define the main principles of a future civil drone market, and its services, in Europe. [321] It stresses the potential of the civil drones market to foster European jobs and growth. As public acceptance is crucial, the Riga Declaration indicates the need for rules that strike a balance between promoting drone services and protecting the high levels of safety, security and privacy enjoyed by European citizens.

In essence, the significant risks of accident associated with the operation of drones require smart regulations based on graduated damage risk levels. Rules ought to be proportionate and based on the risk of each operation. Consequently, drones need to be treated, from the regulator's point of view, as a new type of aircraft. The Declaration also stressed that full integration of drones into European airspace requires the development of new technologies and standards. Member States had been developing their own individual rules for the safe provision of drone services, reflecting concerns about safety, security and privacy. Consequently, despite increasing drone usage at all levels, the regulatory framework for civil drones in Europe was highly fragmented and a clear EU-level framework was missing. [322] Several Member States had already regulated or were planning to regulate smaller drones, i.e. with an operating mass of up to 150 kg. For example, the UK Government enacted legislation to restrict drones from flying above

[320] Remotely Piloted Aircraft Systems
[321] Riga Declaration on Remotely Piloted Aircraft (drones): "Framing the Future of Aviation", Riga, 6 March 2015. https://ec.europa.eu/transport/sites/transport/files/modes/air/news/doc/2015-03-06-drones/2015-03-06-riga-declaration-drones.pdf
[322] European Parliament - "Civil drones in the European Union"- October 2015

400 feet (122 metres) or within one kilometre of airport boundaries, effective as of 30 July 2018. [323]

As several key safeguards were not addressed in a coherent way, the development of a truly European market for drone services and aircraft was being hindered. To tackle these challenges, and to address the operation and registration of UAVs with EU legislation, the EC proposed, under the 2015 EU Aviation Strategy, and building on the Riga Declaration, the development of a **risk-based framework** applicable to all types of civil drone and their operation. Its objectives were the safe use of drones in civil airspace, and legal certainty for the industry. Concerns were to be considered around privacy, data protection, security, liability, insurance and the environment. The potential of drones for jobs and new business was further underlined by top-ranking European policymakers and industry leaders at the Warsaw High Level Conference in November 2016. The Warsaw Declaration called for several coordinated actions to develop the EU drone ecosystem, building on the guiding principles of the Riga Declaration, to be delivered by 2019. [324]

To ensure that future rules for unmanned aircraft are proportionate to the risk involved, and to avoid regulatory overkill hampering new developments, the EC aims to use industry standards where possible, and is collaborating with the European Aviation Safety Agency (EASA), the regulating authority for aircraft, including UAVs. The basic responsibility for the use of a drone is borne by its operator. The drafting of an EU-level regulatory framework was started by EASA with a four-month consultation period on the Notice of Proposed Amendment (NPA) 2017-05, followed by the EASA Opinion 01/2018 [325] published in January 2019, including a proposal for a new Regulation for UAS operations. In spring 2018, the EC published a roadmap for the initiative, 'Detailed rules on unmanned aircrafts (drones)', which aims to reduce 'risks of accidents/incidents involving persons on the ground, manned aircraft, sensitive areas, violation of privacy, data protection and security issues'. [326] After a public stakeholder consultation in summer 2018 and an impact assessment, the EC adopted the EASA proposal and drafted the Commission Implementing Regulation (EU) [327] for feedback through public consultation, ending in November 2018. On this basis, the EC adopted the 'Commission Implementing Regulation (EU) on the rules and procedures for the operation of unmanned aircraft' on 24 May 2019. [328,329] The regulation will be accompanied by an Acceptable Means of Compliance (AMC) and Guidance Material (*GM*). [330]

These changes in the regulatory framework have practical implications for regulatory competences which were hitherto related to the weight of drones. With the publication of the new basic regulation, the EC proposed to extend the scope of European Aviation

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[323] Civil Aviation Authority, 'New drone laws come into effect today as public demands regulation increase to ensure safer flying', 30 July 2018

[324] DG Mobility and Transport: Website on Unmanned aircrafts (drones) https://ec.europa.eu/transport/modes/air/uas_en (accessed 19.02.19)

[325] EASA Opinion 01/2018, https://www.easa.europa.eu/document-library/opinions/opinion-012018

[326] Roadmap of the initiative "Detailed rules on unmanned aircrafts (drones)", available at https://ec.europa.eu/info/law/better-regulation/initiatives/ares-2018-1460265_en

[327] Draft Commission implementing regulation (EU) on the rules and procedures for the operation of unmanned aircraft. Ref. Ares(2018)5119803 - 05/10/2018. Accessible at:https://ec.europa.eu/info/law/better-regulation/initiative/1642/publication/308263/attachment/090166e5be2da4d0_en

[328] An up-to-date description of the regulatory process on "Detailed rules on unmanned aircrafts", C(2019) 3824 final, can be found on the dedicated EC website: https://ec.europa.eu/info/law/better-regulation/initiatives/ares-2018-1460265_en

[329] European Commission (2019): Commission Implementing Regulation (EU) of 24.5.2019 on the rules and procedures for the operation of unmanned aircraft, C(2019) 3824 final.

[330] A draft version of the AMC and GM has been made available, though the text may still be improved.

Safety rules to all drones, regardless of weight, as well as operational requirements and procedures for certain types of drone operations. EU Member States had hitherto taken responsibility for the regulation of drones weighing less than 150 kg, while EASA was responsible for the certification of drones above 150 kg. As a consequence of this harmonisation of EU drone regulations, EASA and the competent authorities of the Members States shall collect, analyse and publish safety information regarding UAV operations in their territory, and UAVs will be able to operate within the same Single European Sky airspace. It is also expected that the extent, content and level of detail of national regulations will undergo successive convergence, and operational authorisations between EU Member States will reach mutual recognition. As soon as a common, harmonised EU regulatory system is achieved, conditions for the sector will be eased and market penetration in various applications is expected to grow. [331]

According to the adopted regulation [325, 329], civil drones are categorised into three main categories – Certified, Specific and Open – based on consideration of the risks involved (Table 14). [332]

Table 14 Categorisation of civil UAS operations according to the EASA proposal

Category	**Description**
Certified	Requires the certification of the UAS, a licensed remote pilot and operational approval for the drone operator to be released by the competent authority, in order to ensure an appropriate level of safety. The certification is comparable to that required for manned aircraft.
Specific	Requires an application-specific[333] authorisation by the competent authority before the operation takes place, taking into account the mitigation measures identified in an operational risk assessment, except for certain standard scenarios where a declaration by the operator is sufficient or when the operator holds a light UAS operator certificate (LUC) with the appropriate privileges; in addition, an examination of mitigation measures by the authority is required before releasing an authorisation prior to the operation.
Open	Does not require a prior authorisation by the competent authority nor a declaration by the UAS operator before the operation takes place.

The three proposed categories have the following characteristics, based on the operations envisaged by UAV operators, and measures to address the related risks. [334]

a) Certified category: high risk operations

- This category would apply for larger-sized UAVs weighing more than 25 kg, used for e.g. transportation of humans or large unmanned commercial aircraft flying over crowds of people. For the 'certified category', a certificate is required for the operation of the UAV and for the personnel, including remote pilots and organisations involved in those activities, or for the aircraft.

b) Specific category: medium risk operations such as urban operations with UAVs

- This category would apply for medium-sized UAVs (a) with a maximum characteristic dimension up to 3 m. In the case of operations over assemblies of

[331] KET4Dual, Study on the dual-use potential of key enabling technologies (KETs), p204
[332] EASA: Website on civil drones (Unmanned aircraft) https://www.easa.europa.eu/easa-and-you/civil-drones-rpas (accessed 19.02.19)
[333] For example, an authorisation for the specific use of the UAV in (i) agriculture; (ii) forestry; (iii) mining; etc.
[334] The Annex to the „Commission implementing regulation (EU) on the rules and procedures for the operation of unmanned aircraft. C(2019) 3824 final" provides a detailed description of the categories and subcategories.

people, this threshold is 1 m. Over sparsely populated areas or controlled ground areas, this category can also apply when flying beyond visual line of sight (BVLOS).
- A very important element of this category will be the operational risk assessment for the intended operation. The unmanned aircraft itself will not require to be certified, but the remote pilots and the UAS operators must fulfil a number of requirements, such as training.

c) Open category: low risk operations

- This category would apply for small drones, with a maximum weight of 25 kg, and flying below 120 m in visual line of sight (VLOS) conditions. This category will be further divided into three subcategories (A1, A2, A3) depending on drone weight [335], maximum operating speed, requirements for the remote pilot etc. Access to reserved areas like airports would also be forbidden, and overflying of assemblies of people is not allowed.
- These drones will have to comply with a CE marking process (through the Delegating Act of the new European Drone Regulation). A new Directive will be developed by CEN (with the support of ASD-STAN experts).

The impact on the drone market of this risk-based regulation is expected to be noticeable. While 'certified' systems have to pass a full aviation airworthiness certification, which closely resembles the process for normal aircraft, this is not the case for the 'specific' and 'open' systems (usually the smaller systems), which do not require such certification beyond general product certification [336], and only a risk-based safety assessment. The approach for the 'specific' category is supported by the Specific Operations Risk Assessment (SORA), which is the safety assessment provided by the Joint Authorities for Rulemaking on Unmanned Systems (JARUS). [337] JARUS is the global organisation for the harmonisation of UAV regulation. These risk-based certification categories correlate with requirements for reliability of operation, and thus also with UAV costs, maintenance intensity and lifetime. It is expected that the technical lifetime of certified UAVs will often reach 30 years or more, while for open UAVs it is more a question of months to a few years.

Certification of military UAVs

The EASA categories are not applicable for the defence sector, where military certifications apply. Although military certification of UAVs is performed at national level, it is largely based on NATO standards. The NATO Airworthiness Codes (Table 15). developed to certify military UAV systems regarding airworthiness, are a prevalent and widely accepted categorisation scheme. Transboundary military operations require the certification (homologation) of UAVs in the respective NATO member airspaces. The categorisation is related to various measures such as maximum take-off weight and/or (maximum) impact energy. [338]

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[335] Weight thresholds are: less than 250 g, less than 900 g, less than 4 kg, and less than 25 kg

[336] This general product certification for drones is currently under development in cooperation with several global standardisation organisations, including CEN-CENELEC, ASD-STAN, BNAE, the Professional Federation of Civil Drones, and other stakeholders and user groups. See: https://www.cencenelec.eu/news/articles/Pages/AR-2018-030.aspx

[337] JARUS is a group of experts from the National Aviation Authorities (NAAs) and regional aviation safety organisations. Its purpose is to recommend a single set of technical, safety and operational requirements for the certification and safe integration of unmanned aircraft systems (UAS) into airspace and at aerodromes. The objective of JARUS is to provide guidance material to help each authority to write their own requirements and to avoid the duplication of efforts. JARUS website http://jarus-rpas.org/ accessed 04.10.2018

[338] The impact energy describes the worst case terminal velocity based on foreseeable failure conditions.

Table 15 The NATO UAS Classification.

UAS CLASSIFICATION TABLE						
Class	Category	Normal Employment	Normal Operating Altitude	Normal Mission Radius	Primary Supported Commander	Example Platform
Class III (> 600 kg)	Strike/ Combat*	Strategic/National	Up to 65,000 ft	Unlimited (BLOS)	Theatre COM	Reaper
	HALE	Strategic/National	Up to 65,000 ft	Unlimited (BLOS)	Theatre COM	Global Hawk
	MALE	Operational/Theatre	Up to 45,000 ft MSL	Unlimited (BLOS)	JTF COM	Heron
Class II (150 kg -600 kg)	Tactical	Tactical Formation	Up to 10,000 ft AGL	200 km (LOS)	Bde Com	SPERWER
Class I (< 150 kg)	Small (>15 kg)	Tactical Unit	Up to 5,000 ft AGL	50 km (LOS)	Battalion Regiment	Scan Eagle
	Mini (<15 kg)	Tactical Sub-unit (manual or hand launch)	Up to 3,000 ft AGL	Up to 25 km (LOS)	Company Squad Platoon Squad	Skylark
	Micro** (<66 J)	Tactical Sub-unit (manual or hand launch)	Up to 200 ft AGL	Up to 5 km (LOS)	Platroon, Section	Black Widow
* Note: In the event the UAS is armed, the operator should comply with the applicable Joint Mission Qualifications in AP XXXX (STANAG 4670) and the system will need to comply with applicable air worthiness standards, regulations, policy, treaty and legal considerations.						
** Note UAS that have a maximum energy state less than 66 Joules are not likely to cause significant damage to life or property and do not need to be classified or regulated for airworthiness, training, etc. purposes unless they have the ability to employ hazardous payloads (explosive, toxic, biological, etc.).						

Source: J.E. Mayer: State of the Art of Airworthiness Certification; NATO STO-MP-AVT-273

The most important UAV-related certification specifications have been developed by NATO to cover the wide field of military applications. They are the 'UAV Systems Airworthiness Requirements' and are published as standardised agreements (Table 16):

Table 16 UAV-related certification specifications for military drones

STANAG Code	APPLICABLE TO	CALLED
4671	Heavy Fixed Wing (i.e MTOW > 150 Kg)	USAR
4703	Light Fixed Wing UAS (i. e MTOW ≤ 150 Kg)	USAR Light
4702	Heavy Rotary Wing/VTOL (i.e MTOW > 150 Kg)	RW-USAR
4746	Light Rotary Wing/VTOL (i. e MTOW ≤ 150 Kg)	RW-USAR Light

Source: SANCHIZ GARROTE, 2014 [339]

[339] SANCHIZ GARROTE, E. Applicable Military Airworthiness Codes in Spain/ Workshop for Spanish Community of RPAS AESA-Madrid, 28.-30.01.2014.

Although civil certification is not mandatory for military drones per se, it is becoming increasingly common to hold civil authorisation in addition (according to the EASA/SORA certification), as this is required for any drone entering civil airspace.

UAVs in the defence sector

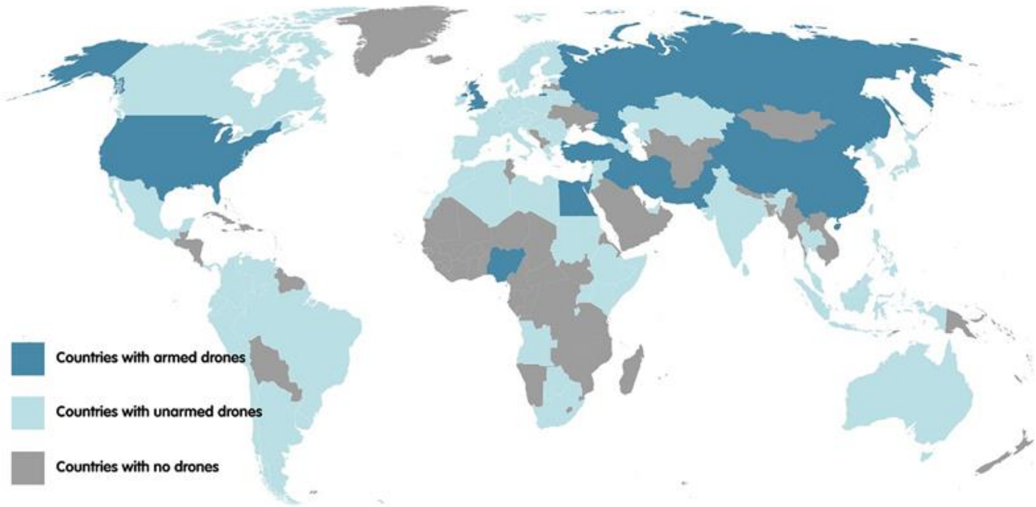
Compared to 'civil drones', where the market is dominated by small UAVs, those in the defence sector are much more diverse. 'Military drones' are a large variety of weights and sizes, and this is reflected in their unit prices. The defence sector uses drones of two types. Firstly, drones developed and manufactured specifically for military use (military drones). These are more costly to develop, due to the higher technical requirements and often lower number of production units (economy of scale). However, they provide – in comparison with civil drones – enhanced robustness and systems security, both mechanically and electronically, in terms of the data link and communications. Indeed, recent operations in Ukraine, where pro-Western drones are mostly unable to fly due to very effective Russian communication-jamming systems, show that the data link issue is a key aspect when ensuring the ability to fly in contested areas. The military also uses UAVs which were developed and manufactured for the civil sector. These are used for basic applications, usually with upgraded data links to protect them against anti-drone measures.

'Military drones' vary widely from very small ones like RAVEN from AeroVironment, which weighs less than 2 kg and costs around USD 25 000 per aircraft and USD 250 000 per complete system (including ground control station), to very large ones like Global Hawk from Northrop Grumman, with an empty weight of almost 7 tonnes, costing up to USD 200 million or more per complete system.

Modern drones have become for many armies an inherent and pertinent part of the military system, in some cases proven by deployment in combat operations for more than a decade. UAVs and unmanned combat aerial vehicles (UCAVs) are both identified as key defence applications, as they are considered strategic assets and represent a force-multiplier on the battlefield. [340] There are numerous types of military application for UAVs and UCAVs in the defence sector. Important military applications for UAVs are, amongst others, tactical reconnaissance (near the contested zone where manned aircraft would not be adequate), air supply to infantry, and the acquisition of intelligence for concrete strikes. UAVs can also be used in various defence applications like chemical, biological, radiological and nuclear defence (CBRN-E defence) with the purpose of early detection for the population and the army. [341] UCAVs carry aircraft ordnance, e.g. bombs, missiles, rockets and gun ammunition, and/or execute drone strikes. With these military capabilities, drones are now a key element in major armies in the world. As can be seen in Figure 47, the use of drone/UASs for defence applications has already been extended to the majority of countries worldwide. However, global drone proliferation is advancing rapidly. In this respect the map shows a snapshot and today more countries have launched the use of unarmed and/or armed drones.

[340] C.C. Pavel, E. Tzimas; Raw materials in the European defence industry; EUR 27542 EN; doi:10.2790/0444, p.22.
[341] KET report, p77.

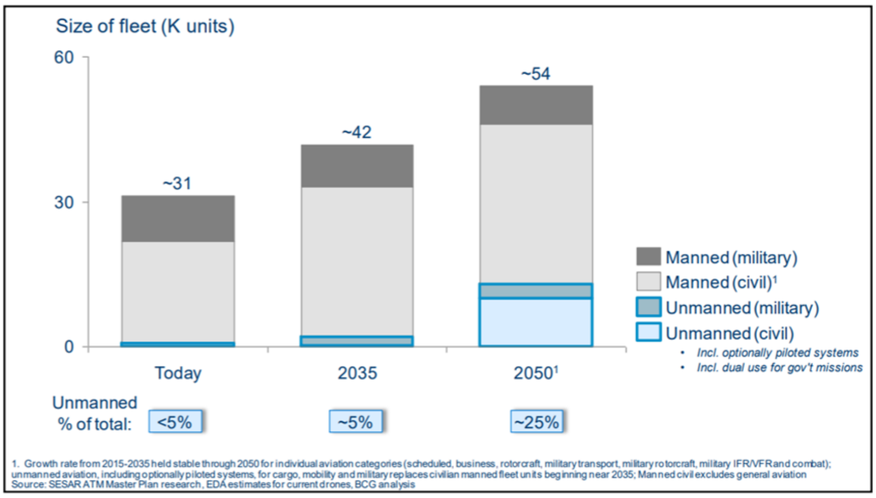
Figure 47 Global drone proliferation, 2017



Source: European Council on Foreign Relations [342]

The role of UASs has grown rapidly in several armies, complementing manned aircraft and other military branches. This contribution has become very important. In fact, since 2014, the USA has trained more UAV pilots than fighter and bomber pilots combined. Although the role of drones in EU countries has not yet reached this level, major EU countries are actively acquiring UAV systems for integration in their armies, and by 2050, 25 % of all aircraft in Europe (excluding general aviation) are expected to be unmanned (Figure 48).

Figure 48 Comparison of defence and certified drones vs manned aircraft in Europe (excluding general aviation)



Source: European Drones Outlook Study [343]

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[342]European Council on Foreign Relations, A European Approach to military drones and artificial intelligence, 2017 (https://www.ecfr.eu/article/essay_a_european_approach_to_military_drones_and_artificial_intelligence)

[343]https://www.sesarju.eu/sites/default/files/documents/reports/European_Drones_Outlook_Study_2016.pdf

Moreover, the maturation of the array of UAVs has entailed a rise in the diversity of defence applications. These range from nano-UAVs (just a few centimetres long), used by commanders to extend the field of view, to large global surveillance and strike systems (such as Global Hawk and Reaper). Due to the very rich diversity of UAV systems, this report cannot cover all types. Instead, it focuses on the characteristics most relevant to their material composition.

Besides Northrop Grumman, other important manufacturers are big USA defence contractors like Boeing (Insitu), Airbus D&S, General Atomics, Thales and IAI. Newcomers to the market who have achieved a significant market share (mostly for smaller systems) include AeroVironments (USA), Aeryon (USA), EMT (Germany), SAAB (Sweden) and UAV Solutions (USA).

Israel has long been a lead nation in the development of military drone systems and continue to play a very important role in mid-range systems. Non-Western countries like Russia and China are also investing heavily in larger drone systems, but there is often little publicly known about these developments. However, they are certainly improving, as can be noted from reports on armed Chinese drones operating in Middle-Eastern battlefields. [344]

For UAVs and UCAVs in the European defence sector, there is strong industrial dependence on USA and Israeli drone technologies. To tackle this dependence, various programmes have been launched by the EC, EDA, the UK and France. A particular case of supply dependence is the medium altitude/long endurance (MALE) UAV/UCAV segment, with the 'Predator family'. European companies are working hard to catch up, for example through the recent EUROMale programme. [345,346] In a very different UAV segment, special mention goes to FLIR Norway, which produces a 'nano-sized' drone specifically for the military market. [347]

The supply chain of larger UASs is different for the military, whose requirements are often totally different (e.g. the use of STANAG-tested/standardised components). Here, a direct government-supplier development programme is often employed, leading to a product suited to the specific needs of the (military) end user.

Unmanned ground vehicles

The land-based counterparts to unmanned aerial vehicles or unmanned maritime systems are unmanned ground vehicles (UGVs). The UGV is a mechanical machine that moves along the surface of the ground, whose task is to transport something. The UGV provides a flexible robotic platform and multipurpose mobility support. It can be considered a mobile ground robot, operating on the ground without a person on board. To enable this, UGVs generally use a set of sensors for observing their environment. They are either autonomous and can make decisions about their behaviour, or are controlled through teleoperation by a human operator at a different location who makes decisions based on the sensor information passed to him or her.

UGVs are under active development for both civilian and military use, to perform a variety of dull, dirty, and dangerous activities, where it may be inconvenient, dangerous, or impossible to have a human operator present. They are used, amongst others, by

[344] https://www.militarytimes.com/news/your-military/2018/10/03/chinese-armed-drones-now-flying-over-mideast-battlefields-heres-why-theyre-gaining-on-us-drones/
[345] European Parliament (2013): The development of a European Defence Technological and Industrial Base (EDTIB). DIRECTORATE-GENERAL FOR EXTERNAL POLICIES OF THE UNION, DIRECTORATE B, p.54.
[346] https://www.airbus.com/newsroom/press-releases/en/2018/04/Airbus-Dassault-Aviation-and-Leonardo-European-MALE-programme.html
[347] https://www.flir.com/news-center/military/top-5-advancements-in-the-black-hornet-3-nano-uav/

emergency services such as police and ambulance services. The major applications of these vehicles are, however, in the defence sector.

UGVs in the defence sector

The applications of military UGVs include providing surveillance information, carrying supplies and assisting in explosive activation. The military has, arguably, already made more progress on automating its vehicles than the civilian side. The DARPA Grand Challenge, for example, saw a series of unmanned vehicles cross a desert autonomously in 2010, demonstrating their ability to handle unstructured terrain.

A key application of unmanned ground vehicles in the defence sector is explosive ordnance disposal (EOD) robots, used to inspect, manipulate and render harmless suspected parcels, bombs, landmines, improvised explosive devices (IEDs) and unexploded ordnance (UXO).

An essential capability of UGVs for application in military operations is their ability to work in harsh environmental conditions. The main differences between civilian and military ground robot systems are therefore mostly related to water-, dust- and shock-proofing. However, it is also key to the military use case to ensure that the enemy cannot make use of the device or of any data collected by it. Securing the data link is therefore crucial, along with issues like tempest shielding.

Next to these issues, there are also (quick) deployment aspects which are more important in the military context than in civil use. Examples include the choice of battery pack, which needs to be optimised for the longest possible operation time; robust and safe operation under extreme temperatures; resistance to shocks; safe air transportability and low maintenance. As well as the batteries, fast deployment requirements also affect the design of the robotic tool itself; such tools are often transported using standardised pallet sizes, which need to be taken into account during the design process. The use of sensor systems (typically IR cameras) under export license are a supply chain issue worth noting.

Important European players are Telerob Gesellschaft für Fernhantierungstechnik mbH (DE), Cobham PLC (UK), Mondial Defence Systems (UK), QinetiQ (UK), BROKK (SE) (owned by investment company Lifco) and AB Precision (DE). Among the global important players are Allen-Vanguard Corporation (CA), Security Defence Systems (IN), MED-ENG (acquired by Allen-Vanguard, CND), Endeavor Robotics (acquired in early 2019 by FLIR, USA) and ICOR Technology (CA).

Nowadays, attention is paid mostly to optionally unmanned vehicles for troop transport, evacuation, logistics, etc. These vehicles are often derivatives of traditional military vehicles that have been 'autonomised' by adding a sensor package and the necessary intelligence for the desired autonomy, for example to follow the lead vehicle of a convoy. Important for military applications in this field is that the sensor package is invisible, to keep the enemy ignorant of which vehicle is unmanned and which is not. The sensors are therefore hidden from external view. For example, the Patria armoured modular vehicle (AMV) is a modern, eight-wheel drive, multi-role military vehicle produced by the Finnish defence industry company, Patria. An autonomous variant has been developed with no visual difference between the manned and unmanned versions, as the sensors are well hidden in the chassis (Figure 49); on the left the autonomous variant of the modern Patria AMV 8×8 armoured vehicle; on the right, for comparison purposes, an unmanned vehicle, whose autonomy is easily detectable due to its readily identifiable sensors.

Figure 49 Comparison of detectability of autonomous vehicles

Source: Defpost [348] and KIT REVIEWS [349]

A state-of-the-art European robotic system under development is the Horiba Mira Viking all-terrain, multirole UGV designed to deliver humanitarian aid or supplies (food, fuel, ammunition etc.) to frontline troops. Once the demands are passed to the Viking vehicle, it adopts its own route on roads, tracks and across complex terrain to deliver the supplies by using its advanced autonomy system. The Viking is designed to deliver up to 600 kg of supplies over 200 km and is one of five prototype systems trialled by the British Army in 2018. [350]

As military vehicles are long-life, successful market penetration means setting up the autonomous capability in a modular way. In the case of Patria, the state-of-the-art autonomous capability is designed and executed in such a way that it can be integrated into all existing and delivered Patria AMV 8×8 vehicles without compromising their manual operation. This means that more than 1 600 Patria AMVs could be autonomous in the future – in addition to future sales. At international level, offensive ground robotic systems are also under development, including the Russian Uran-9 remote-controlled tank (Figure 50), produced by JSC 766 UPTK and launched in 2016 by 'Rosoboronexport', Russia's state intermediary agency for its defence industry, and tested in Syria in 2018. The c.a. 9-tonne tank has a 30 mm cannon and missile-launching capacity, can be operated by one person, and is claimed to be capable of functioning autonomously under limited conditions. [351] It was designed for urban combat and counterterrorism applications.

Figure 50 Russian Uran-9 remote control tank

Source: Military Robotics Innovation [347]

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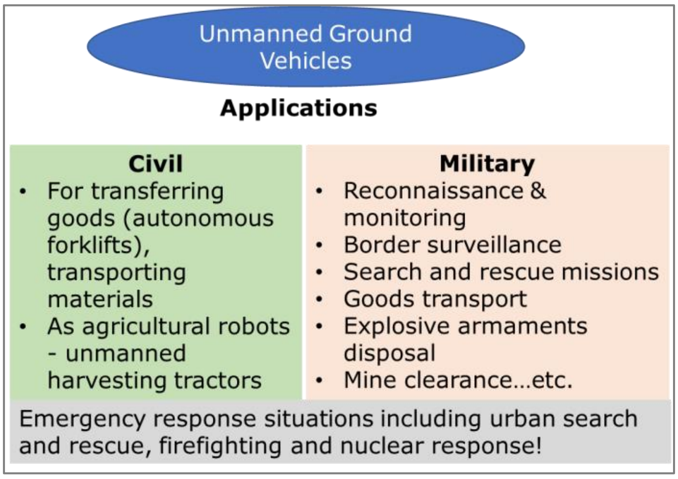
[348] https://defpost.com/autonomous-variant-patria-amv-8x8-armoured-vehicle-european-land-robot-trial-elrob-2018/
[349] http://www.kitreviewsonline.de/tag-der-bundeswehr-in-koblenz-15-06-2019/
[350] https://www.theengineer.co.uk/viking-troops-horiba-mira/, 'Viking enters fray to deliver frontline supplies', 27 July 2018.
[351] https://www.techemergence.com/military-robotics-innovation/, 'Military Robotics Innovation – Comparing the US to Other Major Powers', 14 Sep 2017.

Important UGV manufacturers in Europe are PATRIA (Finland), DIEHL BGT (Germany), BAE Systems (UK), RheinMetall (Germany), Finmeccanica (Italy), Thales (France), Krauss-Maffei-Wegmann (Germany) and Nexter (France). An overview of civil and military (defence) applications for UGVs is presented in Figure 51.

Figure 51 Civil and military applications for UGVs

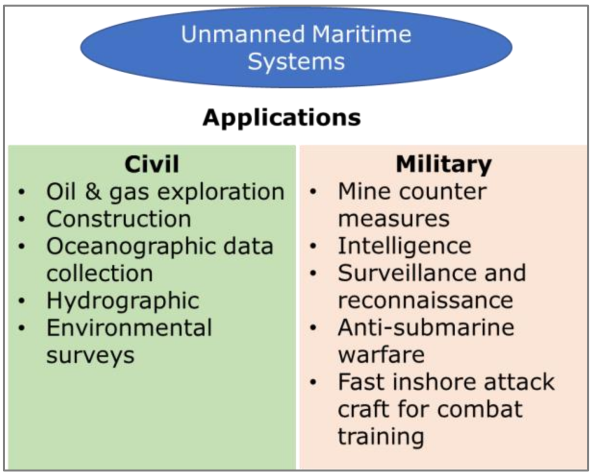


Source: JRC

Unmanned maritime systems in the defence sector

The maritime counterpart to unmanned aerial vehicles, or unmanned ground vehicles, is the unmanned maritime system (UMS), which comprises both USVs and UUVs. These are ideal for mine counter-measures in mined sea areas and therefore require a certain amount of mine blast-resistance. The idea is not necessarily to put armour on the systems, but rather to provide lighter vehicles, with higher resistance against underwater shaking and shocks. Invisibility to mines is another important requirement of these systems, calling for innovative propulsion design, e.g. flapping foils (TRL level still low). Important UMS manufacturers in Europe are the NATO Centre for Maritime Research and Experimentation (CMRE) (Italy), Calzoni (Italy) and L3 ASV (UK). An overview of civil and military (defence) applications for UMSs is presented in Figure 52.

Figure 52 Civil and military applications for UMSs



Source: JRC

5.2 Unmanned vehicle technology development stage

UAVs are a rapidly developing technology that has benefitted from the accelerative advancements of both robotics and aviation in recent decades. Technological progress in civil and military aviation has brought major improvements in power, range and speed. [352] The use of UAVs, and in particular the combined use of fleets of UAVs, require reliable communications bandwidth, which makes satellites an important driver for certain types.[353]

One area of innovation among the key enabling technologies (KET) [354] is the application of 'unmanned vehicles for wide area surveillance in air, land, water and underwater'. A recent analysis [355] revealed that the drones market, and in particular the rotary blade drones market, is expected to grow in the near future, 'owing to the relaxations in government policies and increase in the number of exceptions granted to the companies for the commercial use of UAV drones'. [356]

Products and services related to the drones market will also be supported by drone technology development. Table 17 shows the maturity of certain civilian and military applications by indicating their system readiness level (SRL) [357] and manufacturing readiness level (MRL). [358]

The assessment reflects the intermediate, immature stage of UAV technology development. Technological maturity and manufacturing readiness differ widely across both military and civil applications. For example, remote surveillance is already in use with stable, full-scale production, while other applications like surveillance-strike electronics are still at the stage of concept refinement and process development. However, where drones are concerned, 'remote surveillance' does not include border surveillance, as national borders are usually no-fly zones for drones, excluding any military operations outside wartime.

[352] Manzotti M.E. (2016): New market creation for technological breakthroughs: commercial drones and the disruption of the Emergency market. Dissertation at the Department of Business and Management, Libera Universita Internazionale Degli Studi Sociali LUISS Guido Carli.

[353] KET4Dual, Study on the dual-use potential of key enabling technologies (KETs), p171.

[354] KETs are a group of six technologies that have great potential to fuel economic growth and provide jobs. Each KET has a wide range of product applications, which provide the basis for innovation in a wide range of industries such as automotive, food, chemicals, electronics, energy, pharmaceuticals, construction and telecommunications. They can be used in emerging and traditional sectors.

[355] In the recent report, 'Study on the dual-use potential of key enabling technologies (KETs)', the KETs were analysed to identify the most promising areas of innovation.

[356] KET report, p171

[357] System Readiness Level: 1-Concept Refinement; 2-Technology Development; 3-System Development & demonstration; 4-Production & Development; 5-Operations & support

[358] Manufacturing Readiness Level: MRL 1-2: Material & Process Design&Development; MRL 3-4: Component & Equipment (tooling/machine) demonstrator; MRL 5-6: Component pre-production & System Integration; MRL 7-8: SW & Production planning complete; MRL 9-10: Full-scale stable production / improvement of manufacturing performance (e.g. reduction of cost, waste, etc.)

Table 17 System readiness level (SRL) and manufacturing readiness level (MRL) of selected products, services and applications in the civilian and military sectors

Product, service, application	**Sector**	**SRL**	**MRL**
Remote surveillance	Defence	4	9-10
Radar	Defence	3	7-8
Agricultural monitoring	Civil	3	7-8
Wireless internet provider in remote areas	Civil	3	7-8
RPAS applications – new business services	Civil	3	7-8
Surveillance and security application	Defence	3	5-6
Lightweight and robust power source for powering electronic devices worn by infantry soldiers	Defence	3	5-6
Lightweight and robust power source for mini/micro UAV	Civil	3	5-6
Logistic transportation and remote monitoring	Civil	3	5-6
Humanitarian aids application	Civil	3	5-6
European RPAS development	Defence	2	3-4
Radar	Civil	1	3-4
Wide area camera	Defence/ Civil	1	1-2
Surveillance-strike electronics	Defence	1	1-2
Surveillance and threat detection systems in the military and peace keeping missions	Defence	4	–
Border control, power line monitoring, and gas line surveillance by long endurance drones		4	–
Autonomous control of drone swarms	Defence	3	–

Source: KET4Dual, Study on the dual-use potential of key enabling technologies (KETs)

5.3 Materials used in unmanned aerial vehicles (drones)

In terms of materials used, there are large differences between smaller and larger UAVs, and between non-certified and certified UAVs. Certifications, and airworthiness codes for military UAVs, show a significant correlation with the demands on UAVs, including materials. From a material composition and supply chain perspective, two groups of UAV will be distinguished for the purposes of this investigation, due to the significant linkage between size/type and material composition:

- The larger UAV systems that require an airworthiness certification: ‘Certified UAVs’;
- The smaller UAV systems that do not require it: ‘Non-certified UAVs’.

These two groups of UAV differ fundamentally regarding size and weight, their capabilities and therefore applications, and their supply chain with key players (Table 18). Moreover, there are prominent differences between certified and non-certified UAVs regarding the types of platform used, their overall physical structure and often their material composition too. Medium and large UAVs are rather similar to manned military aircraft in terms of material composition. The weight of medium and large UAVs is more than 150 kg (corresponding with class II/III of NATO classification). In contrast, small and light UAVs, i.e. less than 150 kg (class I of NATO classification), differ massively from manned aircraft. For this class, the aerostructure and engine have less importance in the overall UAV than other subsystems (payload, navigation, communications, batteries, etc.). There is also a general distinction in price between certified and non-certified UAVs.

Table 18 Overview of selected characteristics of certified versus non-certified UAVs

	Certified UAVs	**Non-certified UAVs**
Aircraft weight	high (>150 kg)	low (<150 kg)
Aircraft size	large	small
Work capability[359,360]		
• max. altitude	up to 20 km	up to 1.5 km
• endurance	up to >35 hours	Up to few hours
• range	high	low
Professionalism required for controlling the UAV	high level (military and commercial UAVs)	low level (hobbyist up to semi-professional UAVs)

Source: Report of the USA Army on Unmanned Aircraft Systems Roadmap 2010-2035 'Eyes of the Army', Fort Rucker, Alabama.

These groups will be examined in more detail below. In general, certified UAVs are composed of similar components and materials, as manned aircraft of the same type. As UAVs do not have to carry the pilot(s), cockpit and life support systems, the load capacity is commonly lower than that of manned aircraft. This enables a miniaturisation process with effects in particular on small UAVs, with implications for the required propulsion technologies (batteries and small electric motors), control systems and many more components.

Composition of UAVs

Like any modern aircraft, UAVs are composed of numerous components, often up to several hundred individual parts. As drones and UAVs can be considered a special type of robot, the composition and components are similar to that of robots. Typical robot assemblies are motors, power units and conductors, controllers, electronics, wheels, axles, supporting structures, etc., while UAVs have certain additional assemblies like wings, rotors, and specific sensors or components necessary for aerial navigation.

UAVs consist of various assemblies designed according to their category, correlating with the intended use (Goraj et al. 2004). For example, UAVs with long flight endurance (HALE, LALE) require a different power supply and engines from small UAVs with low endurance (MAV, VTOL). Any additional equipment is tailored to the specific application of the UAV. Given the wide variety of applications with respective differences in equipment, [361] this study focuses on the general UAV components required for unmanned flights, excluding specialised, application-specific components such as infrared sensors for border surveillance.

As UAVs are a specific type of aircraft, we map the relevant assemblies ('sub-systems') of common UAVs using the classification of aircraft assemblies. Table 19 provides an overview of UAV assemblies, composed of various sub-assemblies (components).

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[359] The US Department of Defense differentiates five groups of UAV. The categorisation looks at size and weight, operating altitude and airspeed. Report of the U.S. Army on Unmanned Aircraft Systems Roadmap 2010-2035 "Eyes of the Army", Fort Rucker, Alabama. See: https://www.e-education.psu.edu/geog892/node/5

[360] Clarke, R. 2014. Understanding the drone epidemic. Computer Law and Security Review, 30 June: 230-246.

[361] For example, UAVs in agriculture are often equipped with advanced remote sensing capacities. Military UAVs, however, are able to transport weapons, for example, and related control systems.

Table 19 Assemblies and sub-assemblies required in UAV production. Sub-assemblies, or variants thereof, considered key components in smaller UAVs, are italicised.

Assembly	**Sub-assembly**	**Comments on purpose (P) and/or composition (C) of sub-assembly**
Airframe	Fuselage (body)	P: main body section
	Bearing structure: Wings or airscrew	P: provides flight stability C: Wings often consist of: box, nose and movable parts (flap, spoilers, elevon and wingtip)
	Nose	
	Empennage (tail)	P: provides flight stability
	Steering including actuators	C: Planes: rudder and/or thrust vectoring C: Helicopters: cyclic control and anti-torque control
	Landing gear	P: occasionally retractable C: body with wheels and brakes
Propulsion (motive power unit)	Powerplant (engine with engine assembly, motor, combustor)	P: provides the propulsion of the vehicle. C: Turbine, fan, compressor, nozzle, post combustion Types of engine are: e.g. turbofan engine (Global Hawk), Rotax piston engine (Predator)
	Power supply	Various power systems with energy storage, e.g. electric power system (*battery*, conductors), fuel cells, fossil fuel tanks [362]
	Propellers / rotors, drive shaft	
	Electrical motors with electronic speed control (ESC)	
Actuators		
Avionics equipment (electronic systems)	Aircraft instruments (sensors), for navigation and other purposes	C: altimeter, airspeed indicator, compass/magnetometer, inertial measurement unit (angular rate sensors, accelerometers), gimbals, fuel systems, weather systems, camera, CBRN sensing, radar, LIDAR, electronic intelligence
		C: GNSS [363] receiver (GNSS chipsets. receivers (GSA[364]) and antenna technology,
	Data processors, controller	command and control electronics: GPU, sensor hub (microcontroller for integrating data from different sources and processing them)
		C: Central processing units (CPU), including: resistors, transistors, capacitors, inductors, diodes.

362 https://www.droneii.com/drone-energy-sources
363 GPS & Navigation Systems
364 European Global Navigation Satellite Systems Agency

Assembly	Sub-assembly	Comments on purpose (P) and/or composition (C) of sub-assembly
	Navigation systems (sensors)	*MEMS sensors, fibre-optic sensors (HD-FOS), high-performance magnetometer sensors*
	Flight control systems (steering)	
	Communication systems (transmitter, remote telecommunications system) and identification systems	
	Safety equipment (technical safety device that can deploy an emergency mode[365]	Increases the reliability of commercial aviation, and avoids the involvement of third parties in drone damage [366]
	Specific operation/mission equipment	Various sensors (incl. imaging sensors), payload capacity etc. Military applications require additional components, like airborne radar, electro-optic systems, electronic support measures and defensive aids, as well as military communication systems
Connectors	Wire network	
Weapon systems*	Canon, missile, bomb	P: equipment for fighter aircraft
	Chaff	P: countermeasure
	Flares	

** applicable for military aircraft only*

The entry of UAVs into the unstructured world makes unprecedented demands on advanced computing components, such as graphics processing units (GPUs), which are electronic circuits specialised for algorithms that process large blocks of data in parallel (superior in efficiency to general-purpose CPUs). They are designed to accelerate the creation of images in a frame buffer intended for output to a display device. Modern GPUs are very efficient at manipulating computer graphics and image processing. GPUs are therefore increasingly essential for enabling intelligent UAVs (similar to developments in robotics), as they can run in the real-time, machine-learning applications required for intelligent environmental analysis.

Although **ground control stations** and **launch and recovery systems** are key components of unmanned aerial systems, they are not considered further due to limitations in the remit of this study. Equally, while **computing and software** play an essential role, enabling UAVs to move and perform autonomously, they do not fall within the scope of this report on material bottlenecks.

Smaller UAVs have certain particularities regarding their composition. For smaller UAVs, the quadcopter design has become popular (in contrast with manned aircraft). This affect the materials used in components: multicopters can be made with lighter and weaker materials. Further, as smaller UAVs are battery-powered, battery technology and the materials related to it are essential (as with any mobile robotics). The capabilities of

[365] Actions deployed include the activation of risk mitigation systems, guided landing, ground warnings, audiovisual signals, or flight monitoring via a black box.
[366] Safeair Systems require a triggering system (e.g. Smart Air). Possible triggers include power malfunction, breach flight envelope, loss of control, crossing geo-fencing and cyber detection. https://parazero.com/ accessed 6.9.2018.

UAVs (such as endurance, range and altitude) depend on powerful battery systems. Due to the complexity of the products, and the related specialised technologies and supply chains, European producers of UAVs and UCAVs depend on the supply of a significant proportion of components and processed materials from outside the EU.

Relevant materials per UAV category

UAVs are part of high-tech systems composed of numerous components, regardless of size and weight. As there is no clear UAV classification based on material composition, this analysis is based on some assumptions. As these assumptions are usually specific to certain UAV types, general statements should be interpreted carefully, bearing in mind the material composition context, as they cannot be generalised to all types of drones.

UAVs can be also categorised, in the context of material composition, as larger and smaller. Larger UAVs tend to have longer endurance and thus tend to require greater reliability. Their unit value is more likely to justify the increased costs of using advanced components, materials or technologies. Such an advanced technology is additive manufacturing, or 3D printing, that is becoming increasingly common for the production of drones (chapter 6). Due to its general cost-intensity, compared with conventional manufacturing, 3DP is more commonly used in the production of larger UAVs. Economies of scale favour more conventional techniques like rolling and milling for smaller UAVs.

Larger UAVs

Larger UAVs are those which are similar in size and performance to manned aircraft, like HALE, MALE, and LALE (Figure 45). Most military UAVs and 'certified category' civil UAVs share similar raw materials composition, fulfilling similar requirements with comparable materials and technology. The dimensions, technologies and materials used in larger UAVs are also analogous to those in manned aircraft, which can therefore be taken as an approximation of the larger UAV's material composition.

For (manned) aircraft, the supply chain and materials in use have already been analysed by the JRC report, 'Raw materials in the European Defence Industry' [367]. The assemblies and components at risk have already been explored there in detail; therefore this chapter builds on these findings. Potential bottlenecks were found in (certain) assemblies/components, including structural/basic assemblies. The conclusions drawn in that report for (manned) aircraft will be applied here to certain categories of UAV, which were introduced in section 5.1 and share a similar setup to manned aircraft. These categories comprise:

- UAVs in the defence sector (NATO categories)
  - Category II and III (above 150 kg)
  - Most drones in Category I (below 150 kg)
- UAVs in the civil sector (considering the upcoming EU drone regulation)
  - 'Certified category' [368]

In general, large UAVs do not use the same platform as manned aircraft, but there are some exceptions (without the pilot/cockpit).

Drones in these categories are not produced in large quantities and therefore do not require large volumes of materials. However, they often require very specific materials,

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[367] C.C. Pavel, E. Tzimas; Raw materials in the European defence industry; EUR 27542 EN; doi:10.2790/509931

[368] Although larger military UAVs (categories II and III) have been available to the defence sector for several years, there are no certified civil UAVs available so far. A few civil UAVs exist with an experimental certification of airworthiness (CoA), but none with Type CoA, which would allow mass production of a specific UAV model in that category.

for instance high purity or specialised materials. The carbon-fibre materials used in aeronautics are produced mainly in Japan, for example. [367]

For military applications, the aeronautic sector currently uses high-performance alloys such as Inconel, Monel, Hastelloy and aircraft-grade aluminium, titanium etc., which demonstrate superior heat- and corrosion-resistance and specific expansion characteristics. Investments made by the defence industry in the development of new applications are expected to drive up demand for high-performance alloys. Projects to create the next-generation fighter aircraft, submarine, missile, unmanned aerial/ground vehicle, unmanned combat aerial vehicle and aircraft carrier will all require cutting-edge technology, including high-performance alloys. [369] The JRC Report 'Raw materials in the European defence industry' gives a comprehensive overview of the materials potentially used in unmanned aircraft.

Smaller UAVs

The situation differs for the more numerous smaller UAVs, such as LASE, MAV/NAV and VTOL (Figure 45). There is limited resemblance between smaller UAVs and manned aircraft or between their technical requirements and those of larger UAVs; the platforms, assemblies, components and even materials can differ significantly from their larger counterparts. In addition, their value is usually much lower: below EUR 10 000 per unit, and very occasionally up to EUR 50 000 per unit.

Smaller UAVs correspond to the following categories:

- UAVs in the defence sector (NATO categories)
  - some drones in Category I (below 150 kg), in particular the small types (less than 25 kg);
- UAVs in the civil sector (considering the upcoming EU drone regulation)
  - non-certified categories, i.e. the 'specific' and 'open' categories (Table 14).

For these smaller UAVs, aerostructure optimisation and the use of advanced materials is much less important than for large aircraft (manned or unmanned). In contrast, their capability is predominantly defined by the performance of key components dependent on specific materials. The relevant components are presented in subsection 5.5.1.

In principle, different models of smaller UAV also use different platforms. However, there are some popular platforms for this category, for example DJI S1000, used by various integrators as the basis for their own UAV production.

Relevant materials for UGVs

Various steels are the main structural materials used in unmanned ground vehicles (UGVs). Their production requires the following key elements: Fe, Cr, Ni, Si, Mn, B, Mo, V, Al. The trend to automotive lightweight construction, also true of UGVs, favours light metals and their alloys. Those related metals used on a large scale are Al, Mg and Ti. Automakers are already using Al on a large scale, taking advantage of a 40 % weight reduction compared with steel. For the same reason, increasing use of Mg is expected. In contrast with Al and Mg, the use of Ti is generally too expensive for such applications. Issues relating to costs, fabrication, joining, failure modes, recycling, etc. have to be resolved, along with more cost effective and environmentally friendly refining operations.

In a world of autonomous vehicles, composite materials may replace heavy metals to meet crash-safety and surface-durability requirements. Carbon fibre composites deliver remarkable properties: stronger than steel, high stiffness and absorption of very high impact energy. While these materials are deployed in high-end products, widespread usage, especially in the automotive industry, is hindered by high costs. Cost reduction

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[369] C.C. Pavel, E. Tzimas; Raw materials in the European defence industry; EUR 27542 EN; doi:10.2790/0444, p.66

efforts are under way, based on the use of alternative feedstock and process technologies. For instance, glass and carbon fibre-reinforced composites are typically used for wind energy turbine blades for their light weight and high strength.

Polymers are a natural fit for lightweight applications; high-performance polyurethane materials are already widely used within new ground vehicles. Many thermosetting and thermoplastic polymers utilise carbon fibres and glass fibres. Nanocarbon additives, such as carbon nanotubes, graphene, nanofibres and carbon black materials generate lightweighting advantages. [370] Experts, however, have shared their views on how material selection is likely to diverge from the norm as vehicle automation increases. They recognise that substituting today's high-strength metals with lightweight composite panels would not be viable where both autonomous and non-autonomous vehicles share the road, with the potential for high-speed collisions still prevalent. [371]

Relevant materials for UMSs

The essential factor in the design of underwater vehicles is choosing materials with a high strength-density ratio and good corrosion resistance due to operation in sea water. Materials used in UMSs are: 1) metallic alloys, containing Ni, Al, Cr, Ti, V and high strength steels; 2) composites (e.g. super carbon fibre – SCF); 3) combinations of metallic alloy and composite such as aluminium alloy reinforced with SCF; 4) thermoplastics and 5) buoyancy materials – wood, expandable polystyrene and syntactic foams[372]. Acrylic plastic is also used for vessels' hulls and windows at more than 2 000 metres' depth[373]. Primary batteries, secondary batteries, internal combustion engines, radioisotope batteries, small nuclear reactors and fuel cells are used as power sources in UMVs. Today's prevailing battery technology is silver-zinc, but in recent years, lithium polymer batteries have been introduced. Fuel cells are thought to have good potential as a power source for future UMSs. In terms of critical components, sensors, water resistant cameras, lasers, navigation and communication systems are all important.

5.4 Trends in unmanned vehicles

Technology trends

As exemplified by the UK's Royal Navy, unmanned vehicles are considered one of the most promising next generation applications of additive manufacturing (AM) for military purposes. [374] The purpose of AM in defence is predominantly to repair components and to improve the availability of complex engineering systems and equipment by printing important components at the location of use, significantly reducing the logistic delay time. [375] The additive manufacturing rapid support system (AM-RS2), for example, includes an AM unit and an extended library of pre-loaded pilot geometries of systems and components. The AM-RS2 would thus allow the printing of highly customised components for unmanned air vehicles and unmanned ground vehicles, or even the printing of a whole UAV (printing time c. 20 hours). [376]

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[370] https://www.pangaeaventures.com/blog/advanced-materials-innovation-driving-autonomous-vehicle-development

[371] https://www.automotiveworld.com/articles/autonomous-vehicles-need-lightweight-materials/

[372] https://journals.sagepub.com/doi/full/10.5772/10536

[373] https://ieeexplore.ieee.org/document/1405581

[374] Alessandro Busachi, John Erkoyuncu, Paul Colegrove, Richard Drake, Chris Watts, Filomeno Martina (2016): *Defining Next-Generation Additive Manufacturing Applications for the Ministry of Defence (MoD)".* Procedia CIRP 55: 302-307

[375] Busachi, A., Erkoyuncu, J., & Colegrove, P. (2016). "Additive manufacturing applications in Defence Support Services: Current Practices and Framework for implementation." Flexible Services and Manufacturing Journal.

[376] Alessandro Busachi CEng, Dr. Daniel Kuepper, Dr. Jacopo Brunelli, Dr. Wilderich Heising, Dr. Clemens Moeller, Dr. Drosten Fisher Dr. Chris Watts, Dr. Richard Drake, Kieron Salter, Sara Banfi:

Recent advancements in AM technology provide three main advantages for UVs, achieved through a combination of technical aspects like compactness, design freedom, fully dense metal production, rapid production, delocalised manufacturing, and the potential to develop deployable AM units. The latter aspects are of particular relevance for supporting the needs of specific soldiers and related mission requirements, such as UVs. [377]

The first main advantage is that UAVs can fly greater distances, due to the incorporation of specially-structured lightweight parts, a reduction in the number of subassemblies and the creation of high temperature-resistant parts: a key application of metal AM in UAV engine and propulsion components, as well as components with mechanical loads and high durability (like aircraft exteriors and structures). These clear benefits mean that AM is increasingly attractive for use in avionics, including UAVs.

Furthermore, AM provides opportunities to delocalise manufacturing, ensuring the functionality of products by allowing for parts to be printed or repaired onsite. Thirdly, AM plays a crucial role in cost-effective rapid prototyping and testing, and can generally contribute to material savings, and thus cost savings. AM therefore offers an opportunity to make dramatic financial savings, particularly for smaller systems, and to reduce the time-to-market drastically. For more information on the trends triggered by developments in additive manufacturing technology, see section 6.4.

In the maritime defence sector, UMVs must be extra resistant to shaking or shocks caused by mine explosions. Materials used to support such resistance are (in general, not only for maritime systems) composite materials [378] and speciality steels (armour steels), for example Armox 370T [379] (rolled homogeneous armour plate that combines good resistance to penetration with excellent toughness).

Global market trends

The overall drones market is expected to grow by between 18 % and 27 % CAGR in the next few years, according to various sources. [380,381,382] A much higher growth of >80 % CAGR is anticipated for particular sectors such as smart commercial drones. [383]

According to industry analysts, UAVs are responsible for a market discontinuity due to their disruptive innovation, fundamentally changing the capabilities of the aeronautics sector. [384] The impact on society, and on the military, of the shift from manned aircraft to UAVs is enormous, not only due to the expansion of the number of aircraft, but also the quality of the newly-offered services. Between 30 % and 50 % of manned military

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Additive Manufacturing – Rapid Support System (AM-RS2): Concept Design of a deployable AM unit for War Theatre.

[377] Alessandro Busachi, John Erkoyuncu, Paul Colegrove, Richard Drake, Chris Watts, Filomeno Martina (2016): *Defining Next-Generation Additive Manufacturing Applications for the Ministry of Defence (MoD)".* Procedia CIRP 55: 302-307

[378] For example see: French, M. and Wright A. (2014): Developing mine blast resistance for composite based military vehicles. https://doi.org/10.1533/9781845698034.2.244. Available online 27 March 2014.

[379] https://www.army-technology.com/features/featureheavyweights-take-on-ballistics-explosives-ieds/

[380] https://www.researchnester.com/reports/drone-market-global-demand-growth-analysis-opportunity-outlook-2023/208

[381] https://www.marketwatch.com/press-release/drones-market-2019-to-strengthen-its-position-in-global-industry-at-2018-cagr-regional-forecast-to-2028-2019-01-15

[382] https://www.techsciresearch.com/news/1133-commercial-drone-market-to-grow-at-cagr-27-till-2021.html

[383] https://www.reuters.com/brandfeatures/venture-capital/article?id=62679

[384] *Cost Metrics for Unmanned Aerial Vehicles*. Available from: https://www.researchgate.net/publication/255598559_Cost_Metrics_for_Unmanned_Aerial_Vehicles (accessed Apr 12 2019)

aircraft will be replaced by unmanned ones by 2020 [385], and it looks like a matter of time before a similar revolution will hit the civil sector. While the military sector, still dominant, continues to increase modestly, the number of UAVs in civil use is due to increase much faster, overtaking the military sector. These changes in the portfolio composition (manned vs. unmanned), and the number of units, have considerable implications for the procurement of military equipment by defence ministries.

Compared with unmanned ground and maritime vehicles, UAVs are further developed in terms of market volumes in the various levels of professionalism. Military, professional, hobby, and toy UAVs have all been marketable and in demand for years. The UAV sub-sector has therefore acted as the lead market, with positive signal effects for the overall sector of unmanned vehicles (UVs).

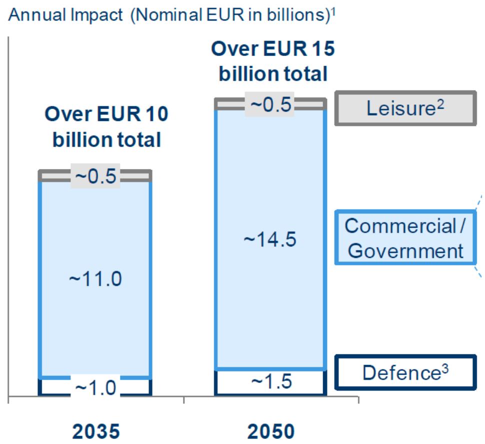
While forecasts generally agree on continuous significant growth in the sector at least until 2030, there is less agreement about the growth rate and saturation level. Though unmanned vehicles appear to be more cost-effective than manned aircraft per flight hour, the limited comparability of these two activities should be borne in mind. [386]

Due to the pace of development, the full impact of innovation in this field is difficult to predict, for both defence and civilian markets. Today, the military market is significantly larger than the civil market, but this is expected to reverse in the coming years, and by 2035, the civil market is expected to be much larger than the military one. According to the European Drones Outlook Study [387], the market volume of the defence UAV sector in Europe will amount to c. EUR 1 billion, while the professional UAV sector will be worth EUR 11 billion (Figure 53). This gulf will widen in the following decades, with a forecast of EUR 1.5 billion in the military UAV sector by 2050, and EUR 14.5 billion for professional drones.

When looking at the number of drones, the contrast is even more dramatic, due to the much higher cost per unit of military drones compared with civil ones. It is expected that almost 400 000 professional drones will be in use, and the number of drones for leisure purposes is expected to grow rapidly and stabilise at more than 5 million. The number of UAVs in military use will be a fraction of that at just 2 000 (Figure 54). Nevertheless, financially, the majority of the UAV market is still defence-related, at more than USD 6.4 billion worldwide in 2017 [388], expected to hit USD 10 billion by 2024. This is because the average cost per unit of military UAVs is, and will remain, much higher than that of professional drones.

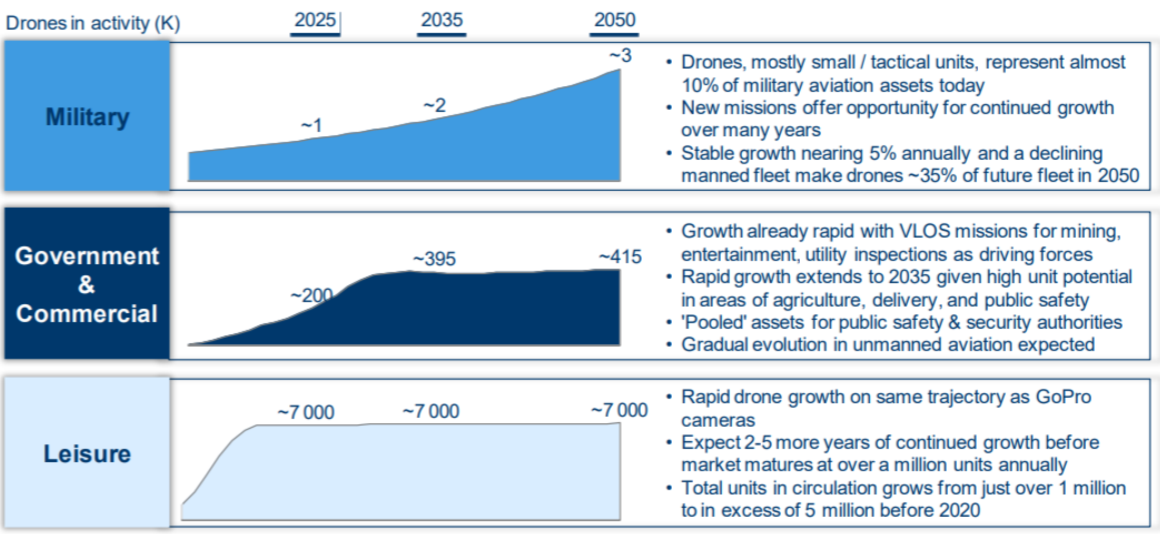
[385] http://www.defproac.com/?p=2041 (accessed 16.04.2019)
[386] https://www.auvsi.org/are-uas-more-cost-effective-manned-flights
[387] Study developed by the SESAR Joint Undertaking: https://www.sesarju.eu/sites/default/files/documents/reports/European_Drones_Outlook_Study_2016.pdf
[388] IHS Jane's Intelligence Review: https://www.defensenews.com/air/2015/10/03/experts-drone-market-to-hit-10-billion-by-2024. Accessed on 23.09.2019

Figure 53 Forecast market segmentation by type of activity



Source: European Drones Outlook Study

Figure 54 Forecast number of drones per type of activity



Source: European Drones Outlook Study

Though the USA still has the upper hand when it comes to drone technology, China is not far behind and is actively working to catch up. China poses a threat to America's dominance in the drone industry in large part because of its ability to make more products at lower prices, with constant improvements in quality. China has seen a dramatic increase in the number of drones sold to foreign countries in recent years, which could spell trouble for the United States. [389]

The global military drone market has been dominated by the USA, but it has restrictive regulations and policies. In 1987, the USA signed the Missile Technology Control Regime (MTCR), an informal and voluntary multilateral export control regime of 35 nations. The MTCR aims to prevent the mass proliferation of missiles and unmanned aerial vehicles by agreeing heavy regulations and tight export controls. China is not constrained by the Missile Technology Control Regime because it never signed the agreement. [390] The

[389] https://www.businessinsider.nl/chinese-drones-swarm-market-2017-11/?international=true&r=US
[390] https://www.businessinsider.nl/chinese-drones-swarm-market-2017-11/?international=true&r=US

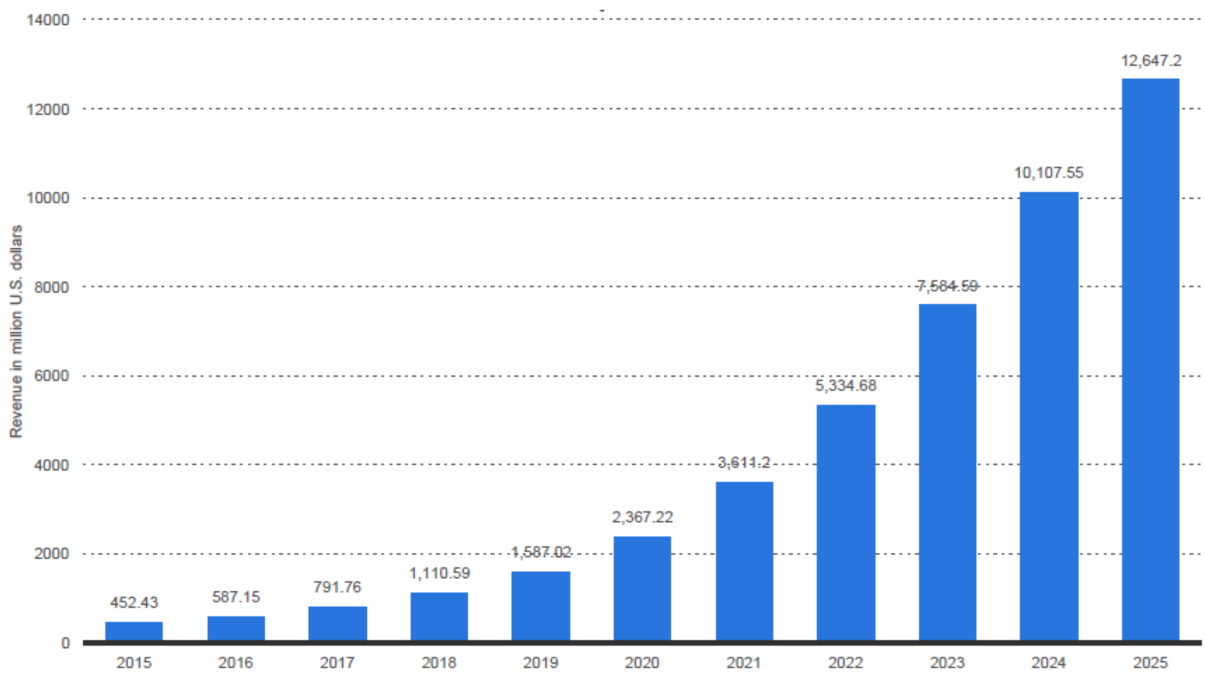
United States maintains strict export controls on military drones, as well as related components, systems, software, and technology, under the International Traffic in Arms Regulations (ITAR). Unmanned aerial systems not controlled by the ITAR, in other words those designed and used for commercial or dual-use reasons, are subject to the Export Administration Regulations (EAR). [391] MTCR and ITAR restrictions limited USA exports in a way, which allowed China to provide UAS technology, including armed UAVs, to USA partners such as the UAE.

This lack of constraints, along with lower prices, intensive investment and plans to increase its satellite capabilities and to set up factories overseas in order to bypass export restrictions entirely, are all factors which could make China the dominant player in the drones market in near future, according to experts. [392]

SMEs have a relatively strong position in the UAV market as it is still young, and SMEs are often well placed to address the small production volumes still experienced in the military and niche markets. However, the UAV market is expected to consolidate, with bigger players applying economies of scale, decreasing the impact of SMEs on the supply chain. The overall UAV market includes the defence, commercial, and homeland security sectors. The global UAV market was valued at USD 10.1 billion in 2015 and is expected to grow robustly, accounting for USD 14.9 billion by 2020, thereby registering a CAGR of 8 % from 2015 to 2020. [393]

Civilian market: The commercial drone market has been expanding apace for several years. It is expected to witness significant growth during the period until 2025; projections indicate that revenues will increase more than tenfold between 2018 and 2025 (Figure 55). [394]

Figure 55 Projected commercial drone revenue worldwide from 2015 to 2025



Source: Statista Dossier 'Commercial UAVs'

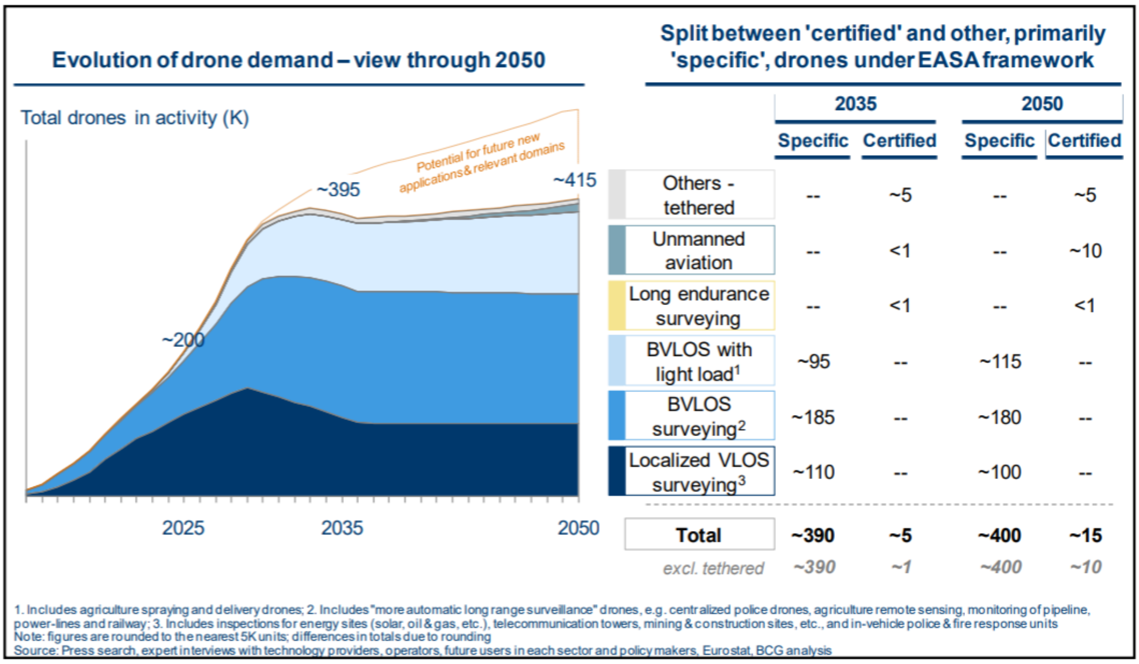
[391] https://www.steptoe.com, 'US Policy on the Export of Unmanned Aerial Systems (UAS): A Detailed Look and Analysis', April 7 2015.
[392] https://www.businessinsider.nl/chinese-drones-swarm-market-2017-11/?international=true&r=US
[393] KET4Dual, Study on the dual-use potential of key enabling technologies (KETs), p317.
[394] Statista Dossier "Commercial UAVs"

Such distinct growth in the drones market is seen as an impact of innovation in the field of unmanned vehicles for surveillance. A relevant factor for this growth is the relaxation of government policies and increased number of exceptions granted to companies for the commercial use of drones. The global UAV market for commercial application is expected to reach USD 5.6 billion by 2020, growing at a CAGR of 32 % between 2015 and 2020. [395] It is estimated that the growth of rotary blade-type drones, which are widely used in the commercial sector, held the largest share in 2014. The growth of this market is driven by the increase in the adoption of multicopters (rotary blade drones) in commercial applications such as media and entertainment, inspection and monitoring and law enforcement.

As a market segment, construction will lead the commercial UAS market over the next 10 years, followed by agriculture. Marked opportunities have also been identified in the health and sanitary protection sector. In particular, the integration of advanced CBRN-E sensors (miniaturised and highly sensitive) in drones represents a significant emerging market opportunity. [396]

In the professional drone sector, about 400 000 units are expected to be in use from around 2030. The vast majority of drones will be used for surveying and light loads (Figure 56), mostly involving small drones of less than 10 kg.

Figure 56 Number of professional and civil drone units per application.



Source: European Drones Outlook Study

Figure 57 forecasts the development of applications in the professional civil drone market, dominated by drones in agriculture, delivery and public safety and security (PSS). Due to the preference in these sectors for small UAVs, **small UAVs will dominate these subsectors by 2035**. However, **by 2050, larger civil UAVs will start to make an important impact on the market (more than 20 %)**, because

[395] MarketsandMarkets – "UAV Drones Market by Type (Fixed Wing, Rotary Blade, Nano, Hybrid), Application (Law Enforcement, Precision Agriculture, Media and Entertainment, Retail), & Geography (Americas, Europe, APAC, RoW) - Analysis & Forecast to 2020" - October 2015
[396] KET4Dual, Study on the dual-use potential of key enabling technologies (KETs), Upcoming breakthroughs

mobility applications will rise exponentially (reaching circa 20 % of the total professional market). These types of UAV, for applications such as urban air mobility (aerial taxis), would require to be certified in the future. Large UAVs will stay behind in terms of unit numbers (15 000 versus 400 000).

Figure 57 Professional civil drone market division by type of application

in EUR	2035 impact				2050 impact			
	Products	Services	Others	Total	Products	Services	Others	Total
Agriculture	800 M€	3 200 M	500 M€	**4 500 M**	600 M	3 200 M	400 M	**4 200 M**
Energy	<100 M	1 600 M	<100 M	**1 600 M**	<100 M	1 600 M	<100 M	**1 600 M**
P.S.S[1]	300 M	800 M	300 M	**1 400 M**	300 M	700 M	200 M	**1 200 M**
Delivery	600 M	800 M	600 M	**2 000 M**	700 M	1 400 M	800 M	**2 900 M**
Mobility	<100 M	<100 M	<100 M	**<100 M**	400 M	2 600 M	600 M	**3 600 M**
Others	200 M	700 M	100 M	**1 000 M**	200 M	800 M	100 M	**1 100 M**

1; Public safety and security
Note: Figures rounded to EUR 50M and 1K jobs, differences in totals due to rounding; Nominal 2016 EUR

Source: European Drones Outlook Study

In recent years, the **defence market has witnessed growing use of unmanned vehicles and cyber security**. It is dominated by large UAVs and it is expected to remain so for the next two decades. The biggest potential growth areas in the defence market are C4ISR (command, control, communications, computers, intelligence, surveillance and reconnaissance), cyber security, embedded computing and unmanned vehicles. [397] Judging by developments in the defence drones market, unmanned vehicles will bring powerful change to the field of surveillance. [398]

It is important to stress the significant transformation expected to be made by autonomous and robotic systems to military operations in the 2021-2040 timeframe, at national and global scale. The USA market, as the primary growth engine of the global market in this area, with drivers similar to those of Europe, is a good predictor. The USA DoD doubled the funding for robotics and autonomous Systems (RAS) between 2018 and 2023. [399] Table 20 provides a summary of their short-, mid-, and long-term objectives, as laid out in the U.S. Army Robotic and Autonomous Systems Strategy. [400]

[397] KET4Dual, Study on the dual-use potential of key enabling technologies (KETs), p202
[398] KET4Dual, Study on the dual-use potential of key enabling technologies (KETs), p317
[399] Department of Defense, Fiscal Year (FY) 2019 Budget Estimates, February 2018.
[400] U.S. Army Training and Doctrine Command, Robotic and Autonomous Systems Strategy, March 2017.

Table 20 Short-term, mid-term and long-term development trends of autonomous and robotic systems

Short-term objectives	The USA Army will mature concepts and programmes to increase situational awareness, lighten the soldier load, improve soldier sustainment, enhance freedom of manoeuvre and augment force protection. This will begin to change how the army operates by steadily **integrating autonomous systems** into combined arms operations. Unmanned vehicles will play a significant role at these combined arms operations.
Mid-term objectives	In the mid-term, the primary focus is improvements in situational awareness, soldier load reduction, sustainment and manoeuvre using developments in autonomy, machine learning, AI, power management, and common control to achieve **more capable UGS and UAS**. There will be **increased use of mixed manned and unmanned teams**.
Long-term objectives	New **autonomous ground and air systems**, fully integrated into military force structures, will allow soldiers and commanders to focus on the execution of the mission rather than the manipulation and direct control of robots. This will reduce human exposure to hazards and give commanders more options. Mixed human-machine teams will operate for extended durations. Soldier exoskeleton technology should incorporate integrated displays that provide a common operating picture, intelligence updates, and **integrated indirect and direct fire weapons systems**.

Source: The U.S. Army Robotic and Autonomous Systems Strategy

Achieving these objectives for mobile robots (ground and air vehicles) will require significant advances in autonomy, AI and common control (software that allows control of multiple ground and air systems by a single human with one controller to reduce cognitive and physical burdens). To reach this goal, common standards and technologies need to be developed to integrate robotic systems into command and control networks. The USA Army aims to achieve this by creating a common operating environment (COE). Developments in autonomy and in the underlying UV technology depend on bottom-up experiences from soldiers and experimental units[401], and are, in this sense, not predictable.

The shift towards robotic systems is likely to make a considerable impact on the procurement of military equipment by defence ministries. As the USA Army is considered a trendsetter for other armies, their enthusiastic entrance into the robotics market indicates massive potential for growth at a global scale.

Box 2: Procurement intensity of the US Army

The US Army has already procured approximately 7 000 UGVs, and over the next five years aims to procure 1 210 medium-sized, man-transportable robotic system robots to provide standoff capability to identify and neutralise explosive hazards etc., and 3 258 common robotic system (individual) man-packable mobile robots for dismounted forces (engineers, infantry, CBRN and EOD units). Then it plans to procure 225 common robotic systems (heavy), vehicle-transportable systems weighing 225-450 kg, to perform ‘highly dexterous manipulation procedures’ for EOD and disarm vehicle-borne IEDs from a safe distance. These systems will be linked together by a common universal controller.

[401] US Army Training and Doctrine Command, Robotics and Autonomous Systems Strategy, March 2017.

Role of software development in UAV development

As with all robotic systems, software development skills are a key enabler for the development of autonomous systems and their incorporation into European military forces. Unmanned vehicles, like robotics, can perform more and more intelligent tasks depending on intelligent on-board data fusion. The increasing quantity and quality of sensors produce increasing amounts of data, which inform decision-making based on powerful software solutions. Key software-related challenges identified in current USA military robotics strategies are discussed below for the USA Army and the USA Air Force.

Achieving USA Army robotics objectives for air vehicles [402] will require significant advances in autonomy, AI and common control (software that allows control of multiple ground and air systems by a single human with one controller).

The USA Air Force [403] has identified challenges that need to be addressed for effective use of automation and autonomy in future air operations:

- creating autonomy software robust enough to function without human interaction;
- reduction in human situation awareness that can occur when using automation (as the human is out of the loop);
- increased cognitive workload from the greater complexity of interactions arising from automation;
- poorly designed decision aids which increase the time to make decisions;
- developing levels of trust tailored to the reliability and functionality of the system in various circumstances.

Overcoming these challenges is essential for achieving USA Air Force plans to increase the use of UAVs in missions that are 'dirty, difficult and dangerous', and to achieve the following military benefits:

- increased range and speed of air operations;
- increased mission capabilities;
- increase reliability, persistence and resilience of air operations;
- reduced manning loads.

This will allow the USA Air Force to broaden the applications of UAV technology from current intelligence, surveillance and reconnaissance (ISR) and offensive missions, to carrying cargo and acting as extensions of manned aircraft. For example:

- F-35 manned tactical aircraft could use drones to carry out reconnaissance and weapons delivery missions in dangerous areas where manned aircraft would potentially be at high risk;
- enabling C-17 Cargo aircraft to operate effectively without aircrew when flying into high-risk forward locations with supplies, weapons and ammunition would again reduce risks to military personnel.

The new paradigm of increasing levels of UAV autonomy with an extended range and increased speed of operations can only be put into operation if the 'need for effective human-autonomy teaming' is carefully considered. In practice, adequate learning techniques are required to develop capable autonomous systems of the future. For their acceptance in safety-critical Air Force operations, new and significantly more advanced

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[402] US Army Training and Doctrine Command, Robotics and Autonomous Systems Strategy, March 2017.
[403] US Air Force, Office of the Chief Scientist, Autonomous Horizons – System Autonomy in the Air Force – A Path to the Future – Volume I: Human-Autonomy Teaming, June 2015.

methods are required for successful verification and validation. Current methods are not capable of this. [404]

Further, the USA Defence Advanced Research Projects Agency (DARPA) envisions networks of more than 1 000 communication nodes, providing individual soldiers with streaming video from drones and other sensors, radio communications to headquarters and advanced situational awareness of other soldiers' location and status.

Multiple software architectures for the development of autonomous systems:

- Joint Architecture for Unmanned Systems (JAUS) [405] was developed as a framework for an open architecture for the domain of unmanned systems;
- Micro Air Vehicle Link (MAVLink) is a protocol designed for communication between ground control stations and UVs (focus on UAVs). [406] It enables full flight control and mission planning to standardised ground control stations (QGroundControl [407]);
- MOOS [408] is a software package (C++ cross software platform middleware). Due to its roots, it is popular mainly for unmanned maritime systems, but today relates to robotics research in general terms;
- the Robot Operating System (ROS) focuses on mobile as well as industrial robots. [409] The ROS community is a worldwide network of about 1 500 users from research laboratories and the commercial sector (mainly USA, Europe and Japan).

As these architectures are open source, there is no direct supply chain issue.

The market for **semiconductors in the military and aerospace market** was expected to reach USD 4 billion in 2018, a 15 % percent increase on 2017. [410] The largest markets for military spending are the USA and China. The semiconductor market is predicted to grow at a CAGR of 4 % over the next five years. Key factors driving the growth of the market (including memory, logic, MOS micro components, and analogue products) are the increasing upgrading and modernisation of aircraft, and the growing use of UAVs[411]. The increasing use of UAVs in many sectors such as military and logistics is expected to drive the demand for semiconductors in the period 2018-2022. Leading companies include Infineon Technologies, Microsemi, ON Semiconductor, Texas Instruments and XILINX.

Trends in military budget for UAV

The budget for military UAVs is predicted to increase from USD 9.6 billion in unclassified procurement and research, development, test and evaluation (RDT&E), from fiscal year 2018 (FY18) to about USD 13 billion in FY27 inclusive. [412],[413] This is an increase of 36 %

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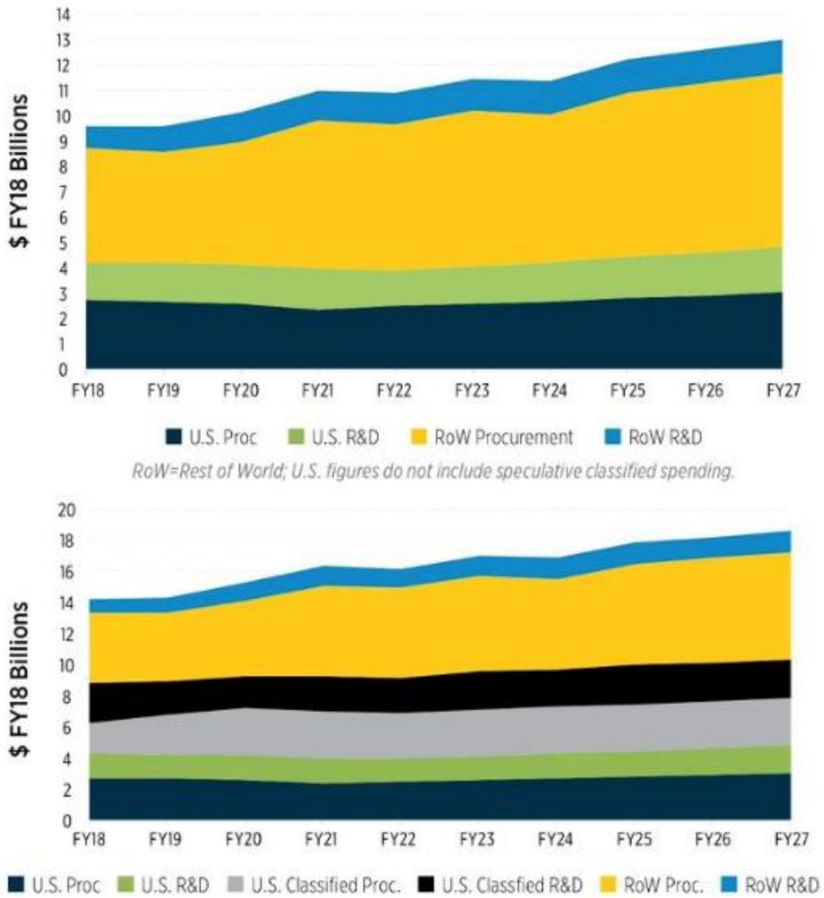
[404] US Air Force, Office of the Chief Scientist, Autonomous Horizons – System Autonomy in the Air Force – A Path to the Future – Volume I: Human-Autonomy Teaming, June 2015.
[405] https://en.wikipedia.org/wiki/JAUS. This initiative was founded in 1998 by the U.S. Department of Defense.
[406] https://en.wikipedia.org/wiki/MAVLink
[407] http://qgroundcontrol.com/
[408] hhttp://www.robots.ox.ac.uk/~mobile/MOOS/wiki/pmwiki.php/Main/Introduction. The abbreviation is derived from the initial name "Mission Oriented Operating Suite". The platform is hosted by the Oxford Robotics Institute.
[409] http://www.ros.org/
[410] Databeans, 2018 Semiconductors in Military and Aerospace.
[411] Technavio, Global Semiconductor Market in the Military and Aerospace Industry 2018-2022, August 2018.
[412] Teal Group, World Military Unmanned Aerial Vehicle Systems: Market Profile and Forecast 2017, November 2017
[413] http://insideunmannedsystems.com/military-uav-market-to-top-83b/, Military UAV Market To Top $83B, April 24 2018

from FY18 to FY27. From FY18 to FY27, defence ministries are expected to spend a total of USD 28.1 billion on RTD&E and USD 83.7 billion on procurement. Note that these estimates exclude micro-UAVs valued at less than USD 10 000, and operations and maintenance expenditure.

The USA will account for 57 % of unclassified R&D spending on UAV technology over the next 10 years, and about 32 % of unclassified procurement over a similar period. If adjustments are made for USA classified UAV development and procurement funding, for example in unmanned combat air vehicles (UCAV), which might effectively double USA military UAV investment, the USA may account for approximately 76 % of global R&D on military UAVs and 49 % of military procurement over the next 10 years. This difference is due to heavier USA investment in cutting-edge technologies and an apparent lag in such research and procurement elsewhere, especially in major aerospace centres such as Europe (Figure 58). [414]

Figure 58 World UAS Budget Forecast R&D and Procurement FY18 to FY27 (excluding and including estimated classified USA expenditure)



Source: Teal Group [412]

The Asia-Pacific area is expected to represent the second largest military market by region in terms of the number of air vehicles produced and their value, followed by Europe. Africa and Latin America are expected to be relatively modest markets for UAVs.

[414] http://insideunmannedsystems.com/military-uav-market-to-top-83b/, Military UAV Market To Top $83B, April 24 2018

The USA accounted for nearly 66 % of the global UAV market in 2015. Further, Israel, China, the UK, Australia, Canada, France and India contribute to the high demand for UAVs. In the European region, countries such as Russia and the UK are home to emerging markets. [415] The potential impact of future innovation can also be inferred from the growth of the network-centric warfare [416] market, which was estimated to be worth USD 46.2 billion in 2016, projected to reach USD 57.7 billion by 2021, at a CAGR of 4.5 % during the period 2015-2020. The unmanned segment is projected to grow at the highest CAGR. This can be attributed to the increased proliferation of unmanned technologies and the use of unmanned platforms for defence operations. [417,418]

Regulatory framework outlook

Beyond the advanced regulatory processes on drones (see chapter 5.1), the EU is preparing a legislative framework for robotics. The European Parliament asked the EC, by a legislative initiative resolution [419], to submit a proposal for a legislative instrument providing civil law rules on the liability of robots and artificial intelligence. The European Parliament proposed the creation of a specific legal status for robots, to cope with the challenges related to the responsibilities emerging from artificial intelligence.

Further, standards were developed for test methods for response robots (in particular in the area of explosive ordnance disposal (EOD)). This process has been driven by the USA National Institute of Standards and Technology (NIST). [420] However, while these tests define how to measure the capability of robotic systems, there is no such influence on the standardisation of equipment (and thus its material composition). [421]

With the rising capabilities of UCAVs and other unmanned combat vehicles, resistance has grown among various non-governmental organisations who want to ban fully autonomous weapons. [422] It is uncertain to what degree this might influence the use of and demand for UCAVs in the future.

Market trends for UGVs and UMSs

The major driver for military UGV and UMS markets is increasing conflict among nations. Countries are forced to embrace new, automated, modern warfare methods and to modernise their armies. It has already been demonstrated that use of military drones in real battle situations provides superiority. The same advantages can also be expected with UGVs and UMSs, which means potential for market growth.

The unmanned ground vehicles (UGVs) market is expected to grow at more than 11 % CAGR by 2023. [423] A similar growth is anticipated for the unmanned maritime systems

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[415] MarketsandMarkets – "Unmanned Aerial Vehicles Market by Class (Small, Tactical, Strategic, Special Purpose), Subsystem (Data Link, GCS, and Software), Application (Military, Commercial and Homeland Security), Procurement by Purpose (Procurements, RDT&E, O&M), Payload & Geography - Global Forecast to 2020" - October 2015

[416] Network-centric warfare, or net-centric warfare, is a military doctrine that was pioneered by the US Department of Defense and that aims for translating information advantage into competitive advantage. This information advantage is partly enabled by modern information technologies.

[417] MarketsandMarkets –"Network Centric Warfare Market by Platform (Land, Air, Naval, Unmanned), Application (ISR, Communication, Computer, Cyber, Combat, Control & Command), Mission Type, Communication Network, Architecture, and Region - Global Forecast to 2021" - July 2016

[418] KET4Dual, Study on the dual-use potential of key enabling technologies (KETs), p317

[419] 2015/2103 (INL): http://www.europarl.europa.eu/sides/getDoc.do?type=TA&reference=P8-TA-2017-0051&language=EN&ring=A8-2017-0005#BKMD-12 . Date of adoption of the resolution: 16.02.2017

[420] https://www.nist.gov/el/intelligent-systems-division-73500/response-robots

[421] https://www.nist.gov/sites/default/files/documents/el/isd/ks/DHS_NIST_ASTM_Robot_Test_Methods-2.pdf

[422] https://www.stopkillerrobots.org/about /

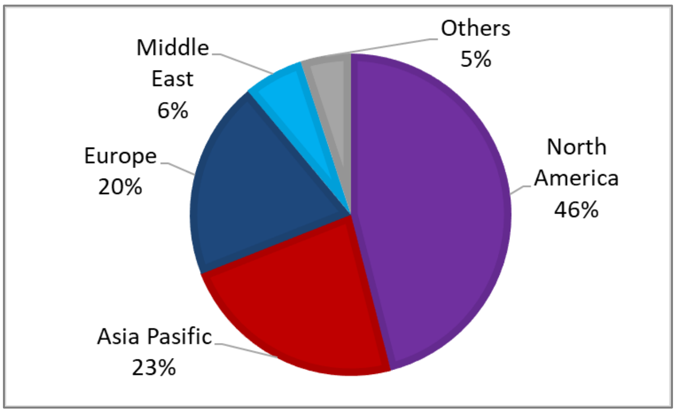
[423] https://www.alliedmarketresearch.com/unmanned-ground-vehicle-UGV-market

(UMSs) market for the same period. [424] Other sources forecast a slower market growth for UGVs than for air and maritime. [425]

The biggest market for UGVs is North America, followed by Asia Pacific. Europe accounts for around 20 % of the global UGV market (Figure 59).

The major factors pushing the global UGVs market, including the civil market, are reduced human intervention, and increased efficiency and flexibility. The demand for UGVs is increasing rapidly in both developed and developing economies; however, the market is expected to lean towards Asian countries in the years to come. [426] Asian markets have become a popular test bed for autonomous driving systems, as illustrated by the following examples. In August 2016, Boston-based start-up, NuTonomy, became the first company to operate a driverless taxi fleet as part of a pilot programme in Singapore. Japan's Prime Minister, Shinzō Abe, has stated his intention that autonomous fleets should operate during the country's Summer Olympics in 2020. Co-founder of CHJ Automative, Kevin Shen, predicts that an autonomous shared car fleet will be operating on city streets in China as early as 2025. Volvo Cars plans to test autonomous driving cars on Chinese public roads as part of its Drive Me initiative – which began in December 2017 in Sweden – with members of the public behind the wheel. [427]

Figure 59 Current unmanned ground vehicles market



Source: MarketsandMarkets, Unmanned Ground V ehicles Market Report, 2019 [428]

UMSs have been under development, especially with USA Navy research funds, for decades. However, meaningful advances in the commercial sector have only been seen in the past 20 years. Europe is the largest market for UMVs. Around 60 % of the UMVs market is dominated by the USA and UK, followed by Canada, France, Norway, Japan, Italy, Germany, Russian Federation, Australia and Sweden (Figure 60).

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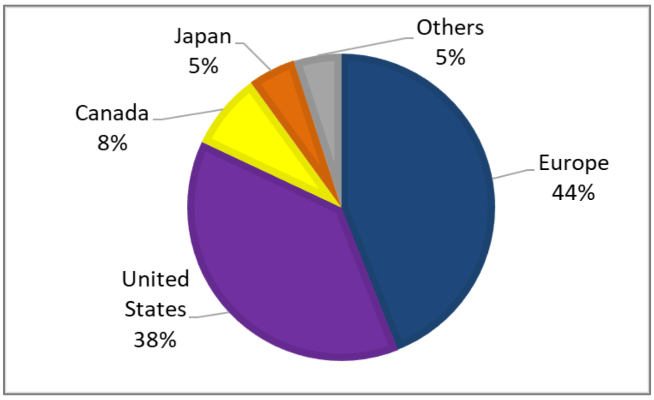
424 https://www.mordorintelligence.com/industry-reports/unmanned-marine-vehicles-market
425 https://www.defensenews.com/digital-show-dailies/ausa/2018/10/09/industry-nations-hope-to-cash-in-on-unmanned-ground-vehicle-growth/
426 https://blog.marketresearch.com/global-unmanned-ground-vehicle-market-to-reach-9.06-billion-by-2023
427 https://www.automotiveworld.com/articles/autonomous-vehicles-need-lightweight-materials/
428 https://www.marketsandmarkets.com/Market-Reports/unmanned-ground-vehicles-market-72041795.html

Figure 60 Active UMVs platforms globally, representing UMVs market



Source: Unmanned Maritime Vehicles: Core Capabilities & Market Background [429]

5.5 Materials supply chain in unmanned vehicles

5.5.1 Main steps of the unmanned vehicles supply chain

Unmanned vehicles, similar to manned vehicles or robotics, are composed of numerous components without which their functionality would be lost or compromised. Any such limitation would damage their success on the competitive UAV market. State-of-the-art drones in military use, with more stringent requirements, make even higher demands on resources. It is therefore crucial to avoid bottlenecks to safeguard the competitiveness of European manufacturers in the UAV supply chain. This section investigates the vulnerability of the UAV supply chain from a component and material point of view, with a focus on unmanned aerial vehicles (UAV) where not otherwise indicated.

This section employs the concept of the supply pyramid (Box 3), the hierarchical structure of suppliers up to the manufacturers of UAVs, i.e. the OEMs that produce the final product. The OEMs source parts from various suppliers, who buy, in turn, from sub-suppliers. This section makes the following divisions in the UAV supply chain: tier 1) OEM and system integrators; tier 2) manufacturers of sub-systems; tier 3) suppliers of sub-components; and tier 4) suppliers of raw materials.

Tiers are often connected not only to the adjacent tier, but also to the one beyond. Tier 1 firms are also the OEM and are commonly supplied by tier 2 and tier 3 firms. Tier 2 firms are typically supplied by tier 3 and tier 4 firms. However, the customers of tier 3 firms can also be other tier 3 firms. The tier 1 firms (system integrators, system manufacturers) also procure software and codes from software providers.

As explained in section 5.1, UAVs can be grouped into certification levels. The varying demands on the systems and assemblies involve different manufacturing processes and components, and ultimately different input (processed) materials. Consequently, the supply chains for these groups are different. However, what is common for any UAV is that its production is always a careful compromise between design constraints, so all levels of the supply chain (processed material vs. component vs. assembly vs. UAV) are equally important.

[429] https://higherlogicdownload.s3.amazonaws.com/AUVSI/b657da80-1a58-4f8f-9971-7877b707e5c8/UploadedFiles/AUVSIUMVCoreCapabilities08-08-13.pdf

Box 3 (*): Hierarchical structure of the supply pyramid, according to the Europe Economics Report

Original Equipment Manufacturers *(*OEMs) sit at the top of the supply chains and have overall responsibility for project delivery. They are considered 'prime contractors' (or short: 'primes'), bringing together the work of lower tier suppliers and responsible for final assembly and delivery of the product to the end customer. They are then sold to the customer/end-user. In the case of military UAVs, the market is restricted as customers are distinct governmental authorities, while in the case of commercial UAVs, the market is free, with thousands of end-users.

System integrators (tier 1 firms) are generally large, technically capable firms engaged in the integrated design, development and manufacture of UAV systems, such as the design of engine, wings etc. These firms have the skills and resources to supply the components needed at this stage and to manage suppliers in the tiers below them.

Manufacturers of sub-systems (tier 2 firms) are engaged in the design, development and manufacture of proprietary equipment and sub-systems. Tier 2 suppliers can be SMEs, mid-caps or larger enterprises, who are typically sub-contractors to Tier 1 companies and deliver complex products with many components.

Suppliers of (sub-)components (tier 3 firms) are supplier of parts or assemblies that manufacture or supply sub-system components and sub-assemblies of UAV systems.

Suppliers of raw materials (tier 4 firms) are those, which provide processing services for raw materials, and processed raw materials, such as aluminium, steel and titanium.

(*) This structure is in the style of the approach of a recent report of Europe Economics, 'Defence SMEs and Defence Supply Chains'.

For the smaller-scale 'open systems', there is often little difference in terms of supply chain between military and civilian UASs. Indeed, the military very often uses off-the-shelf drones from consumer manufacturers, along with commercial and even advanced hobby users. Even the special forces operations of western troops are sometimes carried out with popular UASs manufactured by market leaders in the segment, for example DJI in China. [430] This sometimes gives rise to issues, as these systems record and transmit their location to the producer, thus creating certain risks for the user. However, more often than banning these systems, the solution is to hack or handle them in such a way that data leaks are impossible.

Larger UAV systems are still used almost exclusively for military applications, with only a small share designed for civil professional applications. The supply chain of these larger UAV systems is different to that of the smaller systems, as their requirements are usually very different. For example, military UAVs require STANAG-tested or standardised components. A direct government-supplier development programme is often employed, leading to a product that is suited to the specific needs of the military end user.

Growth rates in the UAV industry are higher than those of mature industries such as the car industry. Global military UAV production is forecast to increase in value terms from USD 4.2 billion in 2017 to USD 10.3 billion in 2026, driven by growth in demand for

[430] https://www.wired.com/story/army-dji-drone-ban, accessed 17.03.2019

larger UAVs, in particular unmanned combat air vehicles and medium altitude/long endurance (MALE) UAVs for operational reconnaissance. [431,432] The related supply of assemblies, components, sub-components and raw and processed materials needs to increase significantly (more than doubling in value terms) within 10 years. The production of commercial UAVs is expected to experience a similar sharp rise as that of military UAVs. This rapid relative growth in the coming years, in both military and civil supply chains, is an obvious challenge, as there will be various sectors competing for the same supply chain inputs, and also a continuous need for chain linkage adaptations.

Due to the rapid qualitative and quantitative developments in the drones sector, the drones supply chain is rather immature, and tends to undergo unusual degrees of modification. According to the supply pyramid concept (see above), supply functions like a cascade. OEM and UAV assembly manufacturers usually obtain the appropriate components from their suppliers, and likewise, the UAV component manufacturers obtain processed materials from suppliers who have processed them from raw materials. UAV supply chain is considered complex due to the numerous assemblies and components required in drones, in combination with the various options of vertical and horizontal integration in the supply chain. For various reasons, some UAV manufacturers partly produce and supply the assemblies, components or even software systems on their own, thus safeguarding their technology and software codes. Likewise, some UAV assembly manufacturers produce the respective components on their own.

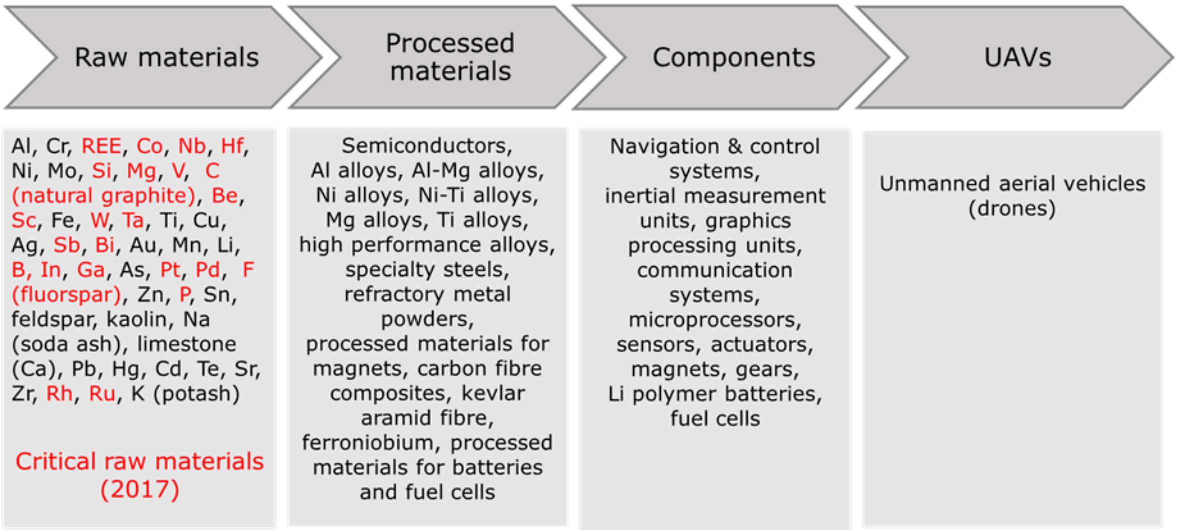
For the sake of clarity, the UAV supply chain can be divided into four principal segments (Figure 61). The supply chain starts with the mining and beneficiation processes of raw materials (step 1), followed by the processing of materials that are then commonly traded as commodities (step 2). Components and assemblies are manufactured from these processed materials (step 3), before the drone manufacturers (OEMs) produce the unmanned aerial vehicle (step 4) as good for final use.

This is reflected in the sequence of stakeholders involved in the UAV supply chain. These can be grouped into suppliers of raw materials, suppliers of processed materials, manufacturers of UAV components, sub-components, and assemblies (up to system integrators), and finally the UAV manufacturers (OEMs). The OEMs develop the UAVs and assemble the assemblies with the software required. The software providers and customers are not considered in the analysis since they are not directly related to particular material aspects.

The participants of the supply chain have customer relations with each other. These relations typically vary along the supply chain. In lower tiers, competitive forces tend to be stronger and relationships more transactional in nature, typically involving simpler buy-sell exchanges with a focus on the commercial transaction (price and quality elements) and less strategic alignment between firms. In higher tiers, the relationship is more integrated, with closer collaboration between firms and more emphasis on flexibility and cooperation. [433] Such collaboration is essential for quality control and continuous quality improvement. As the number of UAV component suppliers is commonly higher than for UAV manufacturers, it is estimated that the suppliers of UAV components can be replaced more easily.

[431] Teal Group, World Military Unmanned Aerial Vehicle Systems Market Profile and Forecast 2017, November 2017
[432] http://insideunmannedsystems.com/military-uav-market-to-top-83b/, Military UAV Market To Top $83B, April 24 2018
[433] This structure is in the style of the approach of a recent report of Europe Economics, 'Defence SMEs and Defence Supply Chains'

Figure 61 Unmanned aerial vehicles: an overview of raw materials, processed materials and components considered in the analysis



Source: JRC

Step 1: Raw materials

In total, 48 raw materials have been identified as relevant for the supply chain of unmanned vehicles. Of these, 23 are deemed critical according to the 2017 criticality assessment. [434]

The raw materials identified as required in the UAV sector are listed in Annex 2 Table 32, together with their key supplier countries. The selection was based on a listing of aerospace materials and high-performance alloys, [435] assuming that the materials in drones coincide to a large extent with typical aerospace materials, including 'aerospace alloys' (lightweight alloys), high-performance alloys (superalloys), speciality steels, refractory metals, specific synthetic fibres, and composite materials.

Specific new materials that appear here in addition to the robotics materials are hafnium and niobium**,** with a rather concentrated supply (see 3D printing section).

Step 2: Processed materials

In total, 14 materials have been selected and analysed as relevant processed materials for drones, namely: Al alloys, Al/Mg alloys, Mg alloys, Ni alloys, Ni/Ti alloys, Ti alloys, speciality steels, high performance alloys, refractory metals, composites (CFC), aramid (kevlar) fibres, magnetic powders, semiconductors and ferroniobium. In addition, processed materials used in Li-batteries and fuel cells were also included in the analysis.

The processed materials used in UAVs are, as in general aeronautical applications, very specialised, innovative and complex materials. [435] Due to the need for short take-off ranges and longer flight endurances, lightweight structures are in great demand in aerospace, and even more so in UAVs. This applies primarily for the load-bearing parts, but also for the others. Materials that address this specifically are called aerospace alloys.

Traditionally, metals and metal-based alloys have been used for aircraft manufacturing due to their high strength, and heat and corrosion resistance. With the evolution of the

[434] European Commission, 2017, Study on the review of the list of critical raw materials — Final report

[435] Pavel, C. and Tzimas, E. (2016): Raw materials in the European defence industry. JRC Science for Policy Report. Table 6.3f

aeronautics industry, these materials are constantly being replaced by new lightweight materials such as titanium alloys, composite materials and high-temperature-resistant plastics. For example, the new generation of aircraft uses up to 50 % composites. These materials offer greater strength characteristics compared with traditional materials, providing greater resistance and less weight. In the defence industry, this translates into higher manoeuvrability and long-distance independency (low fuel consumption) of jet fighters. [435]

For unmanned ground and maritime vehicles, this is less of an issue, although operating distance is a key performance parameter for any autonomous system. Lightweight materials are therefore widely used, depending on cost-performance considerations. In military applications, and advanced professional applications, high-end materials are used where operating distance is of key importance, for instance where vehicles are used for reconnaissance or combat.

As with robotics production, semiconductors (devices) are a potential bottleneck for drone production. In fact, increasing demand for drones, especially UAVs, is driving semiconductor demand until 2022. At the same time, bulk manufacturing is clustered on a few leading companies (including Infineon Technologies, Microsemi, ON Semiconductor, Texas Instruments and XILINX). The dominant markets for military spending are the USA and China. Consequently, the EU's imports of semiconductors depend on the USA and, to a minor degree, South Korea. Leading semiconductor materials are silicon, germanium and gallium (an arsenic).[436] The crucial role of these materials for semiconductor supply is underlined by the fact that epitaxial wafers composed of silicon, germanium, or compounds of gallium or indium are affected by USA Export Administration Regulations (EAR).[437] Important semiconductors with military relevance are silicon-germanium, gallium arsenide and gallium nitride, with the latter fast growing in importance in both military and civil domains.

The introduction of additive manufacturing (AM) has made a marked influence on UAV production. AM is a group of fabrication techniques which make components in a new way, by adding the source material layer by layer. This simplifies the fabrication process and allows components to be made whose form was hitherto impossible. AM is therefore revolutionising the UAV industry. [438]

The processed materials considered in the analysis are Al alloys (lightweight alloys), Ni alloys (including the Hastelloy series[439]), Ni/Ti alloys, Mg alloys, steels, synthetic fibres (e.g. carbon fibre composites, aramid fibre), refractory metals powders, ferroniobium and semiconductors (Figure 61). Processed materials relevant for battery and fuel cell technologies are also included for completeness.

To calculate market shares for all processed materials, various data sources were used, from statistical data (e.g. Statista) to public databases (e.g. Europages) to companies' websites, blogs and other internet open sources. The market shares for countries' key suppliers were determined based on their manufacturing/production capacity (CFC); when no information was available on capacity, sales revenues (advanced ceramics glasses & refractories, semiconductors) or the number of companies per country (Mg

[436] According to the 'Final List of Critical Materials 2018', issued in May 2018 by the US Department of the Interior, the USA identifies germanium (used in optical components for fibre-optics and night vision applications) as one of the three materials out of 35 critical minerals where dependence on foreign sources creates a strategic vulnerability for the US economy and military.
[437] University of Puerto Rico, EXPORT CONTROLS AND OTHER COMPLIANCES, September 2014.
[438] Goh, G.D., Agarwala, S., Goh, G.L., Dikshit, V., Sing, S.I., Yeong, W.Y. (2017): Additive manufacturing in unmanned aerial vehicles (UAVs): Challenges and potential. *Aerospace Science and Technology* 63 (2017): 140-151
[439] Hastelloy is a brand of Haynes International Inc. of twelve nickel alloys resistant against corrosion, high temperature, and high stress.

alloys, Al alloys, special steels, Ni-alloys, Ni/Ti alloys, aramid fibre [440]) was used to estimate the shares. Information on data sources for processed materials used in Li-ion batteries and fuel cells are available in the relevant chapters. The concrete companies considered in the analysis and information on data sources are provided in Annex 2 Table 33.

Step 3: UAV components

Step 3 of the UAV supply chain is the manufacturing of components used in the assembly of UAVs. As with robots and aircraft, UAVs can contain hundreds or even thousands of individual parts. UAV manufacturers often source components, or assemblies, from numerous suppliers. These supply structures, and their complexity, reflect the complexity of the structural design of the UAV. Avionics is of key importance for the flight performance of drones, and electronics, in combination with specific software, ensures the controllability of the device and its ability to act autonomously. The integration of specific functions requires further electronics and software.

Focus on Smaller UAVs

The potential of material bottlenecks is different for smaller UAVs. While bottlenecks for larger UAVs are analogous to those of aeroplanes, which have been addressed in the JRC report, 'Raw Materials in the European Defence Industry' [441], this study focuses on the risk of bottlenecks for smaller UAVs. The components in question are as follows.

Gears, or cogwheels, are rotating machine parts with cut teeth or inserted teeth respectively, which mesh with another toothed part to transmit torque. They are used to alternate mechanical movements including the change of speed, change of force, and change of moving direction.

Actuators [442] are very important components of drones. Most of the smaller UAVs and drones use **electrical motors** for propulsion instead of combustion engines. These electrical motors are used along with specific electronics called **electronic speed control** (ESC), which are able to control the speed of the motor with accuracy.

Various types of **sensor** exist for numerous applications. The three main types of sensor used for navigation are GPS/GNSS chipsets, magnetometers, and inertial measurement units (**IMU**). IMUs are key components for navigation under difficult conditions. For example, IMUs are used in civil UAVs in case of a temporary loss of the GPS signal. For military-grade UAVs, IMUs are used to harden the system against countermeasures such as GPS jamming. There are different IMUs applied, with differing set-ups: angular rate sensors and accelerometers. For smaller UAVs and drones, MEMS-based IMUs are used due to their low price. A wide variety of materials can be used in sensors (see chapter on robotics), as well as polymers and carbon ceramics. [443,444] For some sensors, there is a potential supply chain issue, because European tier 1 and tier 2 firms are often unable to access the most advanced and mature sensor technology available. In fact, most IMU producers are headquartered in the USA, which clearly dominates the market. There are only a few EU sensor providers (e.g. BOSCH, TTTech), and export restrictions in many cases prevent adequate access to this sensor technology, which comes predominantly from the USA and Israel. Examples for this are hyperspectral imaging sensors and infrared cameras. For the defence sector, a specific supply chain issue is the use of sensor systems under export license (typically IR cameras). Companies supplying IMUs are listed in Annex 2 Table 61.

[440] http://www.researchinchina.com/Htmls/Report/2016/10314.html
[441] C.C. Pavel, E. Tzimas; Raw materials in the European defence industry; EUR 27542 EN; doi:10.2790/0444, p.22.
[442] An actuator is an electromechanical device that converts energy into mechanical work. The most popular actuators are electric motors.
[443] https://www.electrochem.org/dl/interface/spr/spr06/spr06_p66-69.pdf
[444] http://www.mdpi.com/journal/sensors/special_issues/IC-MAST

To allow the drone to fly and maintain stability in the air, guidance, navigation and control algorithms are required. For the basic control of a small, light aircraft there is no need for any special electronics, as almost any microcontroller can be used. A higher number and quality of sensors necessitates an increased microprocessor capacity to process the increased volumes of signals received from the sensors and from other sources such as the ground control system. **Processing units**, commonly **microprocessors**, empowered by adequate software, are used for the integration of these algorithms. Accordingly, these processing units or **controllers** are considered the 'brain' of the UAV, allowing it to function autonomously in its surroundings by avoiding collisions etc. For instance, when additional sensors are required to increment the robustness of aerial navigation, especially when GNSS degrades, it is important to integrate miniaturised processing units with GPUs or any other specific hardware that enables the processing of large quantities of data or images in real time. This field of safety equipment is expected to grow strongly in the coming years, as air traffic expands and airspace becomes increasingly crowded, in urban areas in particular. From a market point of view, however, due to advancing developments in cell phone technology, a large variety of vendors are developing such systems (for example Intel, Qualcomm, etc.).

Rechargeable **batteries** are used to enable the propulsion of smaller drones. Battery-powered aerial vehicles are already in use for various functions of military intelligence as well as for commercial, recreational, scientific, surveillance and agricultural applications. The battery commonly used in drones is lithium polymer (LiPo). Nickel metal hydride (NiMH) and nickel cadmium (NiCd) batteries can be also used in drones, but LiPo batteries offer significant advantages over other types. LiPo batteries are lighter and can be made in different shapes and sizes; they have higher capacities, allowing them to hold more power, and also have higher discharge rates, consenting faster power transfer. [445] A drawback of LiPo batteries is their rather short usage time, often limiting flying time to just 20-30 minutes. Intensive efforts are being made to increment the flying time of electrical aircraft; smaller ones in particular. Different approaches have been tested to increment the flying time, including fuel cells.[446] Suppliers of LiPo batteries are mainly Asian (China) with some USA companies. Companies known to supply batteries specifically for drones include Gens ace (China), Grepow (China), LiPol Battery Co., Ltd (China), MINAMOTO BATTERY (HK) LTD (China) and Solidenergy (USA). Other companies manufacturing LiPo batteries include Panasonic (Japan), Celgard LLC (U.S.A), DuPont (U.S.A) and LG Chem (South Korea), TDK Corporation (Japan), Samsung(SDI) (South Korea), Sony (Japan) and Lishen (China). [447] Based on available information in several sources [448,449], the following shares have been assumed for calculation of the supply chain shares for LiPo batteries: China (60 %), USA (20 %), South Korea (10 %) and Japan (10 %).

Although 96 % of today's drones are powered by batteries [450], one of the hottest trends in the UAV industry is the emergence of alternative energy-powered UAVs. Research analysts note that vendors are already experimenting with alternative fuel cell technologies.[451] Even hydrogen-powered drones are strong contenders. Fuel cells are therefore included as a component in the supply chain analysis. [452,453]

Among controllers, **graphics processing units** (GPUs) are of particular relevance as they become ever more crucial for AI-enabled UAVs. To an increasing degree, GPU

445 https://www.droneomega.com/quadcopter-battery-guide/
446 https://www.uasvision.com/2018/11/20/3-hour-endurance-hydrogen-multi-rotor-from-hes/
447 https://perfectherald.com/global-lithium-polymer-batteries-market-2019/
448 https://www.berylls.com/wp-content/uploads/2018/03/20180323_Studie_E-Mobilitaet_EN.pdf
449 https://www.transparencymarketresearch.com/lithium-polymer-battery-market.html
450 https://dronelife.com/2017/06/06/drone-energy-sources-pushing-boundaries-electric-flight/
451 https://www.epsilor.com/sections/blog/Blog20122017/
452 https://www.intelligent-energy.com/our-products/uavs/
453 https://uavcoach.com/hydrogen-drone/

capabilities are integrated with specific hardware units for the processing of data from special sensors (like cameras) in order to enhance the reliability of the drone's navigation system. The miniaturisation of these processing units is a key factor in their applicability for small drones and UAVs.

There is a distinct supply chain issue for GPUs, as there are only two main producers (nVIDIA, AMD), both headquartered in the USA. This means a marked corporate concentration, and a maximum country concentration of GPU supply. GPUs are commonly designed for specific usage; for automated vehicles, nVIDIA Drive PX is common. Due to the competitiveness of the GPU market and high development costs, most of the competition has been bought up, or has focussed on niche markets (e.g. Matrox). The key materials required for GPUs are silicon, tantalum, palladium and gold.

To ensure the reliability of remote telecommunications between the drone and the ground control station or ground pilot, **communication systems** are of key importance. The majority of drones in civil applications still operate within visual line of sight (VLOS), while those operating beyond visual line of sight (BVLOS) become more rampant. B tThere are still not yet specialized specialised vendors for long-range civil UAV communication systems in BVLOS drones. Microhard is one of the most popular producers of communications systems for civil drones, especially for beyond visual line of sight (BVLOS) flights. Control and navigation systems are also vital for unmanned vehicles. Navigation systems are used to calculate a position on the earth's surface by way of timing information received from a network of global navigation satellite system (GNSS) satellites that continually orbit the earth. Important providers of military radio and communication systems include Thales group (France), Honeywell Aerospace (USA) and Aselsan (Turkey). [454]

For simplicity, a selection of the most relevant components has been considered in the analysis: gears, actuators, sensors, controllers, GPUs, inertial measurement units, communication systems [455], control and navigation systems [456] and LiPo batteries as the dominant power supply. Fuel cells have been included as a potential future form of power supply. Suppliers of communication systems and control & navigation systems are listed in Annex 2 Table 56 and Table 57.

Step 4: UAV manufacturers

Manufacturers of drones are considered at this step.

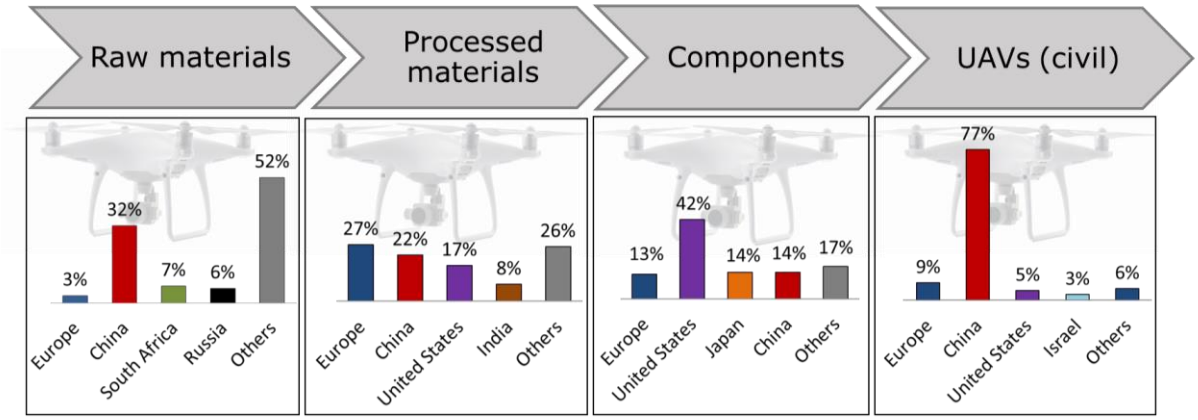
5.5.2 Key players and market share along the UAV value chain

The key country suppliers along the supply chain steps for UAVs are shown in Figure 62.

China is the major supplier, providing more than 30 % of the raw materials required in UAVs. It is the leading supplier for 23 of the 46 raw materials needed. Of the 21 CRMs identified for UAVs, 14 are supplied predominantly by China. China supplies more than 40 % of the CRMs, followed by South Africa and Russia. The supply from European countries of CRMs used in UAVs is negligible (<1 %) (Figure 63).

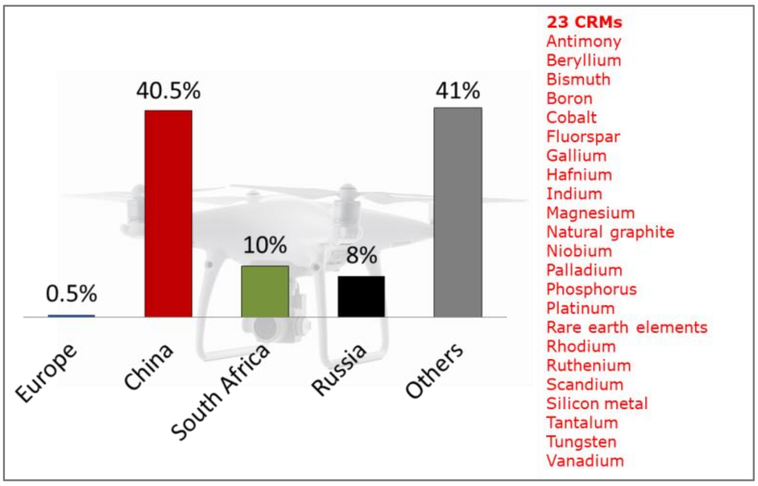
[454] https://www.thomasnet.com/products/military-communication-systems-51260891-1.html
[455] https://www.unmannedsystemstechnology.com/category/supplier-directory/data-communications/
[456] https://www.unmannedsystemstechnology.com/category/supplier-directory/navigation-systems/control-navigation-systems/

Figure 62 Unmanned aerial vehicles: key players in the supply chain for civil applications only



Source: JRC

Figure 63 Supply of CRMs for UAVs: key players



Source: European Commission, 2017, Study on the review of the list of critical raw materials

About 80 UAV manufacturers, worldwide, have been analysed in this study. The UAV market is mainly dominated by manufacturers in China and the USA. Due to the agility of the market, however, company ranking is rather volatile. Recently, 4 of these 80 manufacturers declared bankruptcy, were merged or acquired, i.e. 5 % of the overall sample. Both the civilian and the military drone markets are discussed, but due to limited data on the military sector, only the civilian drone market can be quantified.

Business Insider's Top 10 [457] places seven of the 10 biggest drone manufacturers in the USA. The global market leader in drones manufacturing is Dà-Jiāng Innovations (DJI) [458], with more than 70 % of the global market. Yuneec is the second largest Chinese drones manufacturer. Together, DJI and Yuneec are considered the 'Apple and Samsung' of the drones world. The only European company in the Top 10 is Parrot SA (Table 21).

[457] http://www.businessinsider.com/top-drone-manufacturers-companies-invest-stocks-2017-07?international=true&r=US&IR=T , originally published Sep. 2016, accessed 22.01.2019
[458] full name: Da-Jiang Innovations Science and Technology Co., Ltd

Table 21 Top 10 drone manufacturers globally (not ranked, sorted by country)

Company	Country	Products
Ambarella	USA	Key supplier for DJI; manufacturer of chips for GoPro cameras and video processing chips for other drone makers.
Boeing	USA	Produces medium-sized drones for the space industry.
GoPro	USA	Develops, manufactures and markets pocket-sized, high-definition cameras often used in extreme action video photography.
Lockheed Martin	USA	One of the biggest aerospace and defence giants today; produces drones used by the U.S. military
Northrop Grumman Corporation	USA	Legacy aerospace company that has long been a key drone player in the industry; its products used in USA military operations.
3D Robotics	USA	Produces autonomous drones (e.g. drone SOLO) with GPS point planning, known as a smart drone.
DJI Innovations	China	Current leader in manufacturing civilian drones (c. 70 % share of the drone market).
Yuneec	China	World leader in electric aviation.
Parrot SA	Europe	New entrant into the UAV/quadcopter market (headquartered in Paris); manufactures wireless devices for mobile phones and automobiles (i.e. bluetooth hands-free kits).
AeroVironment	USA	World leader in military drones; also in the civilian market – drones for agriculture and the energy industry.

Source: Business Insider [459]

Figure 64 presents the 20 most important civilian drone companies worldwide, in the third quarter of 2016, according to DRONEII.[460] The volatility of the market is underlined by the fact that only half of the ten companies in the Business Insider list appear in the DRONEII list. The majority (80 %) of these top 20 companies are OEMs/tier1 firms, while the remainder are in software development specific to drones. The key suppliers of UGVs and UMSs are shown in Figure 65.

Globally, there are only a few players involved in the manufacture of UGVs, and the international market generally lags behind the USA on such capabilities. North America has always been at the forefront of technological development and disruption, and has dominated the global UGV market since 2016, followed by Europe and Asia Pacific. Five of the 11 largest companies manufacturing UGVs are USA companies; four are European, located in France, Germany, the UK and Switzerland. Other players are Canada and Israel [461]. The companies considered in the analysis are given in Annex 2 Table 58.

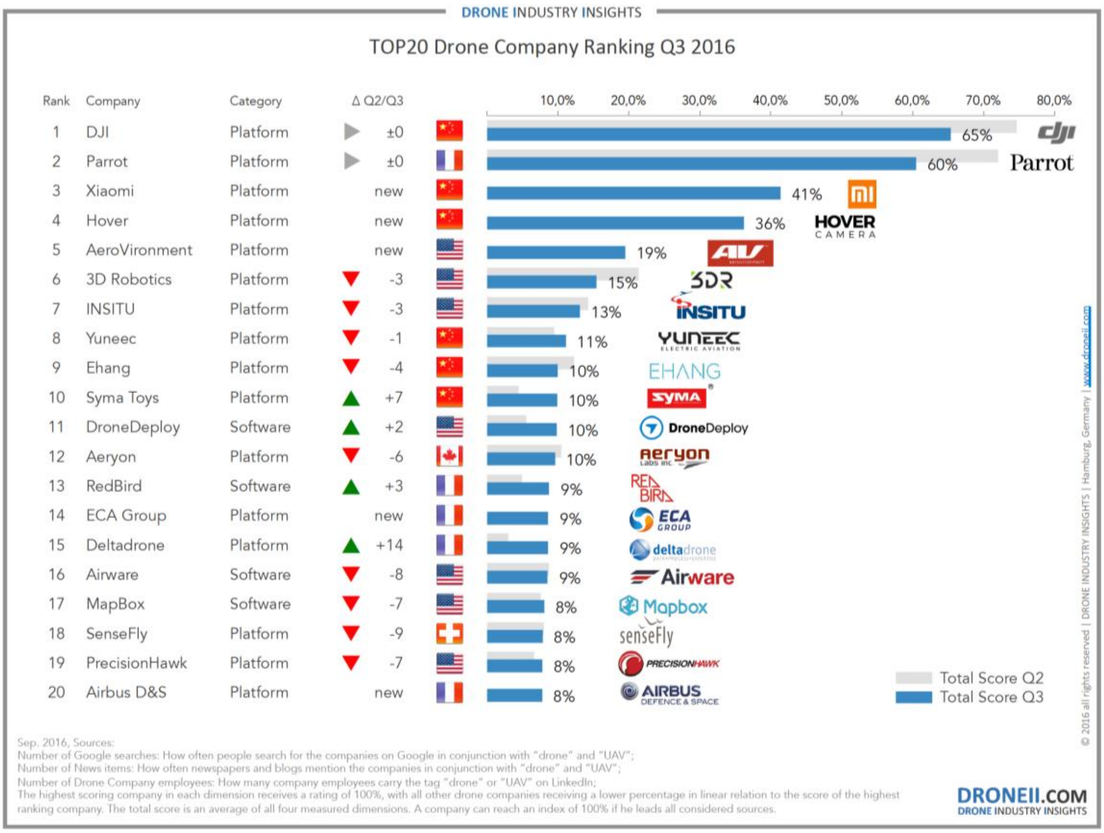
The military sales market of UGVs is currently dominated by Israel, which plans to deploy unmanned vehicles to patrol its borders. [462]

Europe is the biggest market for UMVs, but the USA is the largest manufacturer of such vehicles/systems. The majority of companies producing UMVs are located in the USA, followed by the UK, Canada, France, Japan, Italy, Norway, Germany, the Russian

[459] Business Insider (https://www.businessinsider.com/top-drone-manufacturers-companies-invest-stocks-2017-07?international=true&r=US&IR=T)
[460] Drone Industry Insights UG, Hamburg, Germany, 2016 (https://www.droneii.com/top20-drone-company-ranking-q3-2016)
[461] https://blog.marketresearch.com/global-unmanned-ground-vehicle-market-to-reach-9.06-billion-by-2023
[462] https://en.globes.co.il/en/article-unmanned-vehicles-to-patrol-israels-borders-1001238000

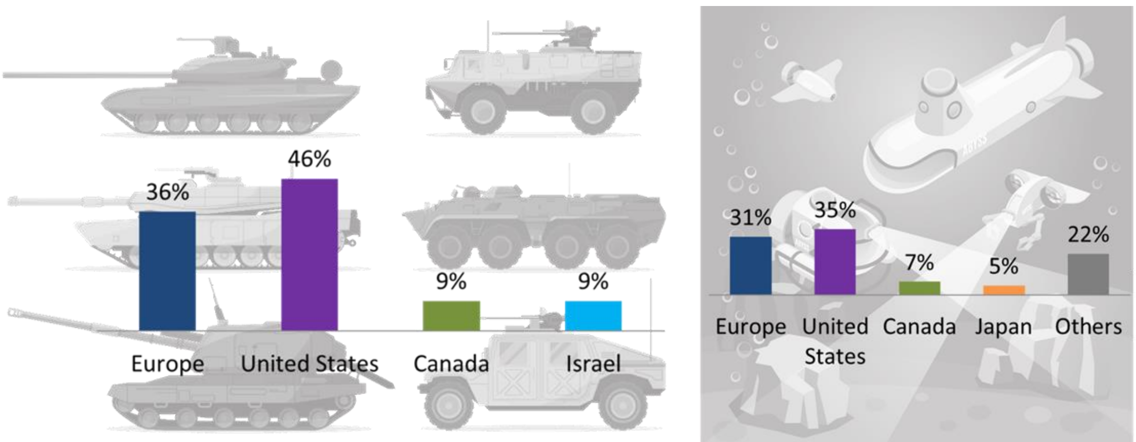
Federation and the rest of the world. More than 220 companies located in 34 countries are known to produce UMVs.

Figure 64 Top 20 Civilian Drone Companies worldwide



Source: Drone Industry Insights [463]

Figure 65 Key suppliers of UGVs (left) and UMVs (right)



Source: Global-unmanned-ground-vehicle-market [461] *and Unmanned Maritime Vehicles: Core Capabilities & Market Background* [464]

463 www.droneii.com

464 https://higherlogicdownload.s3.amazonaws.com/AUVSI/b657da80-1a58-4f8f-9971-7877b707e5c8/UploadedFiles/AUVSIUMVCoreCapabilities08-08-13.pdf

Civilian Drone market

The civilian drone market can be grouped into professional, hobby, and toy drones. The civilian professional drones market [465] has become concentrated. Meanwhile, the market leader, DJI, a Chinese company, controls 74 % of the overall professional drones market worldwide. [466] Parrot, a European company, has the second largest market share (7 %). A well-known subsidiary company of Parrot is senseFly.

To gain as complete and up-to-date as possible an overview of the sector, the analysis is built on a variety of sources, namely Business Insider, the DRONEII listing, and input from experts. As well as different reference points in time and the number of companies shown, the listings vary in scope. Business Insider includes not only manufacturers of drones, but also of drone components. However, while Business Insider is more up to date, the DRONEII listing is more comprehensive (Annex 2 Table 59).

Military Drone market

The military drone sector is very heterogeneous, covering various drone classes. These classes have different market mechanisms and dominance patterns.

Large UAV systems are dominated by big USA defence contractors (like Northrop Grumman, Boeing/Insitu and General Atomics), European ones (Airbus D&S, Thales), and Israeli ones (IAI), which develop and manufacture UAVs primarily for military applications, with civil applications on the side. [467]

Non-Western countries like Russia and China are also investing heavily in large UAV systems, but public information on these is scant. Recent reports of armed Chinese drones operating in Middle-Eastern battlefields [468], however, clearly indicate significant developments.

Europe is working on the development of an answer to USA-Israeli dominance in the market of **MALE UAV systems.** [469]

On **mid-range UAV systems**, Israeli companies have led the development of military drone systems for a long time, and continue to play a very important role.

The market for **smaller UAV systems** is more competitive, with a larger number of competitors. There are large, and also several relatively small, producers manufacturing smaller UAVs for both civil and military applications (dual use), with some variations depending on use. European manufacturers include Sky-Watch [470] and Schiebel Corporation[471]. Other companies originated in the civil market and have extended their product lines to the military UAV market, e.g. by enabling product adaptations. Some of these newcomers have gained significant global military UAV market share, especially in the class of smaller UAV systems, for example AeroVironment (USA), Aeryon (CA), EMT (DE), SAAB and UAV Solutions. FLIR Norway produces a nano-sized drone specifically for the military market.

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[465] drones with a price higher than 500€

[466] https://dronelife.com/2018/09/18/new-report-unveils-drone-industry-market-share-figures/

[467] Companies only manufacturing UAVs for civil applications do not generally provide large UAV systems, with the only known exception being Ehang (the EHang AAV is a low-altitude, autonomous aerial vehicle dedicated to short-medium distance transportation, including passenger transportation).

[468] https://www.militarytimes.com/news/your-military/2018/10/03/chinese-armed-drones-now-flying-over-mideast-battlefields-heres-why-theyre-gaining-on-us-drones/

[469] https://www.airbus.com/newsroom/press-releases/en/2018/04/Airbus-Dassault-Aviation-and-Leonardo-European-MALE-programme.html

[470] European Commission (2017): Dual Use Technology in the EU. Helping SMEs bring innovation to market., https://ec.europa.eu/docsroom/documents/2548

[471] Schiebel is an Austrian SME manufacturing the CAMCOPTER S-100, see: https://schiebel.net/

The various drone classes contribute differently to the overall military UAV market, which is dominated by USA and Israeli companies. Within the USA, four companies lead the market: General Atomics, Northrop Grumman, Textron and Boeing, which together account for two thirds (66 %) of the USD 9 billion market.[472] Major Israeli UAV companies working in the defence sector are Israel Aerospace Industries (IAI), Elbit Systems and Aeronautics Defence Systems. However, the expansion of Chinese companies into UAV development poses a threat to USA and Israeli dominance of the market. [473]

Unlike the USA and other countries, China does not routinely announce arms sales, so it is hard to get an overview of the situation. However, a review of drone spottings gives us some indication of who its customers are and where Chinese drones are already in use:

- In Iraq in October 2015, the country's then-defence minister inspected a CH-4 drone at an airbase in the city of Kut;
- Chinese armed drones have been operating at Jordan's Zarqa Airport, at an airbase in Pakistan and from bases in Egypt in the Sinai Peninsula and near its border with Libya; [474]
- Satellite photographs taken of a mysterious airbase in the United Arab Emirates' deep south — a desert area known as the Empty Quarter — appear to show three Wing Loong IIs; [475]
- Two CH-4s were spotted by satellite alongside surveillance-only Predators purchased by the UAE at Jizan Regional Airport in southern Saudi Arabia, near the kingdom's border with Yemen; [476]
- Outside the Middle East, Nigeria has used Chinese armed drones against the Islamic extremist group Boko Haram.

5.5.3 Supply chain of civil versus military UAV applications

Differences between the supply chains of military UAVs and civil UAVs

The supply chains of civil and military drones can overlap. The still relatively small production figures of military UAV systems affect the influence of the defence ministries commissioning these systems. Looking at UAV system elements, the military differences will:

- be driven by **differences in the applications**, which may require special airframe design and material features unique to military needs (e.g. for signature control to reduce the chance of detection and of being attacked);
- be **more demanding in performance terms** (e.g. longer ranges and higher altitudes requiring more demanding propulsion/power systems);
- require **military-specific payloads** (e.g. CBRN, ESM, weapons systems);
- require **military-specific data links** (e.g. encrypted frequency-hopping communications to make countermeasures difficult).

<u>Examples of UAV system elements:</u>

- Platform/body (frame)
    - Includes actuators, gimbals

[472] https://www.c4isrnet.com/unmanned/uas/2016/04/06/four-companies-dominate-the-military-drone-market/
[473] https://foreignpolicy.com/2018/05/10/china-trump-middle-east-drone-wars/
[474] According to satellite photos analysed by the Center for the Study of the Drone
[475] Reported in January 2019 by IHS Jane's Defense Weekly
[476] According to the Center for the Study of the Drone

- Power supply
- Engines
- Avionics
  - Flight control systems
  - Navigation systems
  - Sensors, including cameras, CBRN sensing, radar, LIDAR, electronic intelligence
  - Communications
  - Computing/software
- Data links

Achieving quality requirements for military UAV applications

The military focus is on the **design and performance of the UAV as a system** (range, endurance, altitude, speed, payload space/weight, mission performance etc.) and **as part of the larger military force structure**, and on the assemblies needed to perform specific military tasks (payloads in particular), rather than individual components and materials. Components and materials, however, gain relevance where there are military-specific requirements such as special materials for signature control to reduce vulnerability.

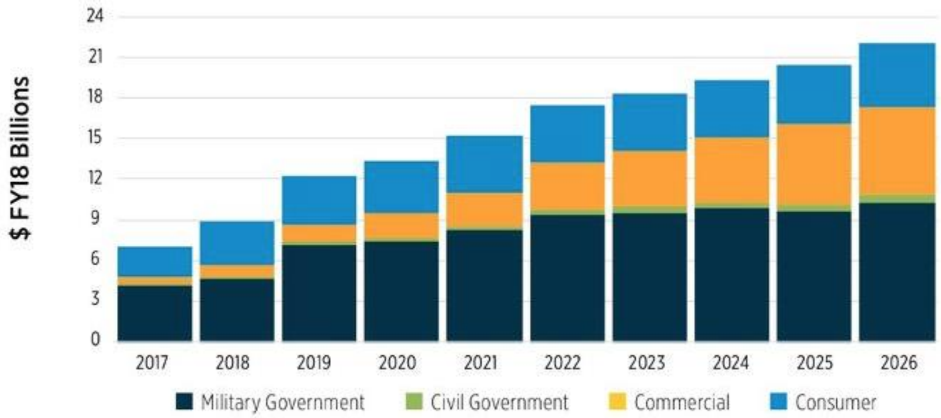
Certain UAV components, such as semiconductors, are of particular interest for the military sector. The European Defence Agency (EDA) components work strand aimed to establish a European supply chain for the next generation of defence applications for radars, communications and electronic warfare (EW) technologies, using gallium-nitride (GaN)-on-silicon-carbide (SiC) semiconductor technology. [477] The strategic importance to Europe of gallium-nitride is expressed by the fact that four consecutive projects have been run on this technology (KORRIGAN, MANGA, MAGNUS, and EUGANIC), and a fifth is under preparation.

Interplay between the supply chain of military UAVs and the supply chain of civil UAVs

The **military market also influences the civil market through market demand**, driving innovation and R&D investment. A comparison of the production value of UAVs [478,479,480] (excluding sensors, ground control, launch and recovery systems and other procurement costs) shows global military UAV production increasing from USD 4.2 billion in 2017 to USD 10.3 billion in 2026, driven in particular by unmanned combat air vehicles and medium altitude/long endurance (MALE) UAVs for operational reconnaissance. The value of the market for military UAVs is expected to continue to be larger than that of individual markets for civil government, consumer or commercial applications until 2026 [481], see Figure 66.

[477] European Defence Agency, Towards Enhanced European Future Military Capabilities, European Defence Agency Role in Research and Technology 2016.
[478] Teal Group, World Military Unmanned Aerial Vehicle Systems Market Profile and Forecast 2017, November 2017
[479] Teal Group, Global Military Unmanned Aircraft System (UAS) Forecast, http://www.tealgroup.com/index.php/teal-group-media-news-briefs-2/teal-group-news-media/item/global-unmanned-aircraft-system-uas-forecast, 25 April 2018
[480] http://insideunmannedsystems.com/military-uav-market-to-top-83b/, Military UAV Market To Top $83B, April 24 2018
[481] http://insideunmannedsystems.com/military-uav-market-to-top-83b/, Military UAV Market To Top $83B, April 24 2018

Figure 66 Global Unmanned Air System Production Value Forecast 2017-2026



Source: Teal Group [482]

USA dominance in military R&D spending and procurement on UAV technology over the next 10 years [482,483,484] will strengthen their military and civil UAV supply chains and help to create a **significant competitive advantage for the USA**. Firms in traditional aerospace, data analysis, semiconductors and telecommunications are all entering the civil UAV market. Technology companies and venture capitalists have invested worldwide more than USD 500 million into start-up investments in 2017 – a record level [485] – and more than USD 2 billion since 2012. USA start-ups have received 76 % of this funding, enabling them to take the lead in the development of drone analytics.

Chinese firms, which received 4 % of the investment, **are focusing on continuing their lead in hardware**, moving from consumer UAV systems (hobby, toys) to commercial systems (professional applications).

Important role of SMEs in the supply chain due to high level of fragmentation

The UAV market is still young, and the role of SMEs in the supply chain is significant. The military UAV market, in particular, is still at the stage where manufacturers are producing relatively small numbers of systems, specially commissioned, commonly by defence ministries. Such markets suit SMEs, which are good at developing and proposing novel solutions to problems. SMEs are also comfortable with producing relatively small numbers of products. **The role of SMEs as (critical) suppliers is therefore important.** Minerva is an interesting example of a case where military and civil needs overlap. [486] It is a UK challenge-led research project, which completed tests in September 2018 of concept drones and ground robots operating in simulated contaminated scenarios in both UK civil and battlefield environments. The goal of this research programme, funded jointly by the UK Ministry of Defence and the Home Office, was to identify and accelerate the development of autonomous technologies that can be used to evaluate potentially hazardous environments. The aim is to reduce the risk to emergency services and frontline troops attending incidents or operations involving hazardous chemical or biological materials. The project funded 18 feasibility studies and

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[482] Teal Group, World Military Unmanned Aerial Vehicle Systems: Market Profile and Forecast 2017, November 2017

[483] Teal Group, Global Military Unmanned Aircraft System (UAS) Forecast, http://www.tealgroup.com/index.php/teal-group-media-news-briefs-2/teal-group-news-media/item/global-unmanned-aircraft-system-uas-forecast, 25 April 2018

[484] http://insideunmannedsystems.com/military-uav-market-to-top-83b/, Military UAV Market To Top $83B, April 24 2018

[485] Teal Group, World Civil Unmanned Aerial Systems 2018 Market Profile and Forecast, July 2018

[486] https://www.gov.uk/government/news/uk-tests-life-saving-chemical-detection-robots-and-drones, UK tests life-saving chemical detection robots and drones, 17 September 2018.

four follow-on development projects: three of the four demonstration system projects involve SMEs as research partners/suppliers and one of the four demonstration system projects is led by an SME.

Further useful examples are the USA DARPA Grand Challenges in Autonomous Vehicles (2004, 2005 and 2007) and in Robotics (2013, 2015). [487] Challenge-led competitions that address civil and military needs (robotics and drones) could be a good way of encouraging investment in new robotics and UAV technologies of civil and military benefit, supporting SMEs that are well placed to develop new concepts in these fields where there is user need. The funding models for such competitions would require appropriate design to encourage the widest possible involvement while at the same time encouraging pull-through and following international best practice.

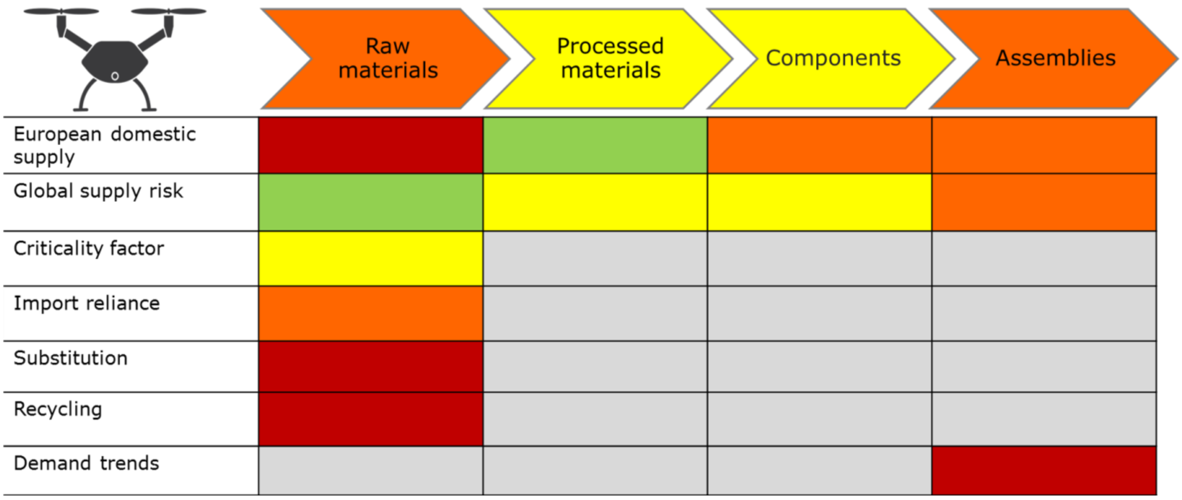
Potential constraint for UAV production related to software development

Software development will be a key enabler for the development of UAVs and their incorporation into military forces. UAVs will become increasingly autonomous over the next 10 years to reduce the burden on ground (and air) controllers and increase mission capabilities. UAVs and supporting ground (and air) systems will carry out a wider range of functions without human intervention in mission planning, operations, and data collection and analysis. Effective use of UAVs within military force structures will require collaborative working where the control of tasks, functions, sub-systems and vehicles can flow between human controllers and autonomous systems, depending on the circumstances. Achieving these military advances will require extensive software design and development for the UASs themselves and for the effective integration of these systems into military forces and operations.

5.5.4 Overview of the supply risks for the UAV supply chain

The estimated supply risks and bottlenecks along the supply chain of unmanned (aerial) vehicles are visualised in Figure 67. The performed bottleneck assessment has shown potential **high risk of supply for the two supply chain steps "raw materials" and "assemblies"**. The other two supply chain steps **"processed materials" and "components" show moderate risk** of supply.

Figure 67 Overview of supply risks and bottlenecks in the supply chain of UAVs



Source: JRC

[487] https://www.darpa.mil/work-with-us/public/prizes

5.6 Opportunities for research and policy actions for unmanned vehicles

5.6.1 Research opportunities

The 'unmanned feature' is one of today's R&D focus areas for military vehicles. Market development is still at an early phase for the military UV sector and its sub-sectors, UAV, UGV, UMV etc., and massive growth is expected in the coming years. The civil UAV market is also expected to experience exponential growth, especially with the new European drone regulation and the development of U-space [488] services that will allow long-range flights and the integration of UAS in airspace (at least below 500 feet or 150 m).

Recent steps to integrate **'alternative' fuel** types for smaller UAVs look promising, given the demand for improved endurance. For example, the use of fuel cell technology or hybrid battery technologies could contribute to extended operating distances for unmanned vehicles, which depend today primarily on lithium polymer (LiPo), or nickel cadmium batteries. Improvements in LiPo batteries and solid state batteries in order to achieve higher payloads and longer flight times have recently received a lot of R&D attention. Achieving high energy density (energy per unit mass) ultimately comes down to research on materials.

Along with the development of efficient power sources, efforts are under way to lighten structures while increasing their strength. The key metals that can be used for lighter structures are Al, Mg and Ti. Aluminium is already widely used by automakers and increasing use of Mg is also expected. Unfortunately, Ti is too expensive for this sort of use. Issues relating to cost, fabrication, joining, failure modes, recycling, etc. have yet to be resolved, along with more cost effective and environmentally friendly refining operations.

Carbon fibre composites are a very attractive alternative, providing a light and strong material. Regrettably, the large-scale use of CFCs is hindered by high costs. Cost-reduction efforts based on the use of alternative feedstock and process technologies are under way, and further developments are needed. Research is also needed on advanced materials such as thermosetting and thermoplastic polymers reinforced with carbon and glass fibres and on nanocarbon additives, such as carbon nanotubes, graphene, nanofibers and carbon black materials – all of them generating lightweighting advantages. Advanced manufacturing technologies are needed for lightweight materials for large UAVs, leading to energy efficiency gains and environmental benefits. However, the cost-benefit relation for these advances applied to light UAVs (less than 25 kg MTOW) is less clear.

Firms in traditional aerospace, data analysis, semiconductors and telecommunications are all entering the civil UAV market. Private funding is shifting from hardware to software and services to make drones more useful. USA start-ups have taken the lead in the development of drone analytics. In the short-term, Chinese firms are focusing on hardware, especially for small and light drones, and moving from consumer (private use) into commercial (e.g. mining and construction) systems. **Software development** will be a key enabler for the development of civil UAVs, and also for the **incorporation of these UAVs into military forces**. UAVs will become increasingly autonomous over the next 10 years to reduce the burden on ground (and air) controllers and increase mission capabilities. **Increasing the autonomy level in civil drones will be a big factor in the success of a number of key applications**. In fact, the new European drone regulation allows the use of autonomous drones within its 'specific' category. Therefore,

[488] 'U-space is a set of new services relying on a high level of digitalisation and automation of functions and specific procedures designed to support safe, efficient and secure access to airspace for large numbers of drones'. Source: https://www.sesarju.eu/U-space/. Accessed 13.08.2019

Europe now has all the necessary components to become a leader in autonomous aerial vehicles: a regulation framework that allows it to happen, a large potential market and an R&D ecosystem for these technologies. Moreover, these **autonomous functionalities and technologies could later be adapted or applied to manned aviation** (once they have proven their success), maintaining European leadership in the aeronautical industry. An example of this duality is the new Wayfinder R&D project by Airbus[489]. The development of U-space services and their deployment should also be promoted in order to enable long-distance flights, whose underdevelopment is the main factor preventing the exponential growth of the UAV civil market. The effective use of UAVs within military force structures will require collaborative working, where the control of tasks, functions, sub-systems and vehicles can flow between human controllers and autonomous systems, depending on the circumstances. Achieving these military advances will require extensive software design and development for the UASs themselves and for the effective integration of these systems into military forces and operations.

The rapid rate of technological change in UAVs (and in the autonomous vehicle sector), driven by significant private investment, is also driving research in **semiconductor advances and innovations**, in particular in GPU-based systems and hardware for AI. Accordingly, advances in **obstacle avoidance**, **intelligent navigation**, **artificial intelligence**, and **context awareness** can make drones more effective across a range of industries like agriculture, construction, infrastructure and security; fertile ground for SMEs.

USA experience in military robotics shows the benefit of **streamlining the procurement process** so that UGVs use a set of common chassis platforms, controllers, modular sensors and other components to make them interoperable and easy to maintain and update. The same is also true for UMVs. **Interoperability** of unmanned vehicles/systems is thus another field of future research.

Due to rapid developments outside the EU, counter-drone systems are without doubt a further important research opportunity. This includes the development of counter-UV capabilities based on swarms of mini-UVs (e.g. mini-UASs), but also **securing the data link** and issues like **TEMPEST shielding**. [490] Accordingly, associated **shielding or supressing materials** are very important for UGVs.

5.6.2 Opportunities for policy actions

Opportunities for policy actions can be split into two threads. The first relates to the challenges of a traditional industrial policy, which aims to **build and maintain a healthy competitive sector,** providing added value and employment, thus contributing to EU industrial policy targets, and to the EU's GDP. [491] The second is the development of a **solid European defence technological and industrial base (EDTIB)** [492] **for strategic purposes**. While the strategic side is related almost exclusively to the military UAV sector, the economic aspect relates to the overall UAV sector, both civil and military. It's not just military UAVs which are of strategic relevance, but also certified civil UAVs and those used for professional applications, as they share similarities with

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[489] https://www.airbus-sv.com/projects/10

[490] 'Transient Electromagnetic Pulse Surveillance Technology', which refers to the equipment and devices that emit or receive and decipher data from electromagnetic resonance, referred to as compromising emanations. https://www.techopedia.com/definition/9697/tempest-shielding, accessed on 22.07.2019

[491] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Stronger European Industry for Growth and Economic Recovery Industrial Policy Communication Update (COM (2012) 582)

[492] European Parliament (2013): The Development of a European Defence Technological and Industrial Base (EDTIB). DIRECTORATE-GENERAL FOR EXTERNAL POLICIES OF THE UNION, DIRECTORATE B

military UAVs, with potential overlap (dual-use technologies) and interlinkages regarding the supply chain.

Certain opportunities for policy actions have been identified along the supply chain and are summarised below.

For large UAVs and UCAVs in the European defence sector, there is significant structural industrial dependence on USA and Israeli drone technologies. To tackle this dependence, various programmes have been launched by the EC, EDA, UK and France. However, more efforts are required to make a difference [493]; measures could include upscaling existing programmes or bringing in additional Member States, especially those with strong technological profiles in the UAV sector.

The European Defence Fund provides funding opportunities for projects on key defence technologies, including, for instance, unmanned systems in a naval environment. [494] A particular case of supply dependence at drone level is the MALE UAV/UCAV segment ('Predator family'). The **EUROMale** [495] programme was launched in May 2015 to address this dependence, as a joint study of France, Germany, Italy and later, Spain. The aim of EUROMale is to define operational capabilities and to design and develop a European **medium-altitude, long-endurance, remotely-piloted aircraft system (MALE RPAS)** deployable for land and sea surveillance. Due to its ambition to support the competitiveness and innovation capacity of the EU defence industry, the multiannual work plan 2019-2020 of the European Defence Industrial Development Programme (EDIDP) [496] foresees an EU contribution of up to EUR 100 million for the EUROMale project. [497]

This shall be realised as a twin-turboprop MALE UAV developed by Airbus, and supported by Dassault Aviation and Leonardo as subcontractors, with delivery planned by 2025. European companies are working hard to catch up with the technological lead of the USA, but further concerted efforts are required to break the USA's virtual monopoly. [498]

In the medium- to long-term, the military needs **smaller and more economic and efficient UVs**, in particular for reconnaissance and logistical support. This will probably require technological advancements in increments. It could be an opportunity to include specific military components of these dual-use requirements into the EDIDP.

The supply chains of selected UAV types should be analysed in more detail. Taking budgetary limitations into consideration, we recommend focusing on UAVs in growing strategic applications like HALE, LALE, tactical UAV (TUAV), or HAPS [499], which are at the same time strong drivers of overall UAV growth. A clear roadmap for the procurement of these UAVs in strategic applications should be used as a basis for identifying the parts of

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[493] European Parliament (2013): The Development of a European Defence Technological and Industrial Base (EDTIB). DIRECTORATE-GENERAL FOR EXTERNAL POLICIES OF THE UNION, DIRECTORATE B, p.54.

[494] European Commission (2017): A European Defence Fund: €5.5 billion per year to boost Europe's defence capabilities. Brussels, 7 June 2017. Press release. https://europa.eu/rapid/press-release_IP-17-1508_en.htm, accessed 20.07.2019

[495] EuroMALE is the abbreviation for the European MALE RPAS project

[496] EDIDP was established by Regulation (EU) 2018/1092) and was published on 19.03.2019. See: https://ec.europa.eu/growth/content/2019-calls-proposals-european-defence-industrial-development-programme-edidp_en, accessed 22.07.2019

[497] 26,35 % in 2019, 73,65 % in 2020. European Commission. Annexes to the Commission implementing Decision of 19.3.2019 on the financing of the European Defence Industrial Development Programme and the adoption of the work programme for the years 2019 and 2020. C(2019) 2205 final, Annexes 1 to 2.

[498] European Parliament (2013): The development of a European Defence Technological and Industrial Base (EDTIB). DIRECTORATE-GENERAL FOR EXTERNAL POLICIES OF THE UNION, DIRECTORATE B, p.54.

[499] The category 'High Altitude Pseudo Satellites' is drawing more and more interest. For example, the last EDA and EDIDP calls have announced funding for the development of HAPS solutions.

the supply chain where the final product (UAV) or its intermediate products (assemblies, components, etc.) exceed acceptable levels of dependence. In these cases, with external procurement dominating, additional efforts are required to strengthen the European market, and to indigenise certain sections of the supply chain. As such an approach is expected to be challenging and probably costly, it is of high importance to prioritise those supply chain sections where indigenisation is most urgent and important.

Because of the vibrant market dynamics, newcomers have entered at OEM level. When the UAV market further consolidates, SMEs will probably experience massive market pressure in the short- to mid-term. SMEs have an important role to play in UAV development because they are well equipped to respond quickly to the rapid rate of technological development, in comparison with large companies.

The issue of **creating manufacturing capability by enabling EU companies to scale up production** is also important for emerging UAV technologies. In order to **maintain and foster innovation in the UAV sector**, it is desirable to support SMEs, e.g. with distinct market measures **for scale-up and manufacturing by the European Defence Fund**, or related targeted funds/programmes. The EDIDP has a category for 'Innovative and future-oriented defence solutions' [500] which encourages the participation of SMEs. Europe is already strong in R&D terms for smart systems integration, but SMEs and other innovators still face many barriers to the market. A report released by DG Connect proposing measures to help to build scalable innovation models leading to production [501] can be used to derive concrete support actions for SMEs.

However, research support mechanisms for SMEs in this field would need to be carefully designed to suit the rapid rate of change, with rapid timescales and flexible programmes, and would need to be built on best practice (in particular in the USA and Europe).

For both civil and military applications, agreeing **specifications for UAV technology** could further contribute to a stronger European UAV sector. In this respect, the recent publication of the new European drone regulation (June 2019) is crucial. In the coming months, guidance material and new industrial standards will be developed to fulfil the requirements of this new regulation. Now is the time to promote the capacity of EU companies (especially SMEs) to develop final products that fulfil these requirements, in order to facilitate the commercialisation of drone-based solutions. Moreover, there are some specific components, mostly related to safety, that should be promoted as possible to design and manufacture within the EU, for example geo-fencing subsystems and network-identification systems. The use of UAVs for long distance flights will require a certain level of assurance in hardware and software development that will create entry barriers for newcomers. In this respect, it is especially important that **European companies will be able to design and develop systems and components that fulfil the new European regulation requirements** defined for long distance flights with light UAVs (mainly below 25 kg MTOW).

When it comes to the military sector, agreements on **new specifications for UAV technology**, in the context of the Capability Development Plan (CDP) between armed forces of EDA Member States, could further contribute to (a) a stronger European UAV sector, and (b) enhanced interoperability of military UAVs across borders. The EDA could include such agreements as mid-term priority in their Capability Development Plans (CDP), which are regularly updated. [502] These cooperation opportunities could be based

[500] call EDIDP-SME-2019
[501] DG Connect (2016): Smart Systems Integration & Smart Objects: How to Enable a 'Fast Track to Manufacturing' in Europe, November 2016. Final Report
[502] For example by including them in the current CDP priorities, "information superiority", "ground combat capabilities", or "cross-domain capabilities contributing to achieve EU's level of ambition". See: https://www.eda.europa.eu/what-we-do/our-current-priorities/capability-development-plan

on a shared operational concept and related harmonisation requirements with the aim of increasing the robustness, sustainability and resilience of ground systems. [503] Beyond intra-EU cooperation, partnerships with other relevant UAV countries that still lack the technical capabilities and funding to manufacture these larger, more complex systems can play a strategic role. [504]

The European Defence Fund calls for more cooperation on procurement in Europe, where more than 80 % is still carried out on a national basis. [505] For UGVs, **streamlining of Member State procurement processes** is recommended in order to agree a set of common chassis platforms, common controllers, and modular sensors and other components. Member States could jointly finance further development of UGVs and ideally procure the final product jointly ('including lifecycle savings in terms of maintenance, logistic support and training facilities and command structure'). This would result in a higher level of interoperability across UGVs, eased interoperability with other types of vehicles, and easier maintenance and updating.

Comprehensive implementation of the EDIDP is fundamental to strengthening the EU's armed forces, supporting the **integration of unmanned vehicles** (beyond UAV/UCAV) into the overall military ecosystem. The full-scale realisation of the Common Operating Environment (COE) can provide maximum benefit from the information that UAVs collect, provided that sensor components and command posts are compatible. From a policy point of view, advances in artificial intelligence, autonomous systems, ubiquitous sensors, advanced manufacturing etc. are expected to transform warfare radically [506] and significantly alter military forces and operations.

Increased competition from the USA and China is expected in future: USA dominance in military R&D spending and UAV technology procurement over the next 10 years is expected to strengthen their military and civil UAV supply chains and help to create a significant competitive advantage. There is also strong competition from China in areas where USA exports are restricted by regulation (MTCR and ITAR).

Military procurement, including that of UVs, still takes place predominantly at Member State level, but joint and cooperative procurement for EU militaries shall be intensified in the future, e.g. by advancing the Defence Procurement Directive. [507] To ensure mid- to long-term interoperability across national fleets, unmanned vehicles should be harmonised with common standards and norms (e.g. within the scope of the European Defence Fund 'capability window'). This should include the outlook towards scalable control interfaces and runway-independent, expeditionary tactical UASs.

Since **communication technologies** will change drastically in the next few years, together with advances in components and information processing, **regular monitoring of the UAV/UV market is recommended**, with updates annually or at least biennially. For the civil sector it is especially important to promote the synergies between 5G and UAV technology developments.

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[503] European Commission. Annexes to the Commission implementing Decision of 19.3.2019 on the financing of the European Defence Industrial Development Programme and the adoption of the work programme for the years 2019 and 2020. C(2019) 2205 final, Annexes 1 to 2.
[504] India might be a candidate for such a type of partnership.
[505] European Commission (2017). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Launching the European Defence Fund. COM(2017) 295 final, Brussels, 7.6.2017
[506] Christian Brose (2019). The New Revolution in Military Affairs, Foreign Affairs May/June 2019.
[507] European Parliament and Council (2009). DIRECTIVE 2009/81/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 July 2009 on the coordination of procedures for the award of certain works contracts, supply contracts and service contracts by contracting authorities or entities in the fields of defence and security, and amending Directives 2004/17/EC and 2004/18/EC 2009/81/EC

A deeper analysis is also recommended to **identify in more detail the potential bottlenecks at UAV manufacturer level** (OEM, tier 1 firms). [508,509]

The supply of higher-level components, for which the EU is very dependent on imports, requires particular attention because of their essential role in technological UAV development. Viable European alternatives are missing. Examples are GPUs, which are increasingly technologically crucial for AI-enabled UAVs, other controllers, GPS/GNSS chipsets, inertial measurement units (IMUs are key components for navigation under difficult conditions) and magnetometers. For GPUs, dependence is two-fold, both at country level (imports 100 % from USA) and company level (only two companies, nVIDIA and AMD). The situation is equally clear but less severe for IMUs, with more suppliers. Funding is recommended for R&D on military grade IMUs (e.g. cold-atom sensors) to support and ensure future market availability in the EU. Further important components are detect-and-avoid (DAA)-related sensors such as LIDARs and radars.

The performance of sensors is expected to become increasingly crucial for military UAVs, so EU research funding should be continued and augmented, especially on hyperspectral sensors, to decrease dependence on USA and Israeli supply. This applies to both hardware development and the means to process sensor data. We estimate that EU R&D funding is most effectively spent at component level and thus recommend channelling the funding to selected types of components, rather than limiting it to certain UAV platforms, taking into consideration the impact of the new European drone regulation.

As with robotics, the success of the development of autonomous systems does not stop at well-developed hardware, but also requires **software development skills**, and the combination of the two. This is even truer for successful incorporation and effective integration into the military forces, where the aim is to increase mission capabilities with or without shared human intervention in mission planning, operations, and data collection and analysis (heightened UAV autonomy [510]). During the 10th edition of European Defence Matters 2016, the European Defence Agency (EDA) proposed that the human machine interface (HMI) would be a priority within the various next generation defence systems, supporting Europe's capabilities to respond to short and longer-term security challenges on its own territory and beyond. [511] Effective use and control of UAVs and UGVs within military force structures will require collaborative working where control of tasks, functions, sub-systems and vehicles can flow between human controllers and autonomous systems, depending on the circumstances. To this effect, extensive software design skills will be crucial in the military sector, and very beneficial in the civil sector. Therefore, a **software strategy** is recommended for the next decade, to achieve high levels of UAV and UGV autonomy, with the potential for explicit linkages to machine learning, artificial intelligence, intelligent navigation, integration into U-space, smart power management, and a development plan for unmanned vehicles interlinked with that of robotics. This should include cyber physical security. The aim is to enable EU manufacturers to keep the development of UAV and UGV control software in-house, and in particular the data link and communication via 5G. It could be made obligatory for certified UAVs, larger UAVs, and medium- and high-risk operations in the 'specific' category, to provide a certain level of insight into the UAV autopilot and communication software. Such a regulation could be introduced via the UAV airworthiness certification

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[508] For example, the RPAS Yearbook, published by Blyenburgh & Co, is a potential source for deeper analysis, providing comprehensive information on the UAV sector and UAV model developments, payloads, onboard equipment, and anti-drone systems, past and present.
[509] https://www.militaryfactory.com/aircraft/unmanned-aerial-vehicle-uav.asp
[510] While full autonomy is not achievable in the mid-term, these developments will lay the groundwork for success in the long-term.
[511] EDA - The next industrial (r)evolution: What implications for the security and defence sector? EDA Brussels - 03 May, 2016 https://www.eda.europa.eu/info-hub/press-centre/latest-press-releases/2016/05/03/the-next-industrial-(r)evolution-whatimplications-for-the-security-and-defence-sector

requirements [512], and the EASA authorisation process in the 'specific' category under the new drone regulation.

Becoming a leader in UAV development requires different strategies for larger and smaller UAVs. Control hardware and aerial platforms are fundamental to large UAVs whether civilian (such as urban air mobility i.e. aerial taxis) or military. In contrast, the light UAV sector is becoming a service industry, with Europe playing a key role. Some experts believe that it is wiser to reinforce this side, investing resources in it, rather than starting a difficult battle on the hardware side. Other experts consider it important that Europe focusses on certain key functionalities, such as autonomous navigation and U-space-related functions. These functionalities will be fundamental to the future development of the UAV sector, and if the EU wants to play an important role in the UAV market, it needs to play a strong role in developing these.

Given the dangers associated with both legal and illegal use of UAVs, countermeasures are of increasing interest, known by the term **counter remotely piloted aircraft systems** (C-RPASs). There are numerous C-RPASs available for commercial and military use, but **there is no common standard for effective C-RPAS technologies**, to guide potential developers. [513] A comprehensive market survey was released by Sandia National Laboratories, on the detection and classification of UAVs, concluding that there were no clear commercial solutions for C-RPASs (at the time of release, in 2015). [514] Additional technical and regulatory efforts are needed to increase the ability of C-RPASs to counteract threats from UAVs. Based on ongoing developments in C-RPAS, intelligence might also be required for effective counter-countermeasures. Increasing development activity has been noted of late in the field of **visual signature reduction,** achieved through active camouflage, for more efficient **stealth operation**. [515] Such reduced signatures in combination with improvements in data linkages and small, guided munitions can increase the survivability of UAVs significantly.

As with robotics, challenge-led competitions that address **civil and military needs in UAVs** could be a good way of **encouraging investment in new UAV technologies of civilian and military benefit**, supporting SMEs well placed to develop new concepts in these fields. The funding models for such competitions would need to be designed appropriately to encourage the widest possible involvement while at the same time encouraging pull-through and following international best practice.

Finally, the **recycling** of aircraft is still a nascent field. Aerocircular [516], a new Belgian company, has started recycling and up-cycling manned aircraft. Its focus is on the certified systems market of manned aircraft, but this could be expanded over time to include unmanned aircraft.

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[512] This regulation would only be fully effective if the ground station was treated similarly. With the market entrance of Huawei into EU 5G communication infrastructures, new uncertainties are emerging.

[513] Buric, M. and De Cubber, G. (2017): Counter Remotely Piloted Aircraft Systems. MTA Review, Vol. XXVII, No.1. http://mecatron.rma.ac.be/pub/2017/Counter%20Remotely%20Piloted%20Aircraft%20Systems.pdf

[514] Gabriel Birch, John Griffin, and Matthew Erdman, "UAS Detection, Classification, and Neutralization: Market Survey 2015," Sandia National Laboratories, 2015, http://prod.sandia.gov/techlib/access-control.cgi/2015/156365.pdf

[515] Z. W. Zhong; Z. X. Ma; Jayawijayaningtiyas; J. H. H. Ngoh (2016): Visual signature reduction of unmanned aerial vehicles. Proceedings Volume 9997, Target and Background Signatures II; 999707 (2016), SPIE Security + Defence, 2016, Edinburgh, United Kingdom, https://doi.org/10.1117/12.2241967

[516] Aerocircular is a new spin-off of the University of Leuven, Belgium. See website: http://aerocircular.green/, accessed 17.03.2019.

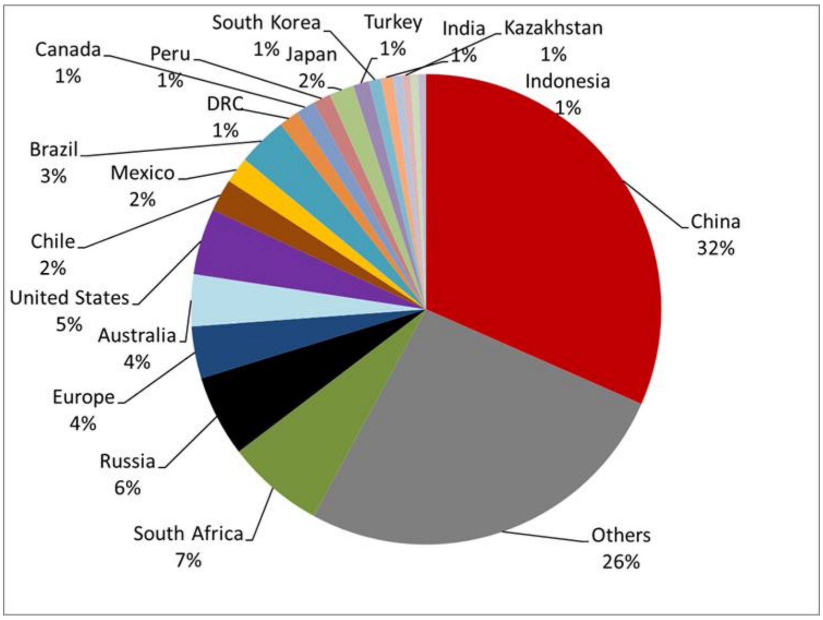
5.7 Unmanned vehicles: summary

Overall, the drones market is expected to grow at an annual growth rate of between 18 % and 27 % CAGR in the next few years. A much higher growth of >80 % CAGR is anticipated for particular sub-sectors such as smart commercial drones. The UGV market is expected to grow by more than 11 % per annum by 2023, largely serving the defence sector. A similar growth rate is expected for the UMV market for the same period.

In total, 48 raw materials and 14 processed materials have been identified as relevant for drones and analysed in this study. In addition, processed materials for lithium batteries and fuel cells were also considered at the 'Processed materials' supply chain step. Europe is fully dependent on the supply of 40 out of the 48 raw materials relevant for UV technologies. The materials of particular importance (primary production concentrated >80 % at a single country) are REE, Mg, Bi, and W, for which the dominating supplier is China, while for Nb the dominating supplier is Brazil. Overall, China delivers more than one third of the raw materials, followed by South Africa (7 %) and Russia (6 %).

Of the 48 raw materials, 23 are flagged as critical in the EU economy, namely Co, Si, C (natural graphite), Mg, V, Sb, Bi, REE, Pt, Pd, B, In, Ga, Rh, Ru, Fluorspar, P, W, Ta, Nb, Be, Sc and Hf. China is shown to be the major supplier of CRMs for drones, delivering more than 40 % of CRMs, followed by South Africa (10%) and Russia (8%). Europe delivers only 3 % of the raw materials and <1% of the critical raw materials for drones. It should be noted that more than 50% of the raw materials are supplied by numerous smaller supplier countries, providing good opportunities for supply diversification. An overview of raw materials suppliers for drones is shown in Figure 68.

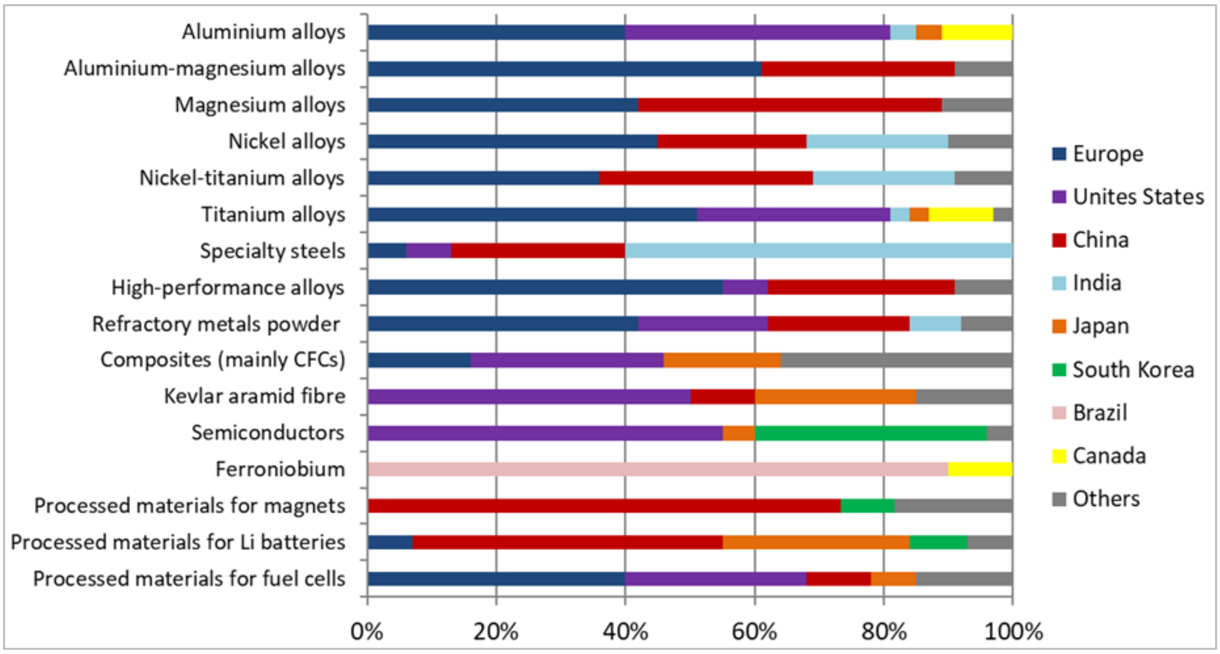
Figure 68 Raw materials suppliers for UAVs: overview



Source: European Commission, 2017, Study on the review of the list of critical raw materials

Europe is the major supplier of the processed materials required in drones, with around one third supply share. It is followed by the China (22 %), USA (17 %), India (8 %) and many other smaller suppliers who deliver around 26 %. It should be noted, however, that Europe is fully dependent on the external supply of aramid (kevlar) fibres, semiconductors and ferroniobium. The country production shares of UVs relevant processed materials are displayed in Figure 69.

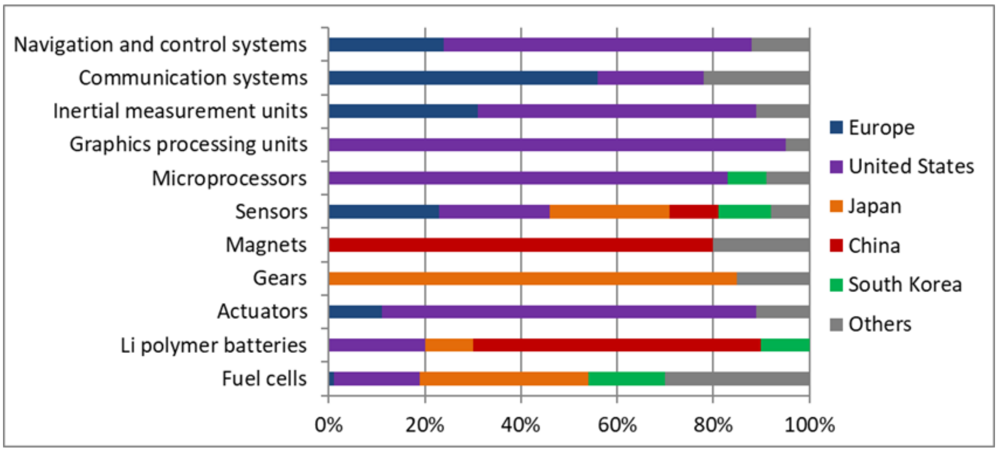
Figure 69 Country production shares of processed materials relevant to UAVs



Source: JRC

The key supplier for components for drones is the USA, with a 42 % share. Japan, China and Europe have similar supply shares, in the range of 13-14 %. Around 17% of the components are provided by a number of small players. The key suppliers for actuators, controllers (microprocessors), sensors, gears, GPUs and fuel cells are noted in the Robotics section above. The additional components here are LiPo batteries and IMUs. LiPo are supplied mainly by Asia (China in particular) and the USA. The USA is also the major supplier of IMUs (around 60 %); however, Europe also hosts some IMU production. **Potential supply bottlenecks are of concern in particular for those components, where the global production is concentrated in few countries, namely GPUs, gears, microprocessors, actuators.** In particular, the GPU production shows an extraordinary high concentration in a single country (95 %) (Figure 70).

Figure 70 Country production shares of components relevant to UAVs



Source: JRC

In the last step of the supply chain – drones production – one can see the notable dominance of China, providing around 80 % of civil drones globally. Less than 10 % of the drones are produced in Europe, while the USA and Israel deliver around 5 % and 3 % respectively. The USA, however, plays the leading role in military drone production, and in technological innovation.

The analysis has also revealed a high level of mergers, acquisitions and bankruptcy in the sector. Deeper analysis is required to better understand the possible pathways of development, and the key factors influencing these developments, including: 1) the implications of the uptake of artificial intelligence in UAVs, increasing the capabilities of robots and drones; 2) the trends regarding mergers, acquisitions and bankruptcy among suppliers, and the market shares of both companies and countries.

Europe is much stronger as a supplier of UGVs and UMVs than of UAVs. Europe is the second largest provider of UGVs and UMVs after the USA. Canada, Israel and Japan are other key suppliers of UGVs and UMVs.

The bottleneck assessment shows a potential high risk of supply issues for two steps of the supply chain: raw materials and assemblies (UAVs). The other two supply chain steps - processed materials and components, show moderate risk of supply.

To conclude, China dominates the civil drones sector, and increasingly the share of professional drones, while the USA and Israel dominate the military drones sector. The EU faces a serious risk of missing the opportunity to catch up with these global leaders on this key technology, which will be decisive for integrating comprehensive real-time geo-referenced intelligence into professional (civil) as well as military applications. Europe is highly dependent on external suppliers for raw materials and components as well as for the final product, i.e. unmanned vehicles (UVs). China is the predominant supplier of raw materials, and also of the critical raw materials used in the manufacturing of UVs. Downstream, the market is increasingly competitive, with the USA strongly dominating certain components (e.g. IMU, GPU and microprocessors) and drones with advanced capabilities in the military sector. Advancements in EU regulation and standardisation are necessary but not sufficient to make the EU a leading supplier of UVs globally. This report recommends the intensification of R&D efforts on selected key strategic components, assemblies, and on certain larger military UAVs to reduce the EU's dependence on imports, as well as the streamlining of military procurement in the EU to boost efficiency and dynamism. Software design skills also need to be supported and strategic UV alliance(s) should be considered.

6 Additive manufacturing (3D printing)

6.1 Description of additive manufacturing (3D printing) technology and relevance to civil and defence sectors

3D printing (3DP) is a rapidly emerging production technology which converts digital imaging into tangible objects. It is often referred to as additive manufacturing (AM), rapid prototyping or rapid manufacturing. The advantages of 3D printing are numerous, potentially allowing weight reduction, fewer parts, reduced material consumption, novel designs with a range of possible materials and more design freedom. As the technology matures, development costs, speed of production and technical capabilities are becoming less of an obstacle to its use to replace more conventional production. [517]

In 2013, the American Society of Testing and Materials (ASTM) issued a standard for AM technologies, grouping current AM process methodologies. In 2018 they produced this clear definition of additive manufacturing/3D printing: [518]

> *Additive manufacturing (AM), also known as 3D printing, uses computer-aided design to build objects layer by layer. This contrasts with traditional manufacturing, which cuts, drills, and grinds away unwanted excess from a solid piece of material, often metal. New equipment, technologies, and materials in AM are driving down the costs of building parts, devices, and products in industries such as aerospace, medicine, automotive, consumer products, and more. 3D printers are proving to be useful in hard-to-reach locations, such as military bases, the International Space Station, and more.*

Ivanova, Williams, & Campbell (2013) define additive manufacturing as a group of emerging and promising technologies that create an object by adding material bottom-up. AM enables rapid conversion of computer-aided design (CAD) files into physical products by merging layer upon layer of heated material. [519] It is the 'process of joining materials to make objects from three-dimensional (3D) model data, usually layer by layer, as opposed to subtractive manufacturing methodology'. As outlined by Campbell and Ivanova (2013), AM technology is a relatively simple process in contrast with traditional manufacturing, which is labour intensive, and requires more resources and complex processes such as machining, forging and moulding.

As visualised in Figure 71, the inputs of AM are raw materials, supports and utilities. On the control side, there is a CAD file which contains the geometry of the object and the parameters, which have up to 150 different variables. Parameters play a crucial role in the process as they have a strong incidence on object quality. On the mechanism side, depending on the technology type, there is the substrate which is the plate on which the object will be grown. The substrate is usually made of the same material which will be deposited and is recyclable.

3D printing is a rapidly emerging technology under the broader category of advanced manufacturing technologies. This, in turn, is part of the key enabling technologies group, which is crucial for the industrial renewal of Europe. [520] According to Statista [521], the main sectors where 3D printing is applied are industrial/machine production, aerospace,

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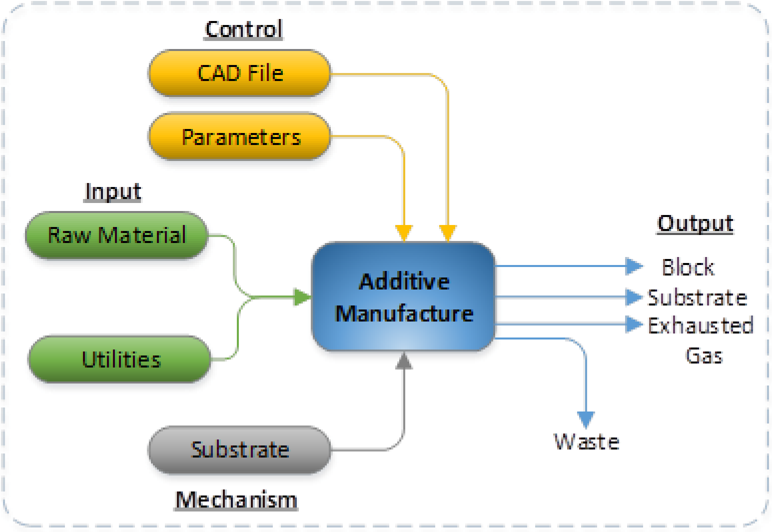
[517] WEARE Group, Presentation of the BU ADDITIVE, 2018
[518] ASTM.org, 2018, https://www.astm.org/industry/additive-manufacturing-overview.html. Accessed on May 31, 2018.
[519] Ivanova, O., Williams, C., Campbell, T., 2013. Additive manufacturing (AM) and nanotechnology: promises and challenges. Rapid Prototyping Journal 19, 353–364. doi:10.1108/RPJ-12-2011-0127
[520] EUROPEAN COMMISSION, EXECUTIVE AGENCY FOR SMALL AND MEDIUM-SIZED ENTERPRISES, IDEA Consult, AIT, VTT, CECIMO, (2016), Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing), Final Report, Brussels, July 15, 2016
[521] Statista – 3D printing market distribution worldwide in 2019 by use case, from statista.com

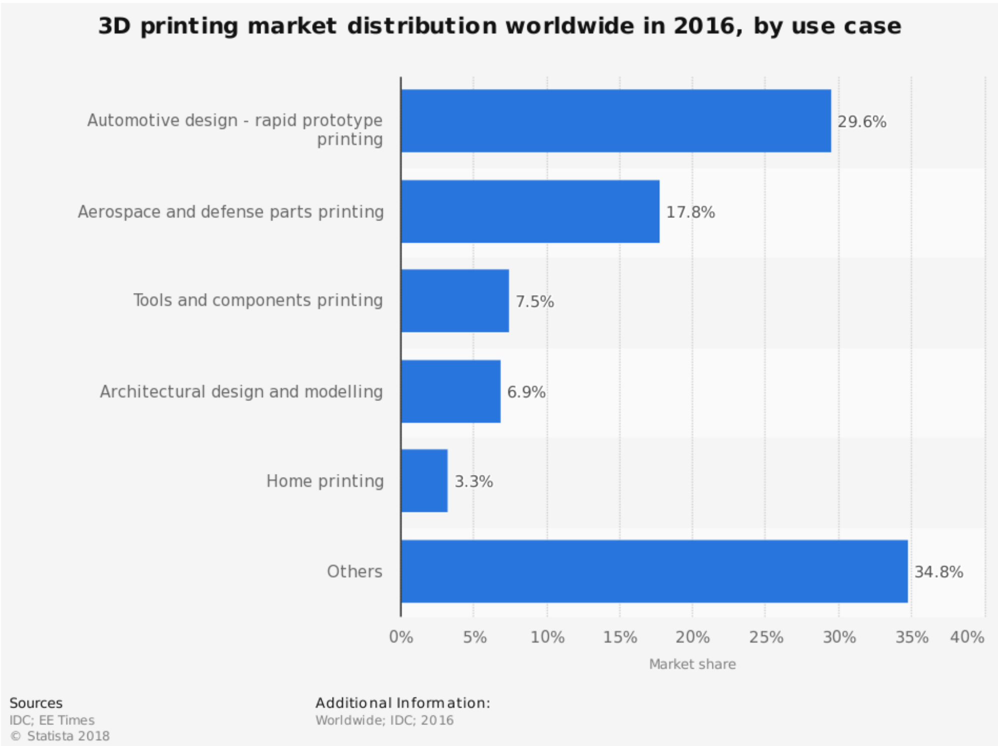
automotive, consumer products, medical and dental, prototyping in research institutes and design bureaus and other specific applications, including space and military. The 2018 shares of these sectors are displayed in Figure 72.

Figure 71 3D printing process



Source: Busachi A. et al, 2017 [522]

Figure 72 Leading sectors using 3D printing in 2016



Source: Statista, 2019 [521]

[522] A. Busachi, Modelling applications of wire + arc additive manufacturing in defence support services, Ph.D. thesis, Cranfield University, June 2017 (https://dspace.lib.cranfield.ac.uk/bitstream/handle/1826/14260/Busachi_A_2017.pdf?sequence=3&isAllowed=y)

3D printing is particularly relevant for the aerospace and defence sectors as it offers specific benefits for the production of low volume, complex and demanding components, as well as for on-demand and on-site production of spare parts in remote areas.[523] Producing new components, for example in remote military locations, can reduce the cost of stocking spare parts and the risk of time delays when supplying such components through traditional long logistics channels. Similar benefits apply, for example, to space applications, where it is difficult and costly to replace faulty components. Other domains within defence where 3D printing is useful are health (e.g. for the creation of prosthesis and preparation of medicines) and even in food (provision of food products during operations), but they are beyond the scope of this study. [524]

According to a recent EDA report: [525]

> ***The defence sector, however, is not yet exploiting the full potential offered by AM technologies****. It is expected that AM technologies could enhance defence capabilities in mobility, sustainability, effect and protection. By implementing repair and maintenance operations in the field it is possible to reduce logistic costs and execution times significantly. Repair parts can be produced on demand when and where required, such as in extreme environments, on a ship or on the frontline. This has an especially high impact in military assets where a large volume of inventory is constantly maintained to ensure operational readiness. It could also lead to improved sustainability and a reduction of both delivery times and logistical footprint, crucial for the smooth operation of warfighting and peacekeeping missions. However, there are still technical challenges that need to be identified to fully achieve AM capabilities, such as the qualification of parts produced in this manner to ensure they will not fail in service.*

3D printing is maturing fast, and is now the object of several standardisation processes, at national and international level. [526] The wide range of applications at various levels of maturity is well illustrated in the 'hype cycle' for 3D-printing.[527] The latest version in Figure 73 illustrates the high diversity of applications (40 possible applications are shown), along with their degree of maturity and acceptance (including innovation trigger, peaks of inflated expectations, disillusionment, enlightenment and finally productivity), as well as an expected timeframe (indicated by dot colour).

Emerging and future areas are linked to a wide variety of applications, for example surgical, for hard tissues in the human body, plastic-based components in all types of consumer goods – notably in the automotive sectors for lightweight purposes, metallic structures for aeroplanes like large wing and fuselage components, the printing of biodegradable materials for drugs and so-called bio-printing, producing spare parts for machines for maintenance and repair, 3D printing of textiles, construction materials for affordable houses and military bases, and even food.

[523] European Commission, Executive Agency For Small And Medium-Sized Enterprises, IDEA Consult, AIT, VTT, CECIMO, (2016), Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing), Final Report, Brussels, July 15, 2016
[524] CEIS, Impression 3D - Des technologies de rupture au service des Armées. Note stratégique, 2016.
[525] European Defence Agency, Additive Manufacturing Feasibility Study & Technology Demonstration, EDA AM State of the art & Strategic report, June 2018
[526] CEIS, Impression 3D - Des technologies de rupture au service des Armées. Note stratégique, 2016.
[527] Gartner: Market Guide for 3D Printer Manufacturers, Published: 11 December 2017 ID: G00319094, https://www.gartner.com/doc/3759564/hype-cycle-d-printing-

Figure 73 Hype cycle for 3D printing as of July 2018

Source: Gartner, 2019 [527]

Table 22 Process types for 3D printing

Process Type	Technique Definition	Example Technology	Material
Vat Photopolymerisation	Liquid photopolymer in a vat is selectively cured by light-activated polymerisation.	Stereo lithography (SLA), digital light processing (DLP)	Polymers and ceramics
Material Jetting	Droplets of build material are selectively deposited.	3D inkjet printing	Polymers and composites
Binder Jetting	Liquid bonding agent is selectively deposited to join powder materials.	3D inkjet printing	Metals, polymers, and ceramics
Material Extrusion	Material is selectively dispensed through a nozzle or orifice.	Fused deposition modelling (FDM)	Polymers
Powder Bed Fusion	Thermal energy selectively fuses regions of a powder bed.	Selective laser sintering (SLS), Selective laser melting (SLM), electron beam melting (EBM)	Metal, polymer, composites and ceramics
Sheet Lamination	A process in which sheets of material are bonded to form an object.	Ultrasonic Consolidation (UC)	Hybrids, metals and ceramics
Directed Energy Deposition	A process that focused thermal energy and fuses materials by melting as the material is being deposited.	Laser metal deposition (LMD)	Metals and hybrid metals

Source: 3D-printing, Final Report [520]

The various process type for 3D printing are highlighted above in Table 22. A more general categorisation of AM processes, which includes polymers, ceramics and metals in powder, liquid and solid materials, is provided in Table 23.

Table 23 Additive manufacturing process categorisation

Additive Manufacturing (AM) Processes														
Process	Laser Based AM Processes: Laser Melting				Laser Based AM Processes: Laser Polymerization		Extrusion Thermal		Material Jetting		Material Adhesion		Electron Beam	
Process Schematic	Laser source; Powder bed		Laser source; Powder supply		Laser source; Liquid resin		Material melt in nozzle		Material jetting		Laser cutting; Compactor		Electron beam; Powder bed	
Name / Material	SLS		DMD		SLA		FDM		3DP		LOM		EBM	
	SLM		LENS		SGC		Robocasting		IJP		SFP			
	DMLS		SLC		LTP				MJM					
			LPD		BIS				BPM					
					HIS				Thermojet					
Bulk Material Type			Powder		Liquid		Solid							

Source: Bikas H. et al [528]

For metal-based 3D printing, there are two main systems: 1) deposition of the layers in powder beds with SLM and EBM technologies; and 2) nozzle systems including micro droplet deposition and direct metal printing. [529] For the purpose of this dual-use analysis, a reduction in scope is needed in order to place meaningful focus on the most relevant military applications and their civil counterparts.

Wire+Arc Additive Manufacturing (WAAM/DED)

According to Ding et al., (2011) [530], wire and arc additive manufacturing (WAAM) (clustered in this report under DED, which also covers powder directed energy deposition processes like LENS and LMD) is gaining industry attractiveness **for the production of large, custom made, near-net-shape metal components** due to its versatility and high deposition rates. WAAM is an additive manufacturing process which uses tungsten inert gas welding (TIG), metal inert gas welding (MIG) or plasma torches to manufacture components by adding sequential layers of material from a wire feedstock without the need of tooling. The system comprises a power source which is the welding machine, a motion control system which is the robot, the torch for controlling the arc, a wire feeder and a chamber (Figure 74). WAAM has several advantages, such as the ability to process super alloys and create large parts, high deposition rates and a reduction of residual stress due to the on-line rolling process. The implementation of the WAAM process could save significant amounts of material.

[528] H. Bikas, P. Stavropoulos, G. Chryssolouris, Additive manufacturing methods and modelling approaches: a critical review Int J Adv Manuf Technol (2016) 83:389–405, DOI 10.1007/s00170-015-7576-2
[529] BIONIC project: Neue hochfeste Aluminiumlegierungen und bionisches Design für den SLM-Prozess, Symposium "Ressourceneffiziente Herstellung von Funktionsbauteilen aus Technologiemetallen, Pforzheim
[530] J. Ding, F. Martina, S.W. Williams, Production of large metallic components by additive manufacture – issues and achievements, Conference "Metallic Materials and processes: industrial challenges", Nov. 2015

Figure 74 Example of WAAM process

Source: WAAMMat Programme of Cranfield University [531]

Martina et al., (2012) [532] carried out an investigation of the benefits of the WAAM process based on plasma deposition for the manufacturing of Ti6Al4V components (see Table 25) for the aerospace industry. They demonstrated the feasibility of the process for large, structural aerospace components and defined a process envelope outlining the correct combination of process parameters. Nevertheless Martina et al., (2012) explained that oxidation and distortion could become an issue. Cranfield's Welding Engineering and Laser Processing Centre has developed a new process called rolled WAAM, which is based on the WAAM process but with the addition of a roller tool which performs on-line deformation to decrease the residual stress of the component. Colegrove et al., (2013)[533] outlined that components processed with WAAM have strong distortion, residual stress and large grain size. This is mainly due to the high heat input of the arc. There is a need to develop mitigation methods to increase the quality of the components. After performing experiments, Colegrove et al., (2013) concluded that the rolling process can significantly reduce the peak of residual stress and the distortion of the material. Moreover, 'slotted' rollers limit the lateral deformation of the sample with a better reduction in residual stress and distortion compared to the 'profiled' roller. Another important conclusion which has a significant impact in terms of lead time is that rolling every four layers produces a similar result to rolling every layer. Rolling has a significant impact on the microstructure of the samples. Colegrove et al., (2013) state that rolling enhances the grain refinement. Adebayo et al., (2013) [534] studied the implication of solid lubricant application during the process. They concluded that even after cleaning the surface with acetone, traces of lubricant are still present, affecting the microstructure and hardness of the deposited material. More precisely, the presence of lubricant increases the grain size and consequently reduces the hardness of the material. There is a need to identify the correct procedure and lubricant for applications such as rolling and machining of WAAM-deposited material.

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[531] BCG Additive Manufacturing 2018

[532] F. Martina, J. Mehnen, S. W. Williams, P. Colegrove, F. Wang, Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti-6Al-4V, · Journal of Materials Processing Technology 212(6):1377–1386, June 2012

[533] P. Colegrove et al., Microstructure and residual stress improvement in wire and arc additively manufactured parts through high-pressure rolling, Journal of Materials Processing Technology 213(10):1782-1791, October 2013

[534] A. Adebayo, J. Mehnen, X. Tonnellier, Effects of solid lubricants on wire and arc additive manufactured structures, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Volume: 228 issue: 4, page(s): 563-571, September 2013

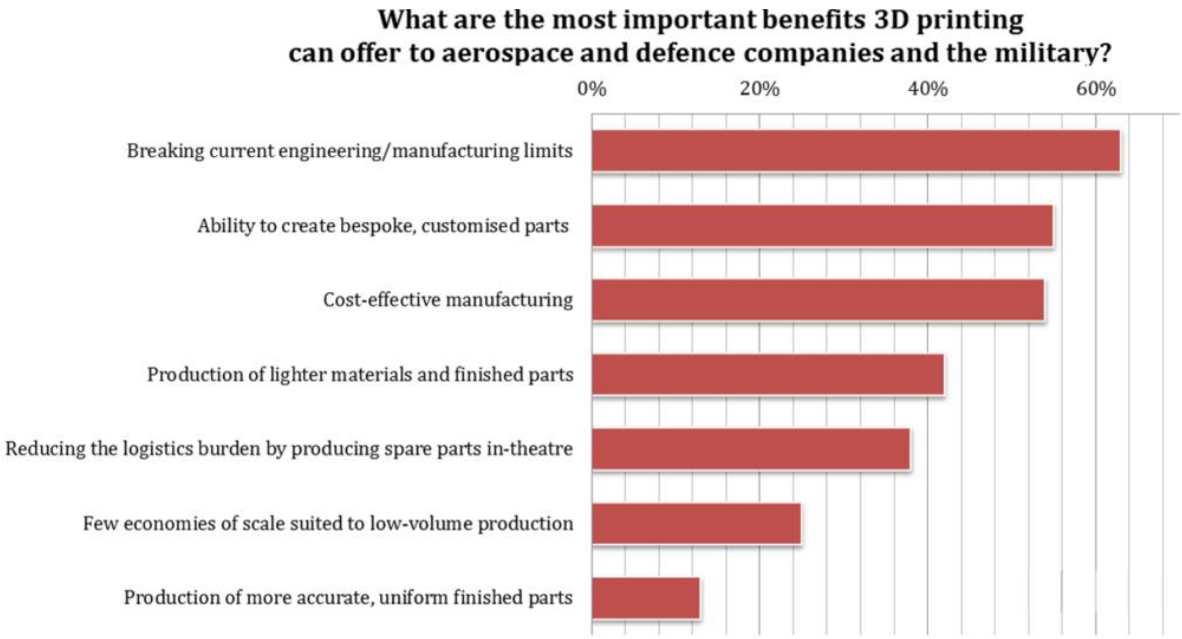
6.2 AM (3D printing) technology development stage

The key characteristics of AM operations are based on manufacturing system engineering, 'lean manufacturing' principles and 'lean product and process development', and are possible due to the delocalisation of AM production next to the point of use and through the involvement of the end-user.

- For aerospace in particular, **AM is an enabler of design freedom** and thus for the production of strong yet lightweight components and complex parts; it can print many types of geometries rapidly, without the need to set up the machine or change tools for relatively small numbers of components. It can also overcome existing engineering limitations and reduce the number of connections. This aspect fits very well where AM is deployed in a platform to serve various complex engineering systems made of an extended number of components which all differ in terms of geometry.
- **AM is an enabler of 'just-in-time' (JIT)**: considering the delocalisation of manufacturing within the platform, the logistic delay time is eliminated or dramatically reduced, in addition to the short production time itself. This combination allows the establishment of JIT principles, meaning stocks of finished goods can be reduced and components produced only when required. A single AM machine can manufacture all types of components when these fail.
- **AM is an enabler of continuous improvement in the workplace**: operators build up direct experience as they carry out their daily activities (with standard tools, jigs, equipment and kits) and can develop and generate new ideas to improve the process. If a platform has manufacturing capability based on AM, they can convert ideas into functional products. For aerospace in particular, many existing components can be redesigned with improved properties and fewer materials, enabling continuous weight reduction as parts are replaced.
- **AM is an enabler of improved product development**. Through daily use, end users can develop and generate ideas to improve their daily routine. Manufacturing is delocalised and takes place at the point of use, with the involvement of the end user (who has direct experience) in product development: these conditions are ideal for continuous improvement, as is the ability to carry out rapid prototyping to test designs at an early stage.
- **AM is an enabler of mass customisation**, allowing for the production of highly tailored products to meet the needs of individual end users. This aspect is fundamental when special tools are required to perform a medical operation, when prosthetics need to be tailored to the unique features of a human body or when providing special tools/small arms/body armour for soldiers.

The most important benefits of 3DP, according to a survey of specialists [535], are listed in Figure 75.

Figure 75 Main benefits of 3DP



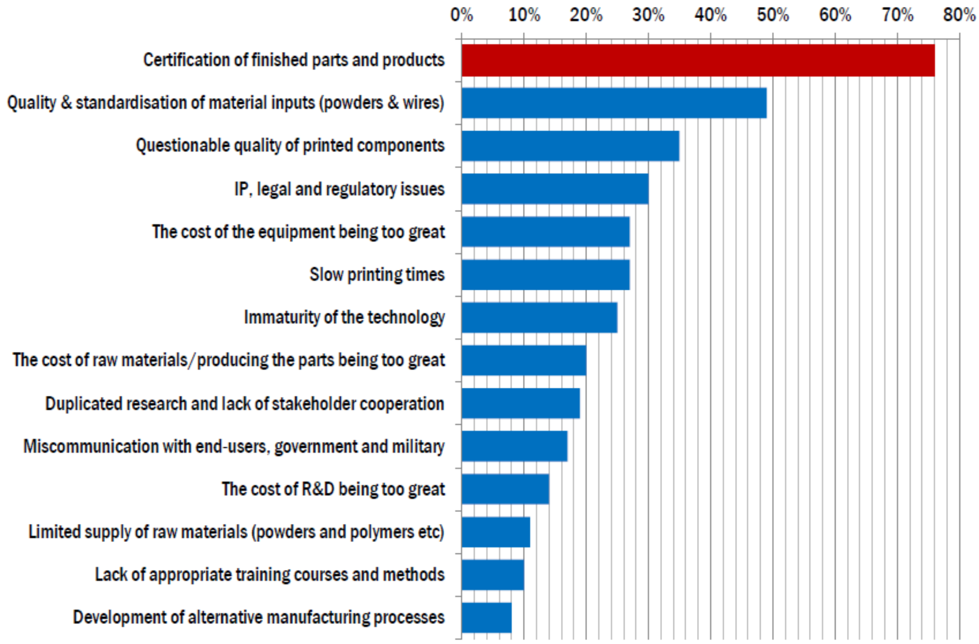
Source: Objectify

Despite the advantages shown above, DefenceIQ [536] also identified the following challenges (Figure 76).

- **Quality constraints**: aerospace restrictions for certification and quality control may affect the notion of continuous improvement. Reducing safety-related legislative barriers is not an option for aerospace. Hence, 3DP as a technology needs to become more mature in terms of parts quality and reproducibility. In fact, demand for high quality from the sector motivates and drives companies to improve and become more competitive in the long term. Certification and quality assurance is a key threshold. The option most preferred by respondents to the DefenceIQ survey was to have this arranged by European or international bodies like ESA, EDA and ISO/ASTM. The aerospace industry would prefer a stable and international standardisation process. At the moment, different standards are observed in the USA, covering various tasks and aspects, for instance in plastics 3DP.
- **Just-in-time and fast manufacturing** is another challenge: the high cost of equipment and raw materials along with **slow printing times and the limited size of powder beds** are a concern, but also an area where rapid improvements are observed.
- Another area for improvement is the **quality and finishing of parts**. There is a specific need for (standards for) non-destructive testing (NDT) and other certifications dedicated to metal AM-produced parts.

[535] http://www.objectify.co.in/additive-manufacturing-and-aerospace/
[536] DefenceIQ, Additive Manufacturing in Aerospace, Defence & Space, Trends and Analysis 2016

Figure 76 Challenges for the deployment of AM



Source: DefenceIQ

Final scope

The state of play in 3DP technology is explored in three important domains: aerospace, spare parts and automotive.

3D printing is relatively mature in aerospace when it comes to non-structural components. Typical applications include aircraft interior components, stator rings, fuel injectors, turbine blades and structural parts for unmanned aircraft (drones). The technology is rather less mature when it comes to large, structural, metallic components such as wings, fuselage parts and brackets. According to the EASME report [537], the value chain is very concentrated around the key original equipment manufacturers (OEMs): Airbus and Boeing in particular. Equipment providers are mainly located in France, Germany, Italy and the United Kingdom. American companies are also active in Europe via their branches or first tier suppliers.

According to EASME, [520] the main automotive applications are jigs and assembly tools (steel-based), prototyping (polymer-based), personalising car interiors and exteriors (non-structural polymer-based materials), drivetrain components (metals) and chassis parts (composites, CFRP). The use of 3D printing in this sector goes back to 1988, in particular for rapid prototyping purposes and later for tooling.

Compared to the aerospace applications above, the 3D printing of spare parts for the military, production machinery and aerospace production machinery seems less developed and more scattered in terms of the types of product covered. For this study it should be noted that no reference framework exists to classify the variety of applications.

For the purpose of this dual-use analysis, a reduction in scope is required in order to focus on the most relevant military applications and their civil counterparts. Technologies involving the consumption of metals have therefore been selected: binder jetting/nozzle

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[537] European Commission, Executive Agency For Small And Medium-Sized Enterprises, IDEA Consult, AIT, VTT, CECIMO, (2016), Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing), Final Report, Brussels, July 15, 2016

systems (3DP and droplet deposition), powder bed fusion (SLM, EBM, SLS) and cladding technologies (LBM, EBM (powder)/WAAM (wire and arc additive manufacturing)). This leaves us with the following applications.

- Aerospace: 3D printing of structural and non-structural parts for civilian and military aircraft. Structural components for civil purposes are just emerging, but the other applications are already more evolved.
- Machinery: spare parts for machines, and engines produced by mobile factories/3D printers (in development)
- Automotive: 3D-printed parts for motors and other lightweight applications, for prototyping and for racing cars.
- Space: 3D-printed parts for satellites and space stations as well as 3D printers for use in space stations
- Affordable housing (civil) and temporary military housing

A decision was made to reduce the focus even further, to the first group of **metal-based 3D-printing (all technologies) for aerospace applications**. This sector has military and civil sides, extremely rapid innovation and complex safety, security and endurance requirements. Finally, while some of the sector is mature, other parts are less mature, covering almost all metal-based technologies and metal alloy types. Some available information on space applications is included, e.g. spare parts for satellites and space stations. Machinery, automotive and temporary military housing are excluded from the scope of this study.

6.3 Materials used in additive manufacturing (3D printing)

3D printing is a special case in the context of materials for dual use, compared with the other technologies in this study. The manufacture of the technology itself consumes materials, but of far more impact is the relatively high consumption of metals used by the technology for the production of parts. On the other hand, due to rapid developments, there is significant potential for reduction, substitution and mitigation to address the use of critical raw materials (CRMs). A distinction therefore needs to be made between three categories:

1. The consumption of specific materials, including electronics, in the 3D printer devices themselves.
2. The consumption of specific critical raw materials during 3D printing; generally more significant than the use of raw materials in the machinery itself.
3. 3D printing as a mitigation strategy via three routes: i) by using scraps (for instance, from dual-use applications) where the necessary raw materials are not available; ii) by substituting parts based on critical raw materials with other types of material such as composites, while still achieving the desired technical specifications; and iii) by avoiding more wasteful conventional milling and drilling approaches, thereby reducing the amount of expensive material used.

Key materials commonly consumed in 3D metal-based printing are aluminium-magnesium, titanium, nickel, stainless steel and their alloys. Aerospace-specific alloys also contain very particular materials such as cobalt and scandium. Aluminium and titanium are not considered critical in the 2017 critical raw materials list. However, for 3D printing, the supply risk for aluminium and particularly titanium (alloy) powder supply is high, and relevant for defence. To some extent, the supply risk for alloy powders also applies to magnesium, which is considered a critical raw material. Scandium is a critical raw material in the 2017 list (not in 2014 and grouped under REEs in 2011). For aircraft parts, $AlSi_{10}Mg$ is used. [517] Other main metals are $AlSiMg_7$, TAV6 ($TiAl_6V_4$), Stainless 316L (FeCrNi based) and Inconel 718 & 625 (CrNiNb based).

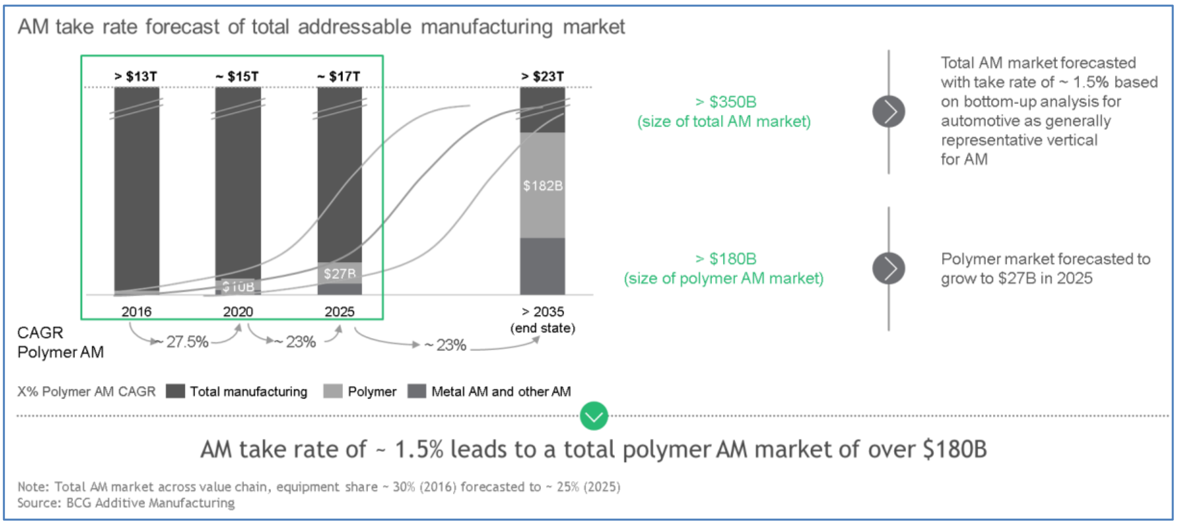
The use of the scarce metal, scandium, is particularly interesting: the use of about 0.5 wt% improves the properties of the material significantly. [538] Al-Sc alloys represent a new generation of high-performance alloys with superior properties over all other Al alloys. Small amounts of Sc (<0.5 wt%) improve the metal's properties, enhancing strength, corrosion resistance, grain size and recrystallisation resistance. Al-Sc alloys generate high performance products, currently used in sporting equipment and the aerospace industry. For instance, an Al-Sc bicycle frame showed a 12 % reduction in weight, a 50 % increase in yield strength, and a 24 % improvement in fatigue life over the best-selling aluminium bicycle frames. The addition of scandium to aluminium limits the excessive grain growth that occurs in the heat-affected zone of welded aluminium components, reduces hot cracking during welding and provides the highest increment of strengthening per atomic percent of any alloying element when added to aluminium.

In general, according to EASME [520], the ability to transform high-end materials into powders is missing in Europe. Whether this is still the case will be investigated in the next chapter.

6.4 Trends in additive manufacturing (3D printing)

The global market for 3D printing, which includes the consumer sector, is projected to grow substantially. Statista projects the value at USD 19 billion in 2019, growing to USD 23 billion in 2022. [521] Similar values, including the share of polymer versus metal AM, are estimated by BCG. It projects the following trends for both polymer- and metal-based additive manufacturing processes, taking a significant part of the total global manufacturing base towards 2035. The BCG analysis indicates a > USD 350 billion AM market by 2035, as illustrated in Figure 77, with a very significant compound annual growth rate (CAGR) of 23 % to 27 %.

Figure 77 Projected 3D printing market



Source: BCG Additive Manufacturing, 2018 [539]

The growth per technology in metal AM is displayed below in Figure 78, with powder bed fusion (PBF) processes having the largest share of the total metal technology capabilities for the coming years.

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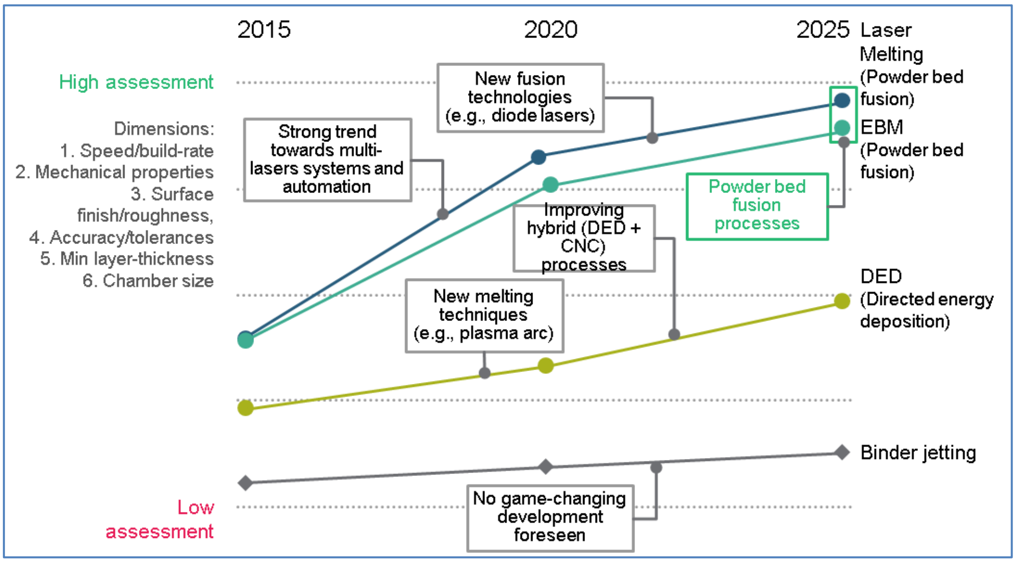
538 SCALE project: http://scale-project.eu/. Last accessed on May 31, 2018
539 BCG Additive Manufacturing, 2018

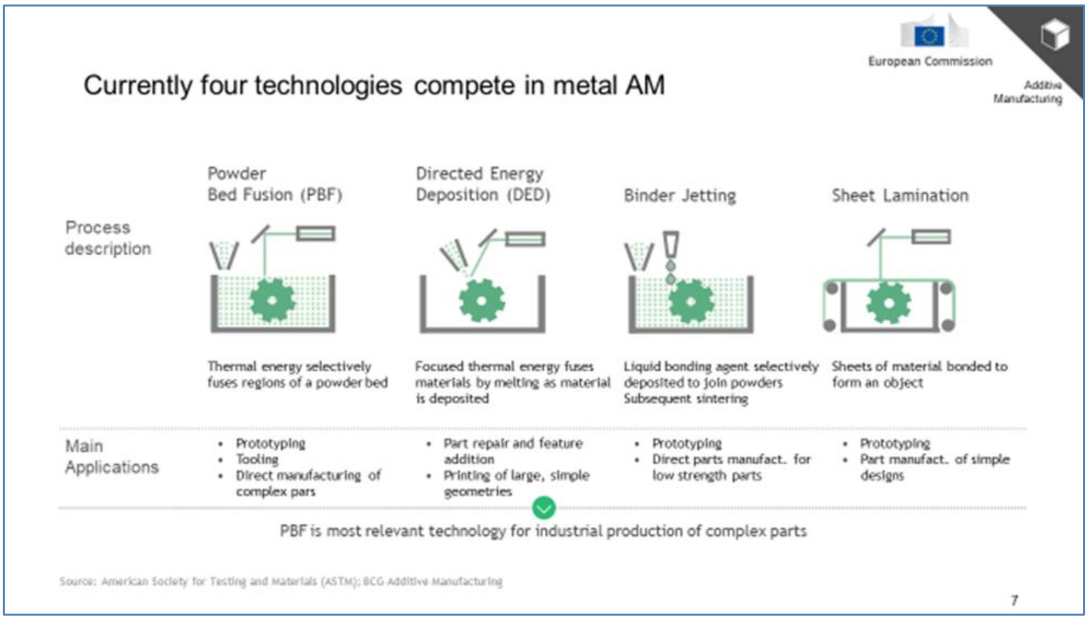
Figure 78 Metal technology capabilities for industrial parts production based on BCG's aggregated technology assessment and outlook



Source: BCG Additive Manufacturing, 2018 [540]

As a consequence, the main competing technologies for the future are PBF and DED. The main applications are illustrated in Figure 79.

Figure 79 Main competing technologies in metal 3D printing



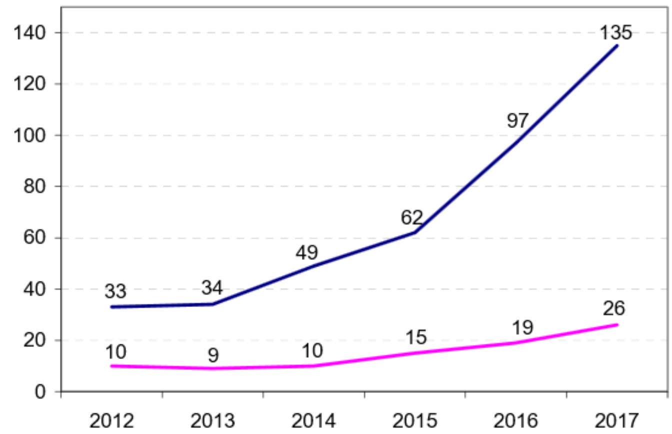
Source: BCG Additive Manufacturing, 2018 [541]

According to Wohlers, [542] the rapid growth in AM systems has accelerated in recent years. Expected growth in global shipments of all industrial 3D printers is growing yet

[540] BCG Additive Manufacturing, 2018
[541] BCG Additive Manufacturing, 2018
[542] Wohlers Report 2018, 3D Printing and Additive Manufacturing State of the Industry, Annual Worldwide Progress Report, Wohlers Associates, Inc., 2018

more rapidly, as illustrated in Figure 80. This growth is primarily based on increased civil uptake, potentially lowering the relative significance of military use in the near future. The blue line below represents the number of producers of 3D printing systems, and the purple line the number of producers who have shipped more than 100 units. A list of metal-based AM systems is provided further. There were 62 providers at the last count in 2018.

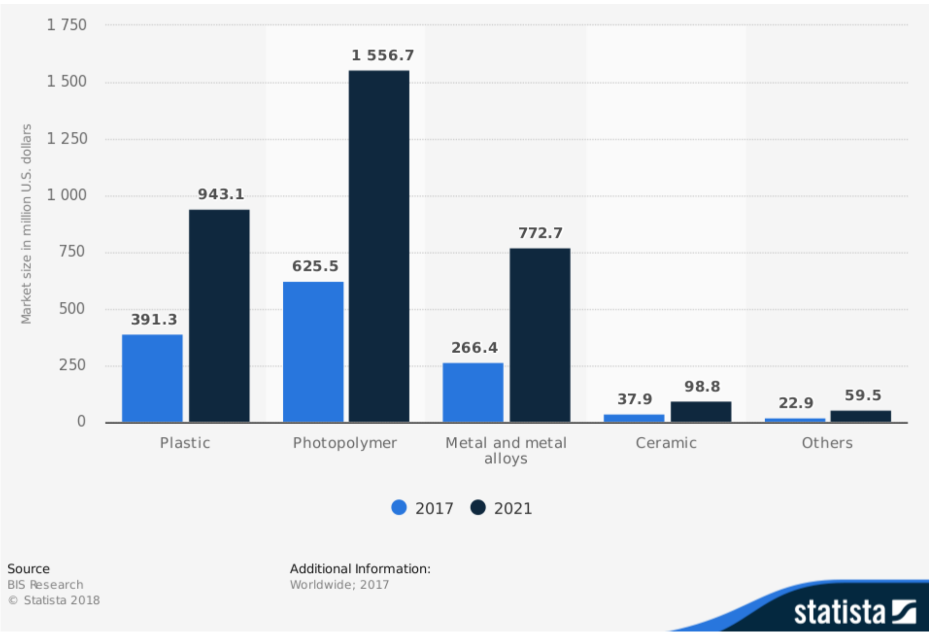
Figure 80 Number of industrial 3D printer producers (>100 units), 2012-2017



Source: Wohlers Report 2018

Statista provides the total revenue projection in 2018 (Figure 81). It shows the market size of the global 3D printing services market in 2017 and 2021 by material type. Plastic 3D printing enjoyed the largest share in 2017 with market revenue of about USD 391.3 million worldwide. Metal-based printing was estimated at USD 266 million and growing, roughly tripling by 2021. [543]

Figure 81 Projected revenue from 3DP services in 2017 and 2021 by material type



Source: Statista

[543] Statista – Additive Manufacturing 2019, study 21960 from statista.com

Looking forward, according to BCG, the main expected trends in technology development are:

- **electron beam (EBM) and laser melting (SLM) systems** which are currently the most dominant, operating at similar technical performance levels and with various advantages for industrial part production;
- **laser melting,** undergoing strong efforts from established and new players (e.g., Additive Industries) to **develop it towards automation**;
- **binder jetting processes** for metal powder, likely to improve continuously but still facing drawbacks regarding part strength relative to PBF processes;
- **DED, established and well known** from coating, limited to simple geometries but staying relevant for specific application (e.g., repair);
- **new variations of DED** (e.g., based on plasma arc melting alloy wire), allowing for high production speed and large parts;
- **hybrid processes**, e.g. combinations of DED and conventional CNC, facing challenges in accuracy (thermal warpage) and process stability;
- potential **new processes** (e.g. particle-jetting or filament-based methods), not expected to be game-changing in the short/medium term.

According to the AM-Motion project, there is a **new development in the form of 4D Printing**. This is a means of incorporating, for instance, internet of things functionalities, by combining 3D printing with a fourth dimension: **the change of functionalities over time, like shape-changing, self-assembly, multi-functionality, self-repair and sensoring capabilities.** [544]

6.5 Materials supply chain in additive manufacturing (3D printing)

The challenges in the 3D printing supply chain are mainly derived from the EASME report[545]. This report comprehensively describes the strengths and weaknesses in existing value chains, and the development and deployment of technologies, primarily from a capabilities point of view. Its main orientation is technological, with more focus on the final stages of the supply chains. This report, however, places more focus on the earlier stages of the supply chain from a materials perspective, and on trade and security issues related to sustainable supply for dual use. Although polymers (CFRP) and specific, ceramic-based 3D printing applications are seen as having potential for aerospace, the scope here is restricted to the metal-based, 3D-printing parts of the aerospace value chain, including stainless steels, nickel, aluminium, titanium and various super-alloys.

6.5.1 Main steps of the additive manufacturing (3D printing) supply chain

A description of this value chain is complicated by the fact that it does not just involve the materials processed during 3D printing, but also the development and availability of the 3D printing machinery and its components in the first place. The two separate strands of materials and 3D printing equipment have rather different supply chains, with specific characteristics for both military and civil applications. At the same time, some

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[544] AM-Motion - A strategic approach to increasing Europe's value proposition for Additive Manufacturing technologies and capabilities, Edited by M. Cioffi, M. Garrone, P. Queipo, 2018

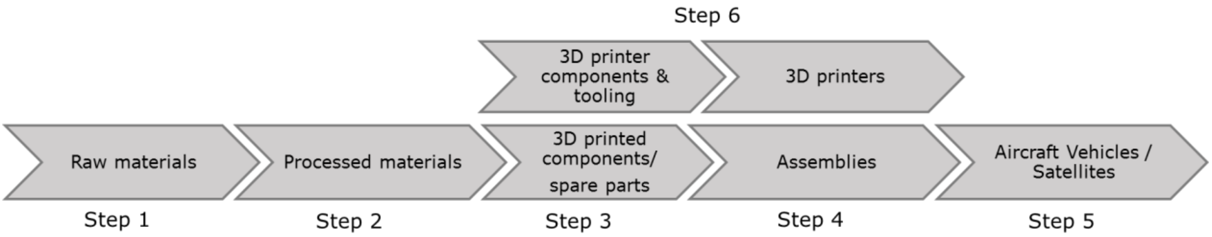
[545] EUROPEAN COMMISSION, EXECUTIVE AGENCY FOR SMALL AND MEDIUM-SIZED ENTERPRISES, IDEA Consult, AIT, VTT, CECIMO, (2016), Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing), Final Report, Brussels, July 15, 2016

vertical integration can be noted, with specific 3D printing equipment companies providing, and sometimes even producing, their own (specific) powders. Additionally, there is complementarity and overlap with the section on robotics, as well as some specific components also used in batteries, fuel cells and unmanned aerial vehicles. Moreover, 3D printing is a potential mitigation strategy in those cases where original components are not available, or when maintenance, repair and operations/overhaul (MRO) requires a very short lead time and local production. Figure 82 shows the main steps in the supply chain for metal 3D-printed aerospace parts.

Since there are many reports and market studies already available regarding the latter stages of the supply chain, the main focus of the analysis which follows is the supply of raw materials (Step 1) and processed materials (Step 2). This is followed by a more compact and qualitative description of 3D-printed components and assemblies (Steps 3 and 4). The role of the current system integrators is described qualitatively for Step 5.

Another consideration in the case of metal-based 3D printing is the rapid pace of technological development. As a new, key enabling technology undergoing rapid evolution, it is difficult to provide quantitative numbers on market shares and the volumes at stake. The quantitative approach therefore focusses more on the geographical locations of the supply chain stages rather than the tonnages produced, or the economic market shares. Here, one crucial extra step is considered in the supply chain diagram, covering 3D printer components and the 3D printers themselves (Step 6).

Figure 82 Supply chain steps for 3D printing technology (aerospace applications)



Source: JRC

The supply chain at the bottom of Figure 82 is divided into five steps, ranging from mining and processing of raw materials to the actual 3D printing of components, which are used in larger assemblies and final applied in end products or systems like aircraft, spacecraft and satellites – the main focus of the analysis. Other dual-use applications include vehicles and tooling for production lines, which are not the main focus. At the top of Figure 82, 3D printer components and systems are highlighted separately, since they play a key role in manufacturing processes. Their development and geographical distribution are discussed in Step 6.

Step 1: Raw materials

The main material families relevant for 3D printing, and used in considerable amounts, are **aluminium, titanium, iron and nickel-based** alloys. Aluminium and titanium are not considered critical in the new critical raw materials list of 2017. [546] However, for 3D printing, the supply risk for aluminium and titanium (alloy) powder is deemed particularly high in the EASME report [547], which will be reviewed in more detail below.

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[546] Study on the review of the list of Critical Raw Materials - Critical Raw Materials Factsheets, Deloitte Sustainability, British Geological Survey, Bureau de Recherches Géologiques et Minières, Netherlands Organisation for Applied Scientific Research, June 2017
[547] EUROPEAN COMMISSION, EXECUTIVE AGENCY FOR SMALL AND MEDIUM-SIZED ENTERPRISES, IDEA Consult, AIT, VTT, CECIMO, (2016), Identifying current and future application areas, existing

According to Japanese suppliers, the demand for titanium and nickel-based powders is expected to rise sharply to about 3 000 tonnes in 2026.[548] Moreover, many additional alloying elements like magnesium, cobalt, vanadium and tungsten are on the criticality list. In addition, chromium, copper, manganese and silicon enhance a wide range of properties, and in smaller quantities, scandium, niobium and hafnium/zirconium are also relevant as alloying elements for very specific applications. Except for scandium, hafnium and niobium, these elements have already been discussed and quantified in the sections on robotics and batteries.

Scandium is rather abundant in the earth's crust, but widely dispersed. Metallic scandium was produced for the first time in 1937, the first pound of 99 % pure scandium metal was produced in 1960, and production of aluminium alloys did not begin until 1971. According to the SCALE project and USGS [549], global scandium production is only about 10-15 tonnes but increasing:

> *The principal uses for scandium in 2017 is in aluminium-scandium alloys and solid oxide fuel cells (SOFCs). Other uses for scandium included ceramics, electronics, lasers, lighting, and radioactive isotopes. In SOFCs, electricity is generated directly from oxidizing a fuel. Scandium is added to a zirconia-base electrolyte to improve the power density and lower the reaction temperature of the cell. For metal applications, scandium metal is typically produced by reducing scandium fluoride with calcium metal. Aluminium-scandium alloys are produced for sporting goods, aerospace, and other high-performance applications. Scandium is used in small quantities in a number of electronic applications. Some lasers that contain scandium are used in defence applications and in dental treatments. In lighting, scandium iodide is used in mercury-vapour high-intensity lights to simulate natural light.* [550]

According to this SCALE project, there are very few specific scandium ore deposits; it is produced almost entirely from by-products from tailings and residues such as bauxite processing. According to USGS, there are scandium resources identified in Australia, Canada, China, Kazakhstan, Madagascar, Norway, the Philippines, Russia, Ukraine, and the USA. [551] Some of these are being actively explored and contain potentially significant reserves compared with current mining output, such as in Australia. [552]

Hafnium/ zirconium

According to the Hafnium fact sheet in the 2017 criticality assessment:

> *The major application for hafnium is as an alloy addition in polycrystalline nickel-based super alloys; for example, MAR-M 247 alloy contains 1.5 % hafnium. These alloys are used in the aerospace industry both in turbine blades and vanes as well as in industrial gas turbines. The super-alloy industry requires the purest form of hafnium, crystal bars, with low zirconium content. Demand and supply for this form of hafnium approximately equal, making the sector volatile.* [553]

The alloys are also found in some of the 3D metal powder data sheets, as well as in case studies of 3D-printed components, quoted below. Hafnium and zirconium are therefore

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industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing), Final Report, Brussels, July 15, 2016

[548] Y. Sugizaki, Outlook on current titanium trends in Japan, Titanium USA 2018 conference, https://titanium.org/page/TiUSA18Proceedings,

[549] USGS 2018, Scandium fact sheet

[550] SCALE project: http://scale-project.eu/scandium

[551] USGS Minerals information 2018 – Scandium

[552] http://www.scandiummining.com/s/nyngan.asp

[553] Study on the review of the list of Critical Raw Materials - Critical Raw Materials Factsheets, Deloitte Sustainability
British Geological Survey, Bureau de Recherches Géologiques et Minières, Netherlands Organisation for Applied Scientific Research, June 2017

included in the list of relevant materials. Another non-3D-printed military application is in nuclear control rods in reactors and submarines.

Niobium

According to the criticality assessment of 2017, about 86 % of niobium (in the form of ferroniobium) is used in the production of high-strength low-alloy (HSLA) steels. Niobium increases strength by refining the microstructure and by forming nano-particles; these strength increases enable significant weight savings in the final product. Niobium-bearing alloys account for about 8 % of global niobium consumption. These alloys, including 718 stainless steel, contain significant quantities of niobium and are typically used in high-performance, specialised applications where traits such as corrosion resistance and high strength at high operating temperatures are sought. For example, alloys such as C-129Y (79 % niobium; 10 % tungsten; 10 % hafnium and 0.1 % yttrium) and C-3009 (61 % niobium; 30 % hafnium and 9 % tungsten) can operate at temperatures of up to 1 650 °C. These alloys are used in the nuclear industry (e.g. reactor parts) and space industry (e.g. rocket thruster nozzles). Other alloys of niobium include niobium-titanium and niobium-tin, which are used to manufacture the superconducting magnets found in magnetic resonance imaging (MRI) scanners. [554] In the analysis in the next section, C-129, C-3009 and a few TiNb alloys are identified as being relevant to specialised 3D-printing applications. Due to the very concentrated supply from Brazil, these raw materials are included in the analysis. See Annex 2, Table 32 for more information on the main raw material-producing countries.

Step 2: Processed materials

The most common alloys used for 3D metal-printing are aluminium, titanium, stainless steel and nickel-based. According to EASME [555], the capacity to transform high-end materials into powders is missing in Europe. This situation will be revisited here, specifically with regard to the four main alloy families relevant to 3D printing.

The Titanium family of **alloys**, TiAl6V4 (grade 5 and 23 (ELI)) and Ti-CP (commercially pure, grade 2), used in structural and non-structural components are most frequently mentioned by producers, as well as some **titanium-niobium alloys** (high temperature engine parts). [556] It should be noted that commercial aircraft already make an increasing and significant use of titanium, from about 8 % for the Boeing 777, to 15 % for the Boeing 787, and more recently the Airbus A350. Most of this is in the form of forgings for landing gears. According to Boeing:

> *For graphite-reinforced composite airframe structures, the natural compatibility of titanium has led to an increase in the fraction of titanium alloys on the airframe, but with concordant increases in build costs. Titanium is galvanically compatible with the graphite in the graphite-reinforced composite, and the coefficient of thermal expansion of titanium is closer to graphite than that of aluminium or steel. This has led to an evolution in the needs of the airframe industry with respect to titanium alloy properties and utilization.* [557]

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[554] Study on the review of the list of Critical Raw Materials - Critical Raw Materials Factsheets, Deloitte Sustainability, British Geological Survey, Bureau de Recherches Géologiques et Minières, Netherlands Organisation for Applied Scientific Research, June 2017

[555] EUROPEAN COMMISSION, EXECUTIVE AGENCY FOR SMALL AND MEDIUM-SIZED ENTERPRISES, IDEA Consult, AIT, VTT, CECIMO, (2016), Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing), Final Report, Brussels, July 15, 2016

[556] EPMA, Introduction to Additive Manufacturing Technology, a guide for designers and engineers, 2nd edition, 2018 from https://www.epma.com/epma-free-publications

[557] J.D. Cotton, R.D. Boyer, G.R. Weber and K.T. Slattery, Titanium Alloy Development Needs for Commercial Airframes, Pre-Print of Proc. Ti-2008 in the CIS Conf., TITAN Assoc., St. Petersburg, Russia, 19 May 2008

Titanium can also be used for anti-ballistic properties instead of rolled steel armour. Although more expensive, its light weight and high corrosion resistance provides improved properties in fuel efficiency, mobility and manoeuvrability [558], which are of high value for defence applications.

Aluminium-magnesium alloys (alloy series 6xxx) are commonly used for aircraft parts $AlSi_{10}Mg$ and AlSi7Mg0.6 and mentioned in many case studies and applications.

Nickel alloys, in particular alloys 316L and 625, are commonly offered as 3D-printing powders and applied in engine parts.

Stainless steels, more specifically alloy types 718 (CrNiNb based), 15-5PH and 17-4PH are used in various aerospace applications and frequently mentioned in the various 3D metal powder datasheets from powder metallurgy suppliers.

Finally, some **specific super alloys** with a certain **cobalt**, **scandium**, **zirconium**, **hafnium** or **scandium** content are identified. Table 24 shows an overview of the alloy families, specific compositions and their main properties and applications.

Wire AM processes use very similar materials to **powder,** except in **wire** form. The main advantage is a more homogenous distribution of alloying elements in the wire-based processed materials compared with powders. According to F. Martina of Cranfield University, the following alloys have already been printed and tested:

- **steel**: ER70, ER80, ER90, ER120 (TRL6), SS306, SS316, SS420, SS17-4PH (TRL5), maraging 250, maraging 350 (TRL4)
- **titanium alloys**: 64 (TRL7), 64 ELI (TRL5), commercially pure, 5553, Timetal 407 (TRL3)
- **Inconel**: 625, 718 (TRL5)
- **aluminium alloys**: 2024, 2319, 4043, 5087, Safra66, ZL205A (TRL3)
- other alloys based on: Magnesium, Bronze, W, Ta, Mo, Invar, Cu.

The following combinations of materials have also been demonstrated:

- steel to copper
- steel to invar
- tantalum to molybdenum
- molybdenum to tungsten
- Ti64 to 5553
- Ti64 to Timetal 407
- tungsten carbide particles in steel matrix
- tungsten carbide particles in copper matrix
- silicon carbide particles in aluminium matrix
- carbon fibre-reinforced polymers with steel plates, including Z-reinforcement.

[558] TitaniumToday, Issue 22, Nr.1, 2018Q4
https://issuu.com/titaniumtoday/docs/titaniumtoday_i22n1_powder_120118_w

Table 24 List of identified alloys used in powder metallurgy AM for aerospace applications

Titanium based:	Composition	Main sectors, properties and select applications
Ti-6Al-4V (grade 5)	Al5.5–6.75; V3.5-4.5; O<0.2; C<0.08; Fe<0.30	Aerospace and medical, high strength, light and corrosion resistant. Low thermal conductivity. Expensive. Can be heat- treated.
Ti64ELI (pure variant, grade 23)	Al5.5–6.5; V3.5-4.5; O <0.13; C<0.08; Fe <0.25	Brackets, sandwich structures (with CFRP), vanes, support structures.
Ti-6.5Al-3.5Mo-1.5Zr-0.3Si	Al6.5-Mo3.5-Zr1.5-Si0.3	Compressor disks and blades
Ti21S	Al3; Mo15; Nb2.7; Si0.2; C0.1	Higher strength than Ti6Al4V and Ti15V3Cr
Ti CP (grade 2, commercially pure)	N<0.03; C<0.08, Fe<0.3, O<0.25	Space: light and stiff. Antenna
Ti-48Al-2Nb-2Cr	Ti; Al 32-36; Cr2-3;Nb4-5.5;Fe0.15;C0.03	High strength and rigidity at high temperatures, low weight: jet engines (LPT). (directly recyclable)
Ti-22Al-23Nb; Ti2AlNb:	Various Ti-Al-Nb types	Engine components: Blades valves, rotors. In GEnx engines
Ti6242	Ti; Al6; Sn2; Zr4; Mo2; Si	Seal rings, rotating parts
Ti (grade 17)	Ti-0.06Pd	Rotating parts, high corrosion resistance
Aluminium/ magnesium based:	Composition	Main sectors, properties and select applications
Al-10Si-Mg	Si10; Mg0.3; Fe<0.55; Cu<0.05, Ni<0.05	Space applications: light and stiff, cabin interiors, complex geometries.
Al-7Si-0.6Mg	Si7;Mg0.6;Mn<0.35; Ni<0.15;Cu<0.2	idem
Nickel alloys:	Composition	Main sectors, properties and select applications
316L	Cr17-19; Ni13-15; Mo2.25 – 3; C <0.03;Mn 2;Cu 0.5	Mounting parts, high ductile and corrosion resistant
625	Cr21;Mo8.5;Co<1,Ti<0,4, Nb3.4, Fe<3	High toughness and strength to 1000 °C, corrosion- and oxidation-resistant. Turbine and engine parts, aerospace.
Stainless alloys:	Composition	Main sectors, properties and select applications
718 (Inconel)	Ni50-55;Cr17-21;Fe bal.; Nb+Ta5; Mo3; Ti 0.65-1.15; Al0.2-0.8	Structural and engine parts, engine casing, engine parts (rake); Can be used for repairs as well. Space: high temperature and pressure.
Hastelloy (2.4665)	Ni; Fe17-20, Cr 20.5-23, Mo 8-10; Co 0.5-2.5; W 0.2-1; C 0.1	Corrosion- and heat- and oxidation-resistant, strong, machining, heat treatment. Engines, turbines
713, 720, 738	Various alloy types	Various applications

15-5PH	Cr15;Ni4.5;Cu3.5; Nb+Ta 0.3; Si1; Mn1;C0.07;	Jet pumps, air-conditioning packs
17-4PH	C0.04; Si0.25; Mn0.40; Cr15.3;Ni 4.5;Cu 3.25;Nb 0.30	High strength steel, hardenable, aerospace structural parts, engine parts.
M300 (1.2709), H13	Ni18.5;Mo5;Ti0.65; Co9Al0.1Mn0.1	Maraging, tool steel
Nickel 99, 230, 247LC, 263, 276	Cr19;Fe19;Nb;Mo3 Cr22;Fe18;Mo9;W0.6;Co1.5 Cr21.3;Mo13.5;Fe4;W3	Engine parts, trumpets, complex geometries Gas turbines, instrumentation, cryogenic Gas turbines
Other special and super-alloys:	Composition	Main sectors, properties and select applications
CoCr F75	Co28;Cr6;Mo	Gas turbines, dental
CoCr (MP1)	Co60-65; Cr26-30; Mo5-7; Si<1	Medical and aero engines
Scalmalloy	Al;Mg4-4.9;Sc0.6-0.8; Zr0.2-0.5;Mn0.3-0.8; Si0-0.4;	Aerospace, specifically for lightweight and high strength applications. Non-structural parts, fittings.
Zirconium based BMG (Bulk Metallic Glass); AMZ4	Zr;Cu23-25,Al3-5,Nb1-3	Sprockets, amorphous; high strength, hardness, elastic, wear and corrosion resistant: springs, gears, sensors
MAR-M247	Ni;Cr8;Co10Mo0.7; W10;Al6;Ti1;Ta3;Hf1.	Turbine blades and vanes and in industrial gas turbines.
Niobium C-103	Nb89,Hf10;Ti1	Rivets in aerospace, Medium strength, complex shapes in propulsion systems
C129Y, C3009	Nb;10W,10Hf,0.1Y Nb61,Hf30,W9	High strength, high-temperature components

Source: EPMA [559], 3D-printing Final Report [560], Individual material datasheets derived from SLM solutions [561], Metal AM [562]

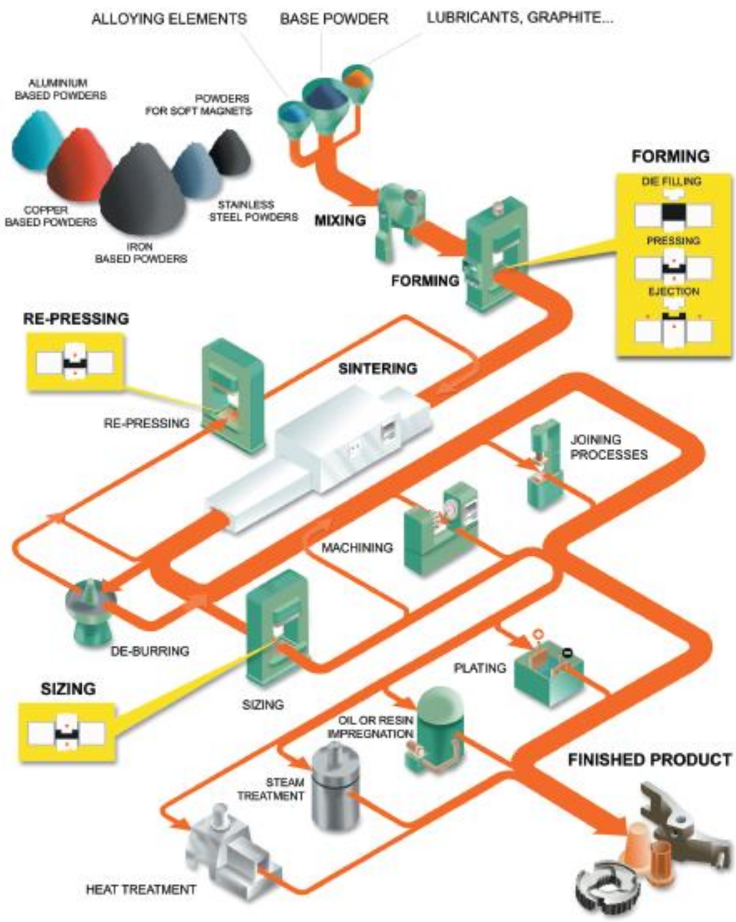
According to the European Powder Metallurgy Association (EPMA), there are various ways in which metals may be produced in powder form. This can be done via comminution of solid metal, precipitation from solution of a salt, thermal decomposition of a chemical compound, reduction of a compound, usually the oxide, in the solid state,

[559] EPMA, Introduction to Additive Manufacturing Technology, a guide for designers and engineers, 2nd edition, 2018 from https://www.epma.com/epma-free-publications
[560] EUROPEAN COMMISSION, EXECUTIVE AGENCY FOR SMALL AND MEDIUM-SIZED ENTERPRISES, IDEA Consult, AIT, VTT, CECIMO, (2016), Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing), Final Report, Brussels, July 15, 2016
[561] Individual material datasheets derived from SLM solutions, Carpenter, Böhler Edelstahl GmbH & Co KG, Carpenter Powder Products AB, EOS Finland Oy, Erasteel SAS, Heraeus Additive Manufacturing GmbH, GKN – Hoeganaes, Höganäs, Oerlikon Metco Europe GmbH, SAFINA a.s., Sandvik Osprey Ltd - Powder Group, IMET, GE Additive, Renishaw and Farinia Group.
[562] Metal AM - The magazine for the metal additive manufacturing industry, Vol.4, No.2, summer 2018.

electrodeposition and the atomisation of molten metal. Of these, the last three account for the bulk of the powders used[563].

EPMA also provides a specific guide to the processes and products being made in Europe. This includes powder for metal injection moulding (MIM), as well as ferrous, magnetic, lubricant and other powders beyond the relatively new ones for AM. Figure 83 illustrates the main steps in producing the various powders. The gas atomisation process and vacuum induction melting (VIM) are key, along with other processes for producing very specific alloys. [564]

Figure 83 Schematic overview of 3D printing from metal powders



Source: EPMA

Step 3: 3D-printed components and spare parts

Table 24 provides a basic overview of metal 3D printing applications and of the components involved. The majority of these components are small, due to size constraints in metal powder beds. However, there is potential for increasing the size of laser beam melting (LBM), electron beam melting (EBM), and laser metal deposition (LMD) technologies over time, and for the integration of parts. The text below is derived

[563] EPMA, introduction to powder metallurgy, the process and its products, 1992 & 2008 European Powder Metallurgy Association, from https://www.epma.com/epma-free-publications
[564] EPMA, Introduction to Additive Manufacturing Technology, a guide for designers and engineers, 2nd edition, 2018 from https://www.epma.com/epma-free-publications

largely from the 'metallic structural parts for airplane' case study contained in (EASME report, 2016). [545]

Unlike the automotive sector, where AM is used mainly for rapid prototyping (because of the huge scale of production), use of AM in the aerospace sector is at its most mature. It is already used in full production for many components, and close to full production for structural and demanding components, with a production manufacturing readiness level of around 7-9. For other applications, such as components for very demanding environments, the TRLs are lower.

Companies make use of AM to achieve optimisation of specific parts, for example, in terms of weight, mechanical performance, assembly time (and cost) and lead times.

The main **aerospace-related components manufactured by AM** can be grouped as follows:

- **Non-structural components**: these components are mainly made by plastic AM, and include pats for the interior of aircraft. AM production is considered mature and the collaboration between Airbus and Stratasys (polymer/CFRP-oriented) is of particular note in this area. Examples include cabin parts and seats, as illustrated in Figure 84, where a 40 % weight reduction is realised. [565]

Figure 84 3D printed seat structure with 40 % weight reduction

Source: Objectify

Another benefit of 3DP is its customisation potential where production numbers are small. In civil aircraft cabins, for example, different airlines have differing specifications; 3DP can create valuable cabin interiors in small numbers without the need for expensive tooling individual to each airline.

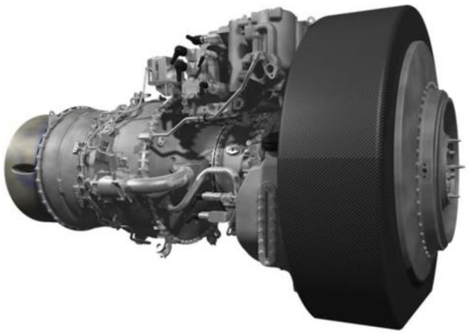
- **Structural parts for jet engine components**: this sub-sector is now considered mature. Notable examples include fuel nozzles (General Electrics (USA), Rolls-Royce (UK) and Pratt & Whitney (USA)), stator rings, fuel injectors (Morris Technologies), and air ducts (Boeing fighters).

Another example is Safran Helicopters (Figure 86), which recently launched a new range of helicopter engines. The Anteo-1K engines have 3D-printed parts [566], including some inside the combustion chamber. Additive manufacturing has enabled Safran to reduce production costs without compromising engine performance. These 3D-printed engines are almost 30 % more powerful than their predecessors, improving performance in areas such as search and rescue.

Safran uses titanium alloys extensively, at about 20 metric tonnes per day (including traditional castings and forgings) in the CFM International LEAP engine for civil use, for the Boeing 737MAX and Airbus A320NEO. [567]

[565] http://www.objectify.co.in/additive-manufacturing-and-aerospace/
[566] http://www.objectify.co.in/additive-manufacturing-and-aerospace/
[567] T. Viguier, SAFRAN, Titanium USA 2018 - https://titanium.org/page/TiUSA18Proceedings,

Figure 85 3D-printed parts in helicopter engines



Source: Aerobuzz [568]

The same source also cites the Pratt & Whitney engine, containing 12 3D-printed parts, used in Bombardier aircraft. The components are mainly fasteners and injection nozzles 3D printed from titanium and nickel. Pratt & Whitney has saved almost 15 months over the entire design process, and the final weight of the parts is 50 % less than their conventional counterparts (Figure 87). The engine manufacturer used electron beam melting (EBM) and direct metal laser sintering (DMLS) technologies. [569]

Figure 86 3D-printed engine parts for P&W [570]

Source: 3dnatives

Renishaw is a British AM company which sells a variety of metal 3D printers. They are working in collaboration with engine manufacturers to create high-speed aerospace turbines, using 3D printing to produce lightweight, high-performance parts, and to measure their effectiveness. They used their metal 3D printer to print parts in nickel-based 'super-alloys' in complex geometries that cannot be created using traditional manufacturing methods.

- **Other structural parts (including large ones):** this includes components such as brackets (Figure 87), large components such as aircraft skeletons, and large metallic structures such as wings, fuselage and empennage. This sub-sector is still under development, mainly because of strict homologation, but also because large components still pose fundamental technical problems for 3D printing; key players are Airbus, Rolce-Royce, Snecma and AvioAereo.

STELIA Aerospace has a 3D-printed reinforced fuselage panel by means of wire and arc additive manufacturing (WAAM) technology. The one square meter demonstrator shows

568 https://www.aerobuzz.fr/helicoptere/nouveau-safran-aneto-motorisera-leonardo-aw189k/
569 http://www.objectify.co.in/additive-manufacturing-and-aerospace/
570 https://www.3dnatives.com/en/3d-printing-aeronautics-010320184/

that additive manufacturing makes it very easy to design the stiffeners of the fuselage panels, offering more design flexibility.

Figure 87 The unified design of the vertical tail plane bracket built with EOS Aluminium AlSi10Mg

Source: EOS

Airbus and Arconic already include 3DP titanium brackets in series production for the A350 programme (Figure 88) [571] and have announced their aim to produce and certify large structural parts of up to one meter in the near future.

Figure 88 3DP Titanium bracket for A350 aircraft

Source: TitaniumToday

Another area of potential for AM in the aerospace sector is that of maintenance, repair and overhaul (MRO), as outlined below.

Production of spare parts in remote areas: 3D printing can be extremely useful in remote areas for the production of spare parts. A good example of this is the installation of a 3D printer in the International Space Station in 2014. 3D printing can also be very useful for defence, in particular for supporting in-house operations and isolated field

[571] TitaniumToday, Issue 22, Nr.1, 2018Q4
https://issuu.com/titaniumtoday/docs/titaniumtoday_i22n1_powder_120118_w

operations: [572] the technology allows for the reactive production of spare parts on the spot, reducing the need for stocks and supply (and hence costs and delays). A 3D printer has been installed on a USA aircraft carrier and parts of drones have been produced on the ship. [573] 3D printing is a very promising technology that performs well against the three critical parameters for the defence sector: cost-delay-performance. [574] While it is common practice in the aerospace industry to 3D-print replacement parts, the practice is only now emerging on the battlefield. [575]

Repair of components: 3D printing can be used not just to produce new parts, but also to repair existing parts. Hybrid technologies, combining conventional machining with directed energy deposition (DED)-type technologies in particular, have been studied intensively, especially in the aerospace and military sectors; one documented example is the repair of aircraft engine compressors, involving Rolls-Royce.

However, 3D-printing for the repair, maintenance and production of spare parts in the defence sector is only now emerging, and remains immature and poorly documented. Initiatives in the area are still brand new. [576] The value chain is not yet established. Only isolated cases can be identified, and are mainly kept under wraps by large multinational firms. It is, however, possible to identify Baden-Württemberg, Dutch North Brabant and Flanders as key regions (with companies such as Siemens, Atlas Copco and Schunk) for this value chain, although they are still explorative.

The most obvious area for repair is maintenance in operational conditions, especially when the spare part normally provided by the manufacturer is not in stock. According to [577], the USA Marine Corps (USMC) has been able to repair an F-35B from Marine Fighter Attack Squadron 121, based in Japan, by replacing a worn out shock absorber on a landing gear door with another, fabricated by 3D printing. Without this process, the Combat Logistic Battalion (CLB) 31 would have had to order not only the spare part but a whole new landing gear hatch from Lockheed-Martin. In war time, being able to restore a combat aircraft quickly is a valuable asset. Progress in 3DP quality and testing means that parts can be manufactured for permanent replacement on the spot, as shown in the image below (Figure 89).

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[572] European Defense Agency, Additive Manufacturing Feasibility Study & Technology Demonstration-The "AMFaD" project, leaflet of EDA, 2017.
[573] https://3dprint.com/85654/us-navy-3d-printed-drones/
[574] CEIS, Impression 3D Des technologies de rupture au service des Armées. Note stratégique, 2016.
[575] EUROPEAN COMMISSION, EXECUTIVE AGENCY FOR SMALL AND MEDIUM-SIZED ENTERPRISES, IDEA Consult, AIT, VTT, CECIMO, (2016), Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing), Final Report, Brussels, July 15, 2016
[576] Airbus Press release: Airbus and Singapore to co-develop digital services for military aircraft, 18 July 2018.
[577] http://www.opex360.com/2019/01/27/lus-air-force-mise-sur-limpression-3d-pour-la-maintenance-de-ses-avions-furtifs-f-22-raptor/

Figure 89 Aluminium part in an F22A replaced by a 3DP titanium one

Source: Opex360

Step 4: Assemblies

Specific information on assemblies produced by AM is hard to pin down, since individual 3D-printed parts tend to be the focus, although they go on to be assembled into larger systems.

One well-documented example of AM assembly is General Electrics' 3D-printed fuel nozzles, as used in the LEAP jet engines produced by CFM International (GE aviation and Snecma), with 19 nozzles per engine. The LEAP engine is 15 % more fuel efficient thanks to AM, and flew for the first time as part of the Airbus A320neo in May 2015. Rolls-Royce's Trent XWB-97 engine, flight-tested in 2015, was said to be the largest 3D-printed aerospace component to fly, with a 30 % lead-time reduction. 3D-printed parts can also be assembled into customised interiors for business jets and private helicopters.

3DP drones

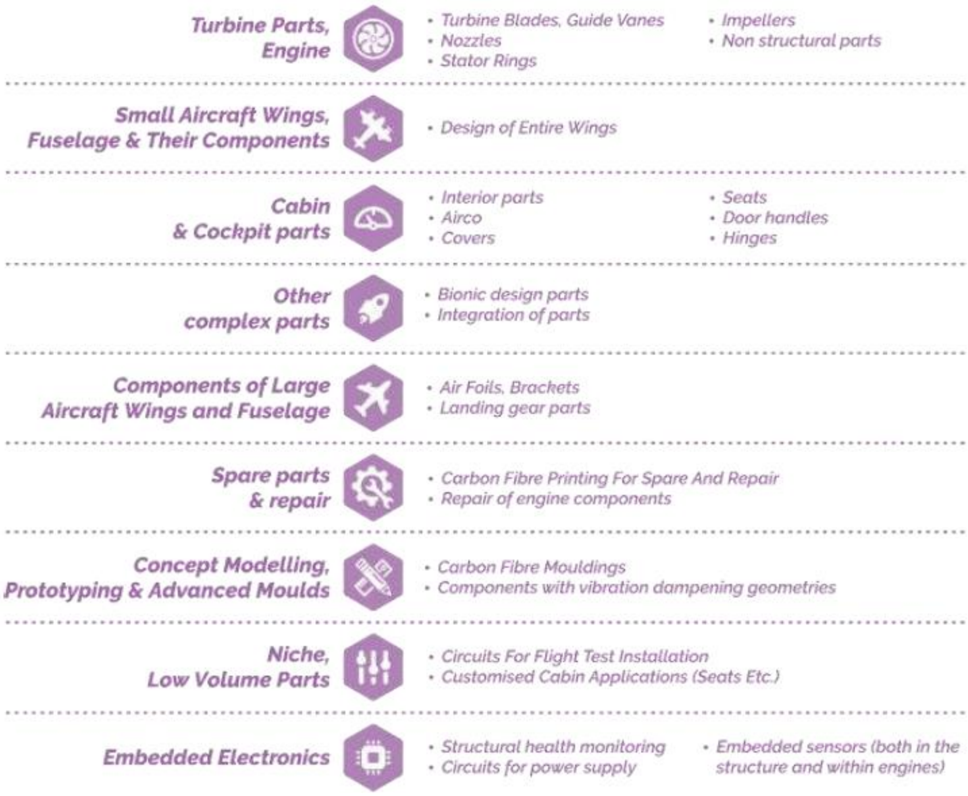
3DP is also used in manufacturing drones. Unmanned vehicles (UVs) are a very promising application for additive manufacturing, due to the design freedom, potential for delocalised manufacturing and significant reductions in weight. Some examples are given below.

Stratasys collaborated with Aurora Flight Sciences in 2015 to create an advanced series of unmanned aerial vehicles with jet propulsion. More than 75 % of the vehicles' parts were 3D-printed using the fused deposition modelling technique.

The USA Army, in collaboration with researchers at MIT, designed 'Perdix' drones and tested them successfully. The USA Army was not new to AM, having previously created concrete barracks using 3D printing. They created 103 drones that perform collectively as one brain. In order to avoid crashing, they use sensors to maintain a safe flight distance. They can jam enemy radars.

The AM-Motion project's final roadmap provides an overview of key innovative products (mainly assemblies) in aerospace (all material types) (Figure 90).

Figure 90 Innovative AM components and assemblies for aerospace



Source: AM-Motion project [578]

Step 5: 3D printing systems

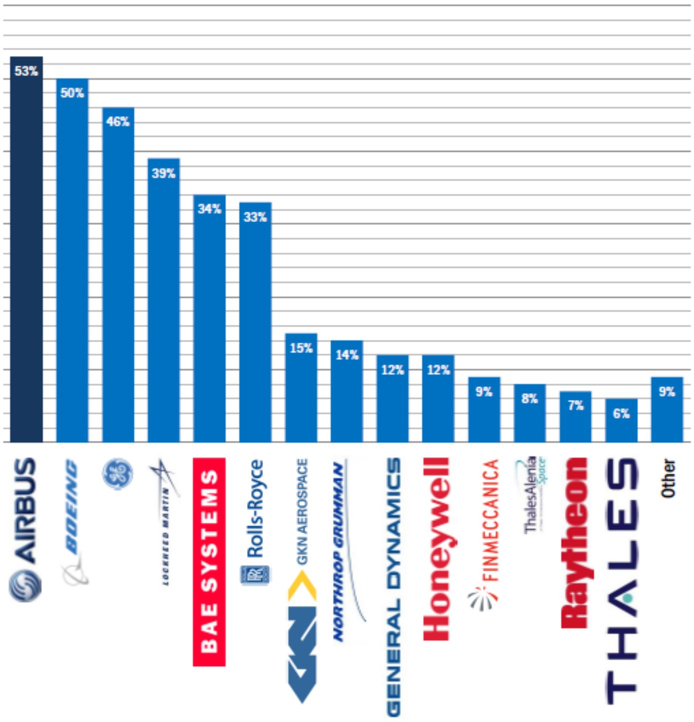
According to the EASME report: [579]

> *This value chain is marked by a very high level of concentration around key OEMs, AM suppliers and integrators such as Airbus (FR) or Boeing (USA) that are known for taking the lead on key developments also in the AM community. The key players in this area can therefore be identified quite easily [*Figure 91*]. Nearly all major aerospace OEMs, including Airbus, Bell Helicopter, GKN Aerospace, Honeywell, Lockheed Martin, MTU Aero Engines, Northrop Grumman, Pratt & Whitney, Raytheon, and Rolls-Royce, have built infrastructures within their corporations to evaluate and implement AM technologies. The key aeronautic players in demand of AM technologies and services are either located in France, the UK or Germany. Even American players (GE, Boeing, Lockheed Martin) are active in Europe through their branches in Italy, Northern Ireland, and the UK. Players such as SAFRAN (FR), Boeing (USA) and AvioAero (branch of GE in Italy), etc. are working with European companies such as EOS, Altair, Techspace Aerospace, MTU Aero Engines (DE)150, ARCAM AB (SE) and Harcotera (ES) to assimilate and develop AM capabilities. USA-based firms such as Stratasys also collaborate with European integrators like Airbus.*

[578] AM-Motion project, Deliverable 5.4 – Final AM Roadmap, October 2018
[579] EUROPEAN COMMISSION, EXECUTIVE AGENCY FOR SMALL AND MEDIUM-SIZED ENTERPRISES, IDEA Consult, AIT, VTT, CECIMO, (2016), Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing), Final Report, Brussels, July 15, 2016

An overview representing the market leaders is presented below in Figure 91.

Figure 91 Aerospace market leaders in AM



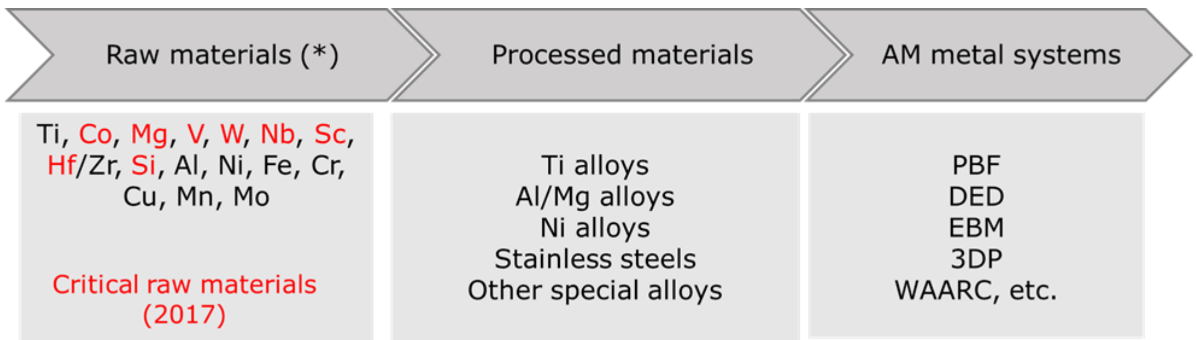
Source: DefenceIQ, 2016 [580]

Step 6: 3D printer equipment

The main providers of 3D metal printing equipment, either with the potential to supply for aerospace use or already active in this field, are considered in Step 6.

Based on the information provided above, a simplified supply chain with three main steps, namely raw materials, processed materials and AM systems, is proposed for further supply chain analysis (Figure 92).

Figure 92 Additive manufacturing (3DP): an overview of raw materials, processed materials and AM systems considered in the analysis



(*) The focus here is on 3DP materials.
Materials required in 3DP systems are similar to the basic materials used in robotics.

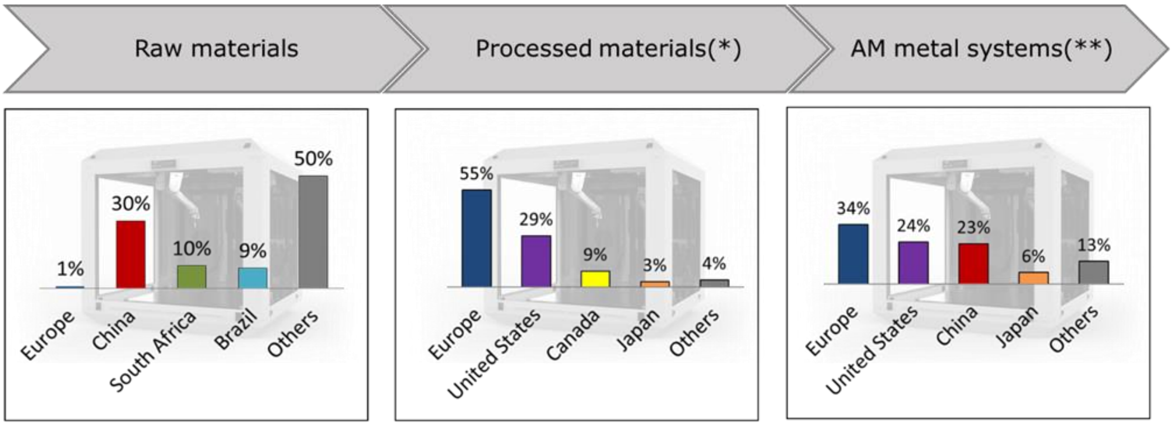
Source: JRC

[580] DefenceIQ, Additive Manufacturing in Aerospace, Defence & Space, Trends and Analysis 2016

6.5.2 Key players and market share along the additive manufacturing (3D printing) value chain

The key players along the simplified supply chain are shown in Figure 93.

Figure 93 Additive manufacturing (3DP): key players in the supply chain

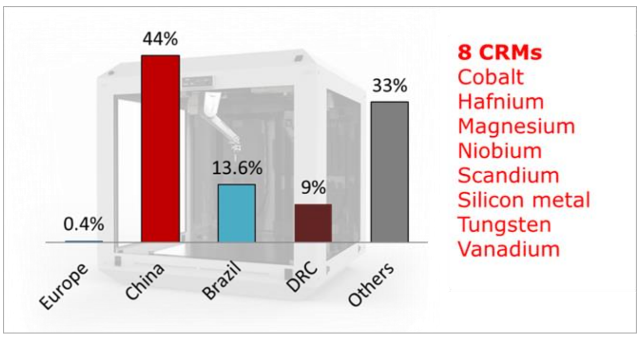


(*) Based on number of suppliers; market shares based on tonnage or value not available.
(**) Based on the number of industrial metal AM suppliers per country.

Source: JRC

In total, 17 raw materials have been identified as relevant for the AM supply chain, of which eight materials are flagged as critical. China is the major supplier of around 30 % of the raw materials required in 3D printing and the largest supplier for 7 out of 17 raw materials relevant for 3DP. South Africa (10 %) and Brazil (9 %) are other key suppliers of raw materials. The key suppliers of CRMs for 3DP are shown in Figure 94. Five out of the eight critical raw materials (CRMs) (EC, 2017) identified for 3DP, namely magnesium, vanadium, tungsten, scandium and silicon metal are supplied from China. China supplies more than 40 % of the CRMs, and supply from European countries is negligible (<1 %). Other key suppliers of CRMs are Brazil and DRC.

Figure 94 Supply of CRMs for 3DP technology: key players



Source: European Commission, 2017, Study on the review of the list of critical raw materials

Europe is strong in the supply of processed materials, and of AM systems. Various companies specialise in different powders. A significant proportion of these are based in Europe, as highlighted in Table 25. This table highlights the expertise of EPMA members per alloy family, as introduced in Table 24, along with additional sources. The overview includes a list of specific alloy families covered. Some of the companies below also provide 3D printing equipment besides metal AM powders and wire. The overview was fully up to date in December 2018.

Table 25 List of companies producing AM powders and wires [581, 582, 583]

Company	Country	Powder = 1; Wire =2 *	Aluminium alloys	Titanium alloys	Nickel alloys	Stainless steel alloys	Other/ specific alloys	Other alloy types	Website
Amastan Technologies	USA	1	YES	YES	YES	YES	YES		www.amastan.com
Ampal/ USA Metal Powder	USA	1	NO	NO	YES	NO	NO		www.usmetalpowders.com
AP&C	USA	1	YES	YES	YES	YES	YES	CoCr, PMs, Cu	www.advancedpowders.com
ATI Specialty Materials	USA	1	YES	YES	YES	YES	YES		www.atimetals.com
Beckaert	Belgium	2	NO	NO	NO	YES	NO		https://www.bekaert.com/
Böhler Edelstahl GmbH & Co KG	Austria	1	NO	NO	NO	YES	YES		www.bohler-edelstahl.com
Carpenter Powder Products AB	Sweden	1	NO	YES	YES	YES	YES		www.carpenterpowder.com
Chinese wire producers***	China	2	YES	YES	YES	YES	YES	All	N.A.
Crystal Titanium	Saudi Arabia	1	NO	YES	NO	NO	NO		www.cristal.com
EOS Finland Oy	Finland	1	YES	YES	YES	YES	YES	CoCr and W	www.eos.info
Equispheres	Canada	1	YES	YES	YES	YES	YES		www.equispheres.com
Erasteel SAS	France	1	NO	NO	NO	YES	YES	CoCr	www.erasteel.fr
ESAB	USA	2	NO	NO	NO	YES	NO		https://www.esabna.com/
Farinia Group	France	1	YES	YES	YES	YES	YES	CoCr	www.farinia.com
GKN sinter metals/ Hoeganaes Corporation Europe GmbH	Germany	1	YES	YES	YES	YES	YES		www.gknpm.com
Global Tungsten & Powders spol. s.r.o.	Czech Republic	1	NO	NO	NO	NO	YES	Tungsten specialist	www.globaltungsten.com
Graphite Additive Manufacturing	United Kingdom	1	YES	YES	YES	YES	YES	Tool steel	graphite-am.co.uk
HC Starck Surface Technology and Ceramic Powders GmbH	Germany	1	NO	NO	NO	NO	YES	Many special powders, ZrO2, Mo,W,Ta,Nb	www.hcstarck.com
Heraeus Additive Manufacturing GmbH	Germany	1	NO	YES	YES	NO	YES	Nb,Mo,W,Ta, Zr, PMs	www.heraeus-additive-manufacturing.com
Höganäs	Sweden	1	NO	NO	NO	YES	YES	Co	www.hoganas.com
IMR Metal Powder Technologies GmbH	Austria	1	NO	NO	NO	NO	YES	Pb, Cu, Sn, Sb	www.imr-metalle.com
Kymera International	Germany	1	YES	NO	NO	NO	YES	Cu	www.kymerainternational.com
Lincoln	USA	2	NO	YES	NO	YES	NO		https://www.lincolnelectric.com/
LPW Technology	United Kingdom	1	YES	YES	YES	YES	YES	Sc,Co,Ta,W,Mo,	www.lpwtechnology.com
LSN Diffusion Ltd	United Kingdom	1	NO	NO	NO	YES	YES	Co alloys	www.lsndiffusion.com

[581] EPMA, Guide to Metal Powder Manufacturers and Powder Metallurgy Equipment Suppliers 2018, from https://www.epma.com/epma-free-publications
[582] BCG Additive Manufacturing, 2018
[583] Wohlers Report 2018, 3D Printing and Additive Manufacturing State of the Industry, Annual Worldwide Progress Report, Wohlers Associates, Inc., 2018

Markforged	USA	1	YES	YES	YES	YES	YES	Tool steels, copper	markforged.com
Metal Technology Co. Ltd	Japan	1	YES	YES	YES	YES	YES		www.kinzoku.co.jp
Metalvalue SAS	France	1	NO	NO	NO	NO	YES		www.metalvalue.fr
Metalysis Ltd	United Kingdom	1	NO	YES	YES	NO	YES	Sc and Nb	www.metalysis.com
MIMETE Srl (FOMAS Group)	Italy	1	NO	NO	YES	YES	YES	Co	www.mimete.com
Molyworks	USA	1	YES	NO	NO	YES	NO		www.molyworks.com
Nanosteel	USA	1	NO	NO	NO	YES	NO	Nanosteel	www.nanosteelco.com
Next Gen Alloys	India	1	YES	YES	YES	YES	NO		www.ng-steel.com
Oerlikon Metco Europe GmbH	Germany	1	NO	YES	YES	YES	YES	CoCr	www.oerlikon.com/metco/
Plansee group (GTP, Molymet)	Germany	1	NO	NO	NO	NO	YES	Mo,W,Ta,Nb,Cr	www.plansee.com
PMCtec GmbH	Germany	1	NO	NO	NO	YES	YES	Mo,W,Ta,Nb,Cr	www.pmctec.com
Praxair Surface Technologies	USA	1	YES	YES	YES	YES	YES	Co	www.praxairsurfacetechnologies.com
Progold SPA	Italy	1	NO	YES	YES	NO	NO		www.progold.com
Pyrogenesis	Canada	1	YES	YES	YES	YES	YES		www.pyrogenesis.com
QuestTek Innovations LLC	USA	1	YES	YES	YES	YES	YES		www.questek.com
Reade	USA	1	YES	YES	YES	YES	YES	Full spectrum, also ceramics	www.reade.com
Renishaw plc	UK	1	YES	YES	YES	YES	YES		www.renishaw.com
RHP-Technology GmbH	Austria	1	YES	YES	YES	YES	YES		www.rhp-technology.com
SAFINA a.s.	Czech Republic	1	YES	NO	NO	NO	YES	Cu, PMs	www.safina.cz
Sandvik Osprey Ltd - Powder Group	United Kingdom	1	NO	NO	NO	YES	YES	Co, Low alloyed steels	www.materials.sandvik.com/metalpowder
SentesBIR	Turkey	1	NO	NO	NO	YES	YES	Co, bronze	www.sentes-bir.com
SLM Solutions (TLS Technik)	Germany**	1	NO	YES	NO	YES	NO	CoCr, CuSn	slm-solutions.com
SMS Group/ Additive Industries	Germany	1	YES	YES	YES	YES	YES	Scalmalloy, no details	www.sms-group.com
Steward Advanced Materials	USA	1	NO	NO	NO	YES	NO		www.stewardmaterials.com
Tekna Plasma Europe SAS	Canada	1	YES	YES	YES	YES	YES	Mo,W,Ta	www.tekna.com
Titanium.com	USA	2	YES	YES	YES	YES	NO		www.titanium.com
TIMET	USA	1	NO	YES	YES	YES	YES		www.timet.com
Toyal	USA	1	YES	NO	NO	NO	NO		www.toyala.com
Tribotecc GmbH	Austria	1	NO	NO	NO	NO	YES	Sb, Sn, Sulfides	www.tribotecc.at
Uddeholm AB	Sweden	1	NO	NO	NO	YES	NO		www.uddeholm.com
United States Metal Powders Incorporated	USA	1	YES	NO	NO	NO	NO		www.usbronzepowders.com
Universal Technical Resource Services Inc	USA	1	NO	YES	NO	NO	NO		www.utrs.com
USD Powder GmbH	Germany	1	NO	NO	YES	YES	NO		www.usdpowder.com
Valimet	USA	1	YES	NO	NO	NO	NO		www.valimet.com
VBC	United Kingdom	2	NO	YES	YES	YES	YES		https://www.vbcgroup.com/
VBN Components	Sweden	1	NO	NO	NO	YES	NO		www.vbncomponents.se
VDM Alloys	Germany	1	NO	NO	YES	YES	YES	CoCr	www.vdm-metals.com
William Rowland Limited	United Kingdom	1	YES	YES	YES	YES	YES		www.william-rowland.com
Wolfmet Tungsten Alloys	United Kingdom	1	NO	NO	NO	NO	YES	W	www.wolfmet.com

* 1= primarily powder production, 2= primarily wire production, the distinction is not always clear,
** Headquarters/ production site,*** The actual number of wire producers in China could not be substantiated

It can be difficult to distinguish the original powder producer from 3D printing companies who also offer powders, which may or may not be produced in house. In any case, a clear vertical integration is observed in the supply chain. For example, GKN Hoeganaes is strongly involved, across its business units, in processed materials (Step 2) and in component and assembly production (Steps 3 and 4). Similarly, EOS and others provide various 3D printer solutions as well as the necessary metal powders. Powders are, however, not the only form of raw material.

Arc wire systems are currently being developed in Spain and the UK, and are now at demonstration phase. Companies are also putting forward electron beam melting as an alternative to selective laser melting and sintering. In the USA, Sciaky uses LBM based on wire, which is claimed to have more variety, availability and lower costs compared to powder products, and includes a wide range of materials: titanium alloys, Inconel 600, 625, 718, nickel and copper nickel alloys, stainless steels 300 Series, aluminum alloys 1100, 2318, 2319, 3000 Series, 4043, 4047, 5183, 5356, 5554, 5556, steel alloys, cobalt alloys, zircalloy, tantalum, tungsten, niobium and molybdenum. [584] As a result, German players such as EOS, SLM Solutions and ConceptLaser along with their European counterparts, Renishaw (UK) and Arcam AB (SE), are competing with different technical, cost and performance promises related to the specific technology-material combination applied[585]. For wire AM products, as indicated in the table above, the main suppliers are those who are already known for producing welding wires: Beckaert, Esab, Lincoln, VBC, Bohler and Sandvik, plus a plethora from China. Future developments in this area will focus on:

- customised feedstock chemistries
- high-strength aluminium
- multi-material structures.

A critical aspect here is that there seems to be an extremely poor early-stage supply chain in Europe as far as wires are concerned. According to BCG, there are very few organisations producing ingots or rods from ingots; many WIP items are imported from China with very little control, but even more importantly from an R&D perspective, there is little opportunity for customisation, meaning that in the case of a new chemical composition, it is virtually impossible to source the necessary processed materials from within the EU.

Since most of the commercially used AM techniques are rigid in terms of input processing variables (even the characteristics of the metal powder to be used), it is very difficult to customise the composition according to end-user applications. Furthermore, the commercially available metal powders are often supplied by the additive manufacturers, at relatively high costs. Typical problems are related to surface roughness, damage tolerance, fatigue and tensile strength, all properties which are sensitive to subtle changes in the chemistry and microstructure, and are frequently highlighted in the literature. [586]

Based on an analysis of the individual websites in Table 24 shows the count of producers, based on location, for powder AM products. Here, Europe-based suppliers are relatively well represented, with 35 identified suppliers forming 60 % of the global total of 58 (Figure 95). This share is highest for stainless steel-based alloys, with 23 of the 40 suppliers (85 %), followed by nickel alloys, with 17 of the 31 suppliers (63 %). Europe is

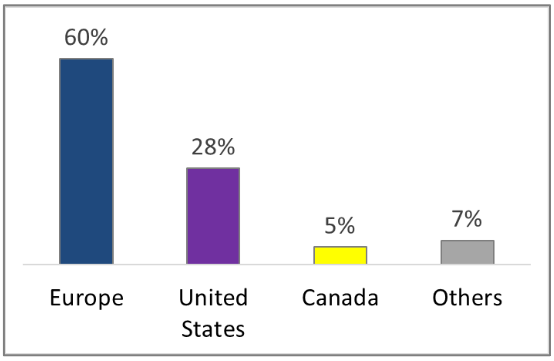
[584] http://www.sciaky.com/additive-manufacturing/wire-am-vs-powder-am

[585] EUROPEAN COMMISSION, EXECUTIVE AGENCY FOR SMALL AND MEDIUM-SIZED ENTERPRISES, IDEA Consult, AIT, VTT, CECIMO, (2016), Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing), Final Report, Brussels, July 15, 2016

[586] Seifi M, Salem A, Beuth J, Harrysson O, Lewandowski JJ. Overview of materials qualification needs for metal additive manufacturing. JOM 2016;68:747–64.

home to 15 of the 30 titanium alloy suppliers (50 %) and the proportion is lowest for aluminium alloys, at 11 of the 27 suppliers (41 %). A more quantified analysis, based on actual quantities or market share, is not possible due to a lack of data. It has also proved impossible to produce an overview or list of potential suppliers of metal wire through contacts in the sector. An unidentified number of large Chinese and USA-based wire suppliers could change the above conclusions considerably.

Figure 95 Powder AM producers based on country location



Source: JRC

From Figure 95 it can be concluded that EASME's statement on the lack of transformative capabilities for powder production in Europe no longer holds true. According to this newer information and the more recent AM-Motion roadmap [587], the bottleneck for metal AM for aerospace is more a question of the cost, quality and consistency of the parts produced from these powders, rather than their availability.

Finally, it should be stated that due to a more direct optimisation of the material properties in relation to the printing technology to achieve similar parts' specifications, considerable material savings are possible over conventional metal processing. The AM-Motion roadmap [588] states that:

> *AM may play a lead role in the Circular Economy by producing high added-value products from recycled or bio-based powders and enabling full re-use of AM by-products in new products. The exploitation of the full potential of AM will also lead to resource and energy saving in the whole value chain and in particular in manufacturing and transportation, thus contributing to the environment".*

However, some potential environmental drawbacks should be noted: in particular, when the technology triggers the consumption of more energy and materials due to the selection of more exotic materials, and when metal powders are not properly recycled or (re-)utilised in the case of PBF. Also, multi-layered or embedded components may hamper recyclability at the end of use. Similar environmental rebound effects are also noted in a recent OECD publication. [589]

Regardless of these impacts, in the case of aerospace components, the most relevant economic driver with a substantial environmental benefit remains the promise of significantly reduced weights and thus lower fuel-burn over the lifecycle of an aircraft.

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[587] AM-Motion - A strategic approach to increasing Europe's value proposition for Additive Manufacturing technologies and capabilities, Edited by M. Cioffi, M. Garrone, P. Queipo, 2018

[588] AM-Motion - A strategic approach to increasing Europe's value proposition for Additive Manufacturing technologies and capabilities, Edited by M. Cioffi, M. Garrone, P. Queipo, 2018

[589] J. Faludi, N Cline – Thomas, S. Agrawala, 3D printing and its environmental implications, Chapter 5 - The next production revolution – implications for governments and business, OECD, 2017

Moreover, existing parts with wear and tear can be rebuilt with targeted metal depositions, extending life-spans and thus also contributing to material savings.

Table 26 lists the main providers of 3D metal printing equipment, which can be used or is already in use for aerospace applications. The top providers are marked in bold. The list is based on market reports and on the individual websites of manufacturers, and is up-to-date as of December 2018, but changing rapidly with many newcomers entering the market.

Some smaller companies are developing newer technologies, especially under the binder jetting column in the form of pellets (Vader systems), plastic matrix powders (Markforged) and nano-metal powders (Xject) application. In addition, the EBM approach allows the use of wire materials as an input, as used by Sciaky in the USA, allowing for a wider range of materials to be used than with powder-based systems.

Based on Table 26 [590, 591, 592, 593] the share of countries is visualised in Figure 96 (using the locations of headquarters).

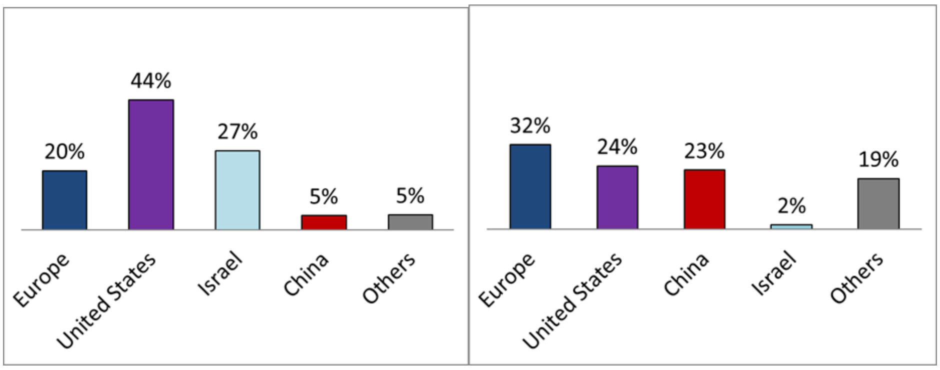
Table 26 List of most relevant companies providing 3D metal printers

Company	**Country***	**SLS/SLM/DMLS (=DMP)** (Powder bed fusion)	**LPD/LENS/DMD/ SLC** (Direct Energy Deposition)	**EBM, EBAM, WAARC** (w=wire based) (Electron Beam)	**3DP** (Binder/ material jetting)	**Website**
3D Systems	USA	YES				www.3dsystems.com
3D4Mec	Italy	YES				www.3d4steel.com
Addilan	Spain			YES, w		www.addilan.com
Additive Industries	Netherlands	YES				www.additiveindustries.com
AddUp	USA	YES	YES		YES	www.addupsolutions.com
ADMATEC	Netherlands				YES	www.admateceurope.com
Arcam (GE Additive)	Sweden			YES		www.arcam.com
Aurora Labs	Australia	YES				www.auroralabs3d.com
BeAM	France		YES			www.beam-machines.com
Bright Laser Technologies	China	YES				www.ex-blt.com
Chervona Hvilya	Ukraine			YES		www.chervonahvilya.com
Concept Laser (GE Additive)	Germany	YES				www.concept-laser.de
Cytosurge	Switzerland				YES	www.cytosurge.com
Desktop Metal	USA				YES	www.desktopmetal.com
Digital Alloys	USA		YES, w			www.digitalalloys.com
Digital Metal	Sweden				YES	www.digitalmetal.tech

590 EPMA, , from https://www.epma.com/epma-free-publications
591 https://www.3dnatives.com/en/metal-3d-printer-manufacturers/
592 Wohlers Report 2018, 3D Printing and Additive Manufacturing State of the Industry, Annual Worldwide Progress Report, Wohlers Associates, Inc., 2018
593 Guide to Metal Powder Manufacturers and Powder Metallurgy Equipment Suppliers 2018, from https://www.epma.com/epma-free-publications

DM3D Technology	USA		YES			www.dm3dtech.com
DMG Mori	Japan	YES	YES			en.dmgmori.com
Eplus 3D	China	YES				www.eplus3d.com
EOS Finland Oy	Finland	YES				www.eos.info
Ermaksan	Turkey	YES				www.ermaksan.com.tr
ExOne	Germany				YES	www.exone.com
Fabrisonic	USA	YES				www.fabrisonic.com
Farsoon	United Kingdom	YES				en.farsoon.com
Fonon	USA	YES				www.fonon.us
Formlabs	USA	YES				www.formlabs.com
Hanbang 3D	China	YES				www.hanbang3d.com
Huake 3D	China	YES				www.huake3d.com
GE Additive (See Arcam and Concept Laser)	USA	YES		YES		www.ge.com/additive
Gefertec	Germany			YES, w		www.gefertec.de
InnsTek	South Korea		YES			www.insstek.com
Laseradd	China	YES				www.laseradd.com
Lasers and Apparatus	Russia	YES				www.laserapr.ru
Long Yuan	China	YES	YES			www.lyafs.com.cn
Matsuura	Japan	YES				/www.lumex-matsuura.com
Markforged	USA				YES	markforged.com
Mazak	Japan	YES				www.mazak.co.jp
Norsk Titanium	Norway			YES		www.norsktitanium.com
Noura	Iran	YES				www.noura3dp.com
Optomec	USA		YES			www.optomec.com
OR Laser	Germany	YES				www.or-laser.com
Raycham	China	YES	YES			en.raycham.com
Realizer	Germany	YES				www.realizer.com
Renishaw plc	United Kingdom	YES				www.renishaw.com
RPMI	USA		YES			www.rpm-innovations.com
Quickbeam	China	YES				www.qbeam-3d.com
Sciaky	USA			YES, w		www.sciaky.com
Sentrol	South Korea	YES				www.sentrol.net
Sisma	Italy		YES			www.sisma.com
SLM Solutions GmbH	Germany	YES				www.slm-solutions.com
Sodick	Japan	YES				www.sodick.co.jp
SPEE3D	Australia		YES			www.spee3d.com
Syndaya	China	YES				www.syndaya.com
Trumpf	Germany	YES	YES			www.trumpf.com
Vader Systems	USA				YES	vadersystems.com
Wuhan Binhu	China	YES				www.binhurp.com
Xact Metal	USA	YES				www.xactmetal.com
Xery	China	YES				www.xery3d.com
Xjet	Israel				YES	xjet3d.com
Yongnian	China	YES	YES			en.yn3dp.com
Zhuhai CTC	China	YES				www.ctcprinter.com
Zrapid	China	YES				www.zero-tek.com

Figure 96 Shares base on the number of units sold between 2007 and 2017 for polymer systems (left); and the number of metal-based 3D printer systems (right)



Source: Wohlers Report 2018 [594]

Figure 96 (left) shows the units sold by providers of 3D printer systems for all types of AM, including polymer ones. The chart on the right shows the number of suppliers per country for metal AM systems. A detailed split between types of AM systems cannot be made; the technology is only identifiable per supplier. Overall, the EU has 18 out of 62 suppliers for all metal technologies combined (29 %), 10 suppliers of PBF systems compared with 40 globally (25 %), 3 suppliers for DED compared with 14 globally (21 %), 3 out of 7 for EBM systems and 3 out of 9 for 3DP material jetting systems.

Vertical integration versus collaboration along the value chain

One of the particularities of the aeronautic AM value chain is that integrators and assembly producers at supply level seem to be moving along the value chain. This is the case, for example, for some OEMs dealing with raw materials, such as GKN through Hoeganaes or Airbus with its Scalmalloy for structural applications. GE absorbed two AM companies in 2013 – Morris Technologies and Rapid Quality Manufacturing (RQM). More recently, GE Additives has bought a majority stake in ARCAM (Sweden) and ConceptLaser (Germany) and owns AP&C, which appears to be the powder supplier for the group. These recent developments are highlighted in Figure 97. [595]

As a tentative conclusion, in Europe, vertical integration appears to take place more in the form of partnerships, where for example GKN and Hoeganaes have merged and are in close cooperation with EOS in Finland as the 3D equipment producer. [596] Similarly, SLM Solutions and TLS Technik (Germany) seem to have built a joint venture [597] for the provision of 3D metal powders. Different business models can be found, either leading to a concentration of AM capabilities under the same roof or to a distribution of capabilities across an eco-system that is formed around one (or more) OEM(s) or integrator(s).

Moreover, assembly producers and system integrators are large multinational companies making significant investments in AM. They collaborate with printer manufacturers but also with AM service providers. Many of the companies above, plus others, also provide various types of software, prototyping, design validation and advisory services. These are not yet listed separately, but can substantially affect the functioning of the supply chain. In this regard, a considerable amount of vertical integration is observed, which shall be elaborated upon in the next chapter. This leads the value chain towards more decentralisation. Service providers (including software providers) also collaborate with

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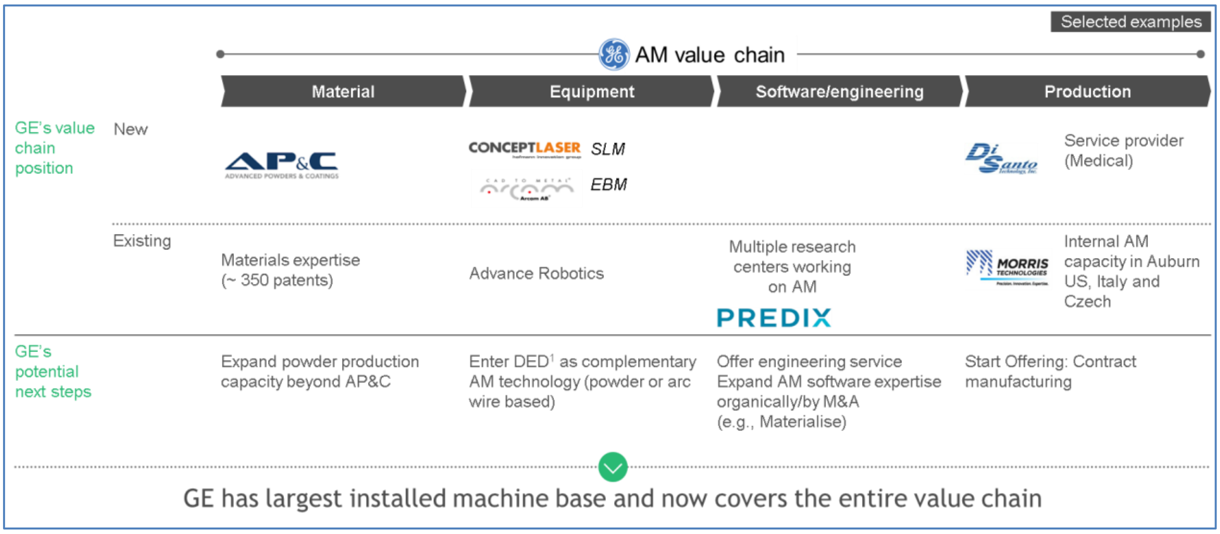
[594] Wohlers Report 2018, 3D Printing and Additive Manufacturing State of the Industry, Annual Worldwide Progress Report, Wohlers Associates, Inc., 2018
[595] BCG Additive Manufacturing, 2018
[596]http://www.gkngroup.com/hoeganaes/media/news/Pages/GKN-and-EOS-collaborate-to-transform-Metal-AM-into-digital-manufacturing.aspx
[597] http://www.pm-review.com/slm-solutions-to-begin-metal-powder-production/

integrators (Airbus, Boeing, Bombardier and Dassault). RTOs are collaborating closely with the aeronautic industry (mainly in western European regions). Collaborations also exist across value chains and the same companies active in the aeronautic field have links with both the defence and space sectors. Similarly, collaborations can be seen between the aeronautic and automotive industries.

The distribution of 3D-printing capabilities in Europe is not homogenous, with western regions at the forefront. The adoption and deployment of AM is strongest in countries which have historically been strong in aeronautics: France, Germany, the UK and Italy.

Figure 97 Increasing vertical integration in the 3D printing supply chain



Source: BCG Additive Manufacturing, 2018

6.5.3 Supply chain of civil versus military 3D printing applications

There are clear similarities between 3D printing for civil aircraft manufacturing and military and space applications; all subject to difficult operating environments and high levels of investment. Although they differ strongly in many regards (mainly regarding the number of parts produced), they involve common players and share technical concerns. If 3D printing provides significant performance benefits over alternative fabrication techniques then widespread adoption (for civil and subsequently military applications) is likely to follow.

Looking at the aerospace domain, considering that most of the integrators (e.g. Airbus and Boeing) and OEMs (e.g. GKN) have not only civil but also military activities, it is likely that the supply chains for 3D printing for civil and defence applications will be rather similar. One difference between the two sectors in recent years is that commercial aerospace has been doing rather well, macro-economically, whereas defence budgets and thus R&D investment in new technologies has been more constrained. As a result, the defence sector may have a slower adaptation pace compared with the civil sector. [598]

The domain of 3D printing for repair and maintenance of equipment seems of particular relevance for the defence sector, for example in remote zones and in operation. This domain is poorly documented and will require further analysis.

For 3D printing, the main security of supply issues for raw materials are the high EU dependence on China for the supply of scandium, and on Brazil for the supply of niobium. To a lesser extent, this also applies to the alloying elements of Co, V, W and

[598] DefenceIQ, Additive Manufacturing in Aerospace, Defence & Space, Trends and Analysis 2016

Mg, which are similarly dependent on China, and to Hf/Zr, which has significant production in France but 57 % comes from Russia, Ukraine and the USA.

For processed materials, the main concern is limited European supply of metal AM wire products, with only one supplier identified, in Belgium. There is little information available in this area when compared with that available on powder suppliers. Powder production is evenly distributed around the globe, with a rather high presence of EU manufacturers for stainless steel and nickel alloys. Based on the number of powder suppliers, the USA and Canada have a >50 % market share in aluminium alloys.

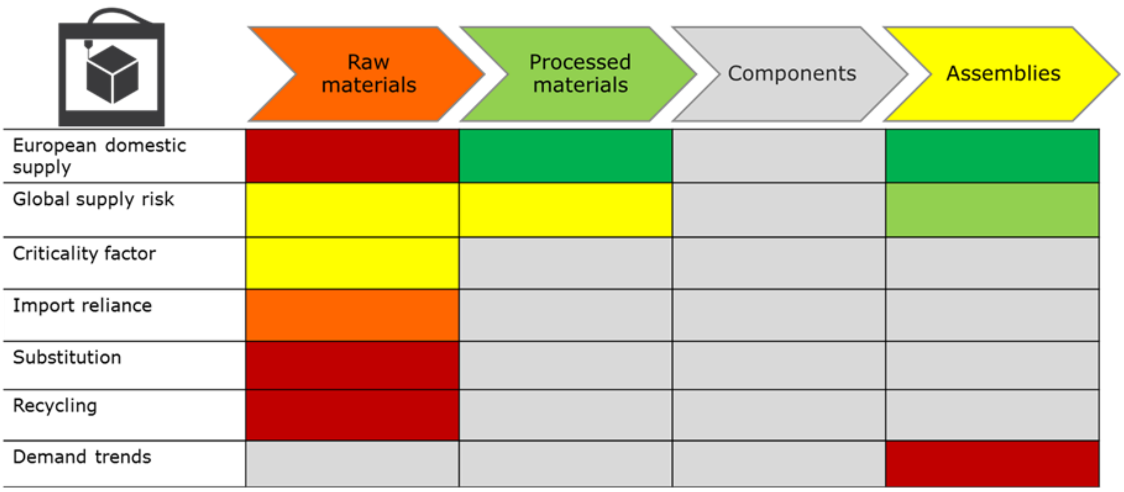
For 3D printer systems, information is available from Wohlers [599] on the total unit shipments for each country from 2007 to 2017, for the combined total of polymer and metal AM industrial machines with a value of USD 5 000 or more. On this basis, the EU has only 20 % of market share and the USA and Israel (both Stratasys locations) represent over 71 % of units. In analysis of the number of manufacturers of metal AM machines, the EU performs slightly better. Nevertheless, for the two key technologies, PBF and DED, the dependence is 75 % and 79 % respectively. For PBF, China has a high number of suppliers with 35 %, followed by the USA with 18 %. However, China has many relatively new entrants to the market with low unit shipments, whereas the USA has the manufacturers with the largest global market shares. Similarly, for DED technologies, the USA has 36 % of the total number of suppliers, followed by China with 21 %.

On the software side, Europe is also relatively well placed: software enabling 3DP needs to be distinguished here between product design software like CAD (USA-based) and CATIA (EU-based), software which converts drawings for the actual manufacturing process, and post-processing software. In general, the USA is more advanced in this area, but European companies are, again, well represented.

6.5.4 Overview of the supply risks for the 3D printing supply chain

The performed bottleneck assessment has shown potential **high risk of supply issues only for the raw materials step** and **medium supply for the last step of the supply chain (supply of AM metal systems)** mainly due to expected rapid demand growth (Figure 98).

Figure 98 Overview of supply risks and bottlenecks in the supply chain of 3DP



Source: JRC

[599] Wohlers Report 2018, 3D Printing and Additive Manufacturing State of the Industry, Annual Worldwide Progress Report, Wohlers Associates, Inc., 2018

6.6 Opportunities for research and policy actions for additive manufacturing (3D printing)

The analysis reveals specific opportunities for follow-up research. Dedicated research is needed regarding the **effectiveness of specific policy tools and instruments**, and in particular on the potential policy implications of the actions proposed in the AM-Motion roadmap, for developing and maintaining a strong and sustainable European AM sector in the long term. This applies specifically to the following areas.

- **Enhancing convergence between key emerging technologies** such as artificial intelligence, robotics, sensing technologies and, of course, 3D printing.
- **Enhancing education and training to improve the availability and skills of the workforce.**
- **Improving business and finance conditions.** Bringing prototypes to production, for example, by securing their reproducibility, remains a critical point for the industry.
- **Improving standardisation to achieve high quality, consistency and lower costs for AM powders.** Standards and quality assurance systems need to be developed, in particular for the finishing, testing and certification steps after parts manufacturing.
- Further **investigating the availability and customisation potential of wire products.**
- Developing **more effective IPR strategies**.

Finally, a more centralised, strategic and comprehensive discussion is recommended, on the role and future competitiveness of the EU metal AM sector for Industry 4.0 developments; and in particular on material availability, sustainability, IPR protection and digital security for key military and civil supply chains.

Other areas of concern are summarised below. According to DG RTD, after the AM-Motion report, numerous discussions with the AM community identified AI, skills and industrial scale-up as key areas of concern.

- **Bringing artificial intelligence to the world of AM** can lead to faster processes by giving smart advice on design choices, materials and technologies.
- **Education and training to plug skills gaps** currently faced by industry: technicians, engineers, designers and operators specialised in technical and non-technical aspects of AM.
- AM is still perceived too much as a technology solution instead of a business solution. Hence, there is a need to **improve business and financing by bringing prototypes to production more quickly.**

The Lamy report on maximising the impact of EU Research & Innovation programmes, LAB-FAB-APP [600] , reflects these areas of potential for policy actions. Its main recommendations, 2,3,4 and 8, are of particular relevance for AM:

- Promote and invest in innovative ideas with rapid scale-up potential;
- Educate for the future and invest in people who will make the change;
- Future programme pillars should be driven by purpose and impact;
- Mobilise and involve citizens, stimulate co-design and co-creation.

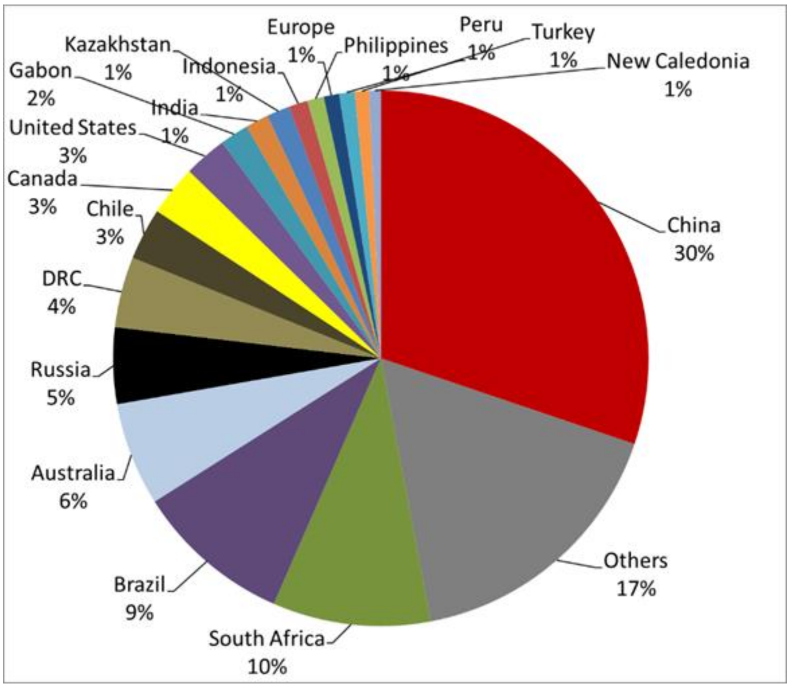
[600] European Commission, Report of the independent High Level Group on maximising the impact of EU Research & Innovation Programmes, 2017; http://ec.europa.eu/research/evaluations/pdf/archive/other_reports_studies_and_documents/hlg_2017_report.pdf

As the main source of information in this area, the AM-Motion project provides a thorough overview of cross-cutting technical and non-technical challenges as well as those specific to the aerospace sector. [601] The AM-Motion report (Chapter 5) primarily describes actions proposed for funding in upcoming European projects and contains a comprehensive list of needs and suggested activities to strengthen European supply chains. Combined with additional actions, these suggested (policy) actions are grouped and summarised within four clusters to maintain Europe's strong position in the long term. In addition to a **few potential bottlenecks in the raw materials supply** chain stage, three other areas are identified for potential action below. These are **technology development**, **standardisation** and **protection/valorisation of IPR**.

Raw material supply bottlenecks

A key area for policy action arising from the analysis is the **diversification of raw material extraction** to reduce dependence on a small number of countries for certain materials. For 3D-printing, this applies specifically to **titanium, REEs, vanadium, scandium** and **niobium**. Improving relations and mining conditions under the scope of new trade agreements, with Australia and Canada for instance, is of particular relevance. An overview of raw materials suppliers for 3DP is presented in Figure 99.

Figure 99 Raw materials suppliers for 3DP: overview



Source: European Commission, 2017, Study on the review of the list of critical raw materials

Europe is years ahead in wire-based DED technologies. However, according to BCG, Europe's supply chain for metal wires is extremely poor, with very few organisations producing ingots or rods. The majority is imported from China with very little control. More important, from an R&D perspective, is the resulting **lack of customisation capabilities**. This means that in the case of a new chemical composition, it is virtually impossible to have products made in the EU. This applies particularly to aluminium and titanium wire products. Most of this is addressed more elaborately in the AM-Motion roadmap, for which the most relevant items are summarised in Annex 3 – Policy and research actions 3D printing. In the case of raw materials, the roadmap's technical

[601] AM-Motion project, Deliverable 5.4 – Final AM Roadmap, October 2018

cross-cutting action number 11 focusses on the availability of **high quality, environmentally friendly and cost-effective materials**. According to this action, the AM community relies on a limited selection of conventional feedstock materials and the range of available materials needs to be expanded, to include, for instance, high-class titanium powders. Graphene-based 3D printing through fused filament fabrication is expected to be the next big innovation in additive manufacturing. [602]

Technology development

The technological limitations outlined above are not expected to remain for long: **the high speed of development will provide** more capable machines and high-quality materials **for each part of the market, including the military sector** with its high-performance demands. The patent analysis confirms this pace of development. In the past, around half of patents were related to processed materials. In recent years, patents relating exclusively to technology have taken centre stage. The analysis shows that the **current disadvantages** of metal 3DP **are the focus of much research worldwide.**

The 3D printer market is currently very immature and therefore still open to successful intervention. However, the pace of development in China appears to be way ahead of the EU. This is addressed explicitly in the AM-Motion roadmap in a range of technical cross-cutting actions, focussing on:

- The role and **importance of recycling parts and unused powders**, including guidelines for maintaining or restoring material properties (Technical cross-cutting action 8);
- **Developing a knowledge repository of materials and process parameters** (Technical cross-cutting action 9);
- The **identification of powder properties** for quality and consistency of powder production (Aerospace action 3);
- The **development of new sustainable materials and processes** and related characterisation in the field of multifunctional materials, multi-materials and materials with highly improved functionality for aerospace applications (Aerospace action 4);
- **Increasing the size of envelopes for the production of larger airframe structures** through AM technologies (Aerospace action 13).

The use of 3DP for **repair and maintenance** of equipment is of particular relevance **for the defence sector**, for operations in remote locations for example. This domain is poorly documented and r**equires further analysis and R&D effort**.

Standardisation and certification

Certification and quality assurance have been identified as a key threshold for AM. The option most preferred by respondents to the DefenceIQ survey [603] was to have these arranged by European or international bodies like ESA, EDA and ISO/ASTM. The preference in the aerospace industry is to have a stable international standardisation process. At the moment, different standards are observed in the USA, covering different tasks and aspects. This is also addressed in the AM-Motion roadmap. The development of standards is paramount for the certification process in the aerospace sector in particular. Needs are identified for:

- **Process-, material- and application-specific design guidelines** (Technical cross-cutting action 3);

[602] http://namic.sg/wp-content/uploads/2018/04/global-additive-manufacturing-market_1.pdf
[603] DefenceIQ, Additive Manufacturing in Aerospace, Defence & Space, Trends and Analysis 2016

- **Increased industry engagement on standards development**, addressing fragmentation of standardisation initiatives (Technical cross-cutting action 10);
- The further **development of quality management systems** (Technical cross-cutting action 12);
- **Enhancing convergence between key emerging technologies** including artificial intelligence, robotics, sensing technologies and 3D printing (Technical cross-cutting action 15);
- **Improved safety assessment and management**, and guidelines and education on EHS challenges with AM (Non-technical cross-cutting action 4);
- The **development of non-destructive testing (NDT) and inspection criteria** (Aerospace action 12).

Digital Security and the protection & valorisation of IPR

Europe is particularly strong in innovation in metal-based AM. This requires particular attention to the functioning of IP regimes to protect developed copyright and to the subsequent valorisation of IP that fosters global and European aerospace industries in a fair manner:

- There is a need to develop and promote **effective intellectual property strategies in AM** and better awareness of IPR issues (Non-technical cross-cutting action 7). Of particular interest for security reasons is the protection of information provided with or within CAD files.
- There is a need to promote the **creation of a suitable IP framework** (Non-technical cross-cutting action 8) since the understanding of the implications of AM in relation to original designs will take some time to be developed.

For more information on the specific activities proposed, see Annex 3.

6.7 Additive manufacturing (3D printing): summary

The additive manufacturing market is expected to grow substantially, with a CAGR of between 15 % and more than 30 % in the next few years. It is expected that the aerospace, automotive, and medical industries will account for 51 % of the 3D printing market by 2025. 3D printing in medical devices is expected to grow by 23 % between 2015 and 2025, while for the aerospace and defence industries an annual growth rate of around 26 % is expected. [602]

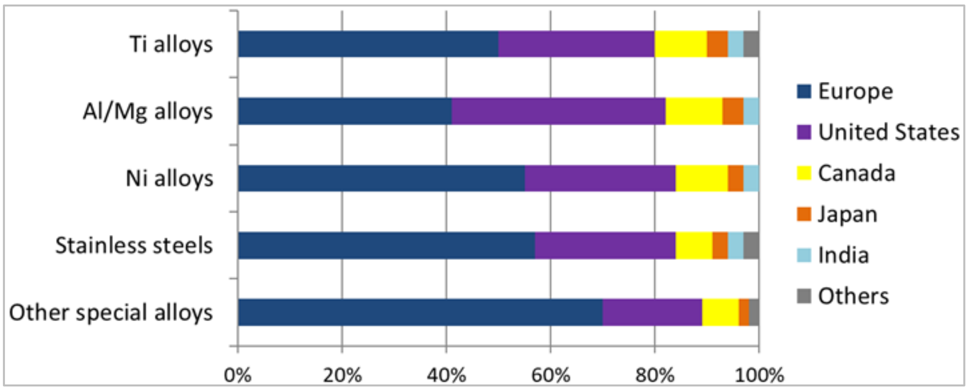
The focus on raw and processed materials for AM has delivered a more comprehensive and up-to-date overview than we have had until now. The often neglected early stages of the supply chain are a key starting point. This is particularly true for 3DP, where mastering the availability and quality of raw and processed materials for further processing offers a crucial competitive advantage.

In total, 17 raw materials and 5 processed materials were identified as relevant for AM and analysed in the study. 8 of the 17 raw materials are flagged as critical for the EU economy, namely Co, Mg, V, Hf, W, Sc, Nb and silicon metal. China is shown to be the major supplier of CRMs for 3D printing, delivering 44 % of them, followed by Brazil (ca. 14 %) and the Democratic Republic of the Congo (9 %). The analysis showed that China is also the major supplier of one third of the raw materials required in this technology. Other suppliers are South Africa (10 %) and Brazil (9 %). Europe delivers only 1 % of the raw materials for 3D printing. It should be noted that 50 % of the raw materials are supplied by numerous smaller supplier countries, providing big opportunities for supply diversification.

Europe is shown to be the major supplier of the processed materials required in 3D printing technology, with around 55 % supply share. It is followed by the USA (29 %), Canada (9 %), Japan (3 %) and other smaller suppliers delivering the remaining 4 %.

The country production shares (based on number of suppliers) of processed materials relevant to 3D printing are visualised in Figure 100.

Figure 100 Country production shares of processed materials relevant to 3DP



Source: JRC

Europe has a relatively strong position in 3D printing, and in metal-based AM in particular. Europe is the key supplier of AM metal systems globally, providing more than one third, followed by the USA (24 %), China (23 %) and Japan (6 %). Around 13 % of the systems are provided by small players.

The bottleneck assessment shows a potential high risk to supply for one step of the supply chain: raw materials. No significant supply issues are to be expected for processed materials and moderate supply risk is perceived for AM systems due to high demand expected in future.

Relatively speaking, there are fewer bottlenecks identified for AM than for the other technologies in this report. Europe has a relatively strong position in 3D printing, and especially in metal-based additive manufacturing for aerospace applications. At the same time, some bottlenecks have been identified at the early stages of the supply chain, with a high dependence on raw materials, in particular for titanium and strategic minor elements used in special alloys, like scandium and niobium.

Whereas previous research by EASME has highlighted that there is 'a serious lack of capabilities in terms of high quality powder supply, and in particular in the fields of aluminium, magnesium and titanium', a different conclusion can be drawn here. Europe is strong in the production of 3DP powders, and in particular for steel- and nickel-based alloys. Europe is less well represented in aluminium and titanium powders (dominated by the USA and Canada) and appears to have a gap in the supply chain in the case of metal wire products. The latter could not be further substantiated due to a lack of data. In the case of aluminium, and especially titanium wire products, this may result in a lack of customisation capabilities.

The key challenge identified for 3DP is achieving sufficient quality, cost and consistency to meet certification demands. There is a clear need for standardisation of metal AM powders and wire on the one hand, and the quality and reproducibility of parts on the other. This applies to aerospace in particular, with strict safety and performance requirements. Europe is well represented in the latter stages of the supply chain. Here, the main concern is to maintain a leading role against the rapid pace of technological development. The 3D printing market is growing rapidly via both top-down R&D investment from large integrators like Airbus and its direct suppliers, as well as bottom-up development by many innovative SMEs, who are maturing the technology quickly. These smaller enterprises could very well overtake traditional manufacturing over time. Mastering the availability and quality of raw and processed materials is vital for the EU to remain competitive, innovative and sustainable in the field.

7 EU funded R&D projects

The key terms used to select relevant FP7 and H2020 projects are described in Table 27.

Table 27 List of key terms used for selecting the FP7 and H2020 projects of relevance

Technology	Key terms used
Batteries	Lithium-ion battery, LIB, Li-ion battery, Lithium(Li)-ion cell(s), Lithium-battery pack
Fuel cells	Fuel cell(s), Membrane electrode assembly (MEA), Fuel cell electrodes, Hydrogen, Hydrogen storage, Hydrogen tanks
Robotics	Robotics, Robotic systems, Exoskeleton
Drones[604]	Unmanned aerial vehicle (UAV), unmanned aircraft, unmanned aerial system (UAS), Micro UAV (MAV), Nano UAV (NAV), High-Altitude Long Endurance UAV (HALE), Low-Altitude Long Endurance UAV (LALE), Low-Altitude Short Endurance UAV (LASE), Medium-Altitude Long Endurance UAV (MALE), Vertical take, VTOL, Unmanned Combat Aerial Vehicle (UCAV), Remotely piloted aircraft, Remotely piloted aircraft systems (RPAS), multirotor, multicopter, octocopter, hexacopter, quadrocopter/quadcopter, tricopter, drones
3D Printing	Additive Manufacturing, 3D printing Aerospace, Metals, alloys, Directed Energy Deposition (DED), Direct Metal Deposition (DMD), Electron Beam Manufacturing (EBM), Laser Metal Deposition (LMD), Powder Bed Fusion (PBF), Selective Laser Cladding (SLC), Selective Laser Melting (SLM), Selective Laser Sintering (SLS)

The technology, '3D Printing', required a more tailor-made approach, reflecting the specificity of additive manufacturing technology with regard to both the development of printer technology, and the AM materials used (metal powder etc.). Further, projects predominantly focusing on coordination and support, training, or polymer-oriented AM were filtered out from the initial list of AM projects by analysing each one individually. This was amended and complemented with the support of one particular AM project which provides a dataset on past and ongoing EU-funded AM projects, and with the authors' own assessments regarding the focus of the projects (processes for powder metal, design, CSA, battery/polymer, polymer/nano, training support etc.).

There are several limiting factors when aiming to become a market leader in a certain technologies. These factors all need to be addressed in a consistent way, including those related to the potential supply chain bottlenecks. Strategies are required to make the supply chain more resilient at various levels, for example by advancing options for substitution (e.g. raw material, processed material, component level), or increasing the resource efficiency. To achieve this, it is important to increase the innovation capacity for the five technologies by, for example, stimulating adequate research funded by both public and business sources. This chapter analyses the role of EU-funded R & D projects in the five technology areas.

The EU supports research and innovation with a series of dedicated R&I programmes. With nearly EUR 80 billion of EU funding available for the period 2014-2020, the current

[604] From the pre-filtered projects, those ones were excluded that addressed the rotorcraft industry in general, as its scope on helicopters was considered too unspecific regarding the purpose of this study.

EU R&I programme, Horizon 2020, exceeds the preceding programme, FP7, by almost half, and is thus the biggest EU R&I programme ever. The total investment is actually higher than EUR 80 billion, as the funding schemes are designed to attract additional private investment. Horizon 2020 is the financial instrument which implements the 'Innovation Union', a Europe 2020 flagship initiative aimed at securing Europe's global competitiveness. H2020 promises breakthroughs, discoveries and innovations and route to market. [605] This chapter monitors recent EU funding regarding the support of research, technological development, and innovation in the area of the five technologies. The analysis comprises the following steps:

1) Determination of EU R&D projects [606] addressing one of the five target technologies:

a) Identification of possibly relevant past and ongoing projects funded by FP7 or H2020; filtering the projects by a selection of key words per technology, in the fields 'acronym', 'title', and 'objectives' of the CORDIS database. [607] The key words applied are shown in Table 27. [608]

b) Verification of relevance of the projects by plausibility check, using the project description ('abstract') against the scope study with regard to each technology (if applicable). [609]

2) Visualisation of the results for the period 2007-2023:

a) histogram on the number of past and ongoing projects, and

b) histogram on the summary budget volume of all projects identified as relevant. For multiannual projects, the annual share was calculated by the distribution of the project budget by calendar years. For simplification, incomplete calendar years were considered as full calendar years. The overestimation of the average project duration was considered negligible for the purpose of analysis in this sub-chapter.

The results show the trend how intensively each of these technologies was addressed by the EU Framework Programmes for Research and Technological Development (number of projects in FP7, Horizon 2020). The earliest FP7 projects covered start in 2007, and the latest H2020 projects are scheduled to end by 2023. The visualised results are thus considered as appropriate proxies for monitoring the course of intensity of EU-funded research in each of these five technologies. The results are less appropriate for **comparing R&D intensities across technologies**, because certain types of project (e.g. pilot projects), or projects in certain research fields, empirically imply higher funding than other ones, due to technical requirements or an above-

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[605] See https://ec.europa.eu/programmes/horizon2020/what-horizon-2020 (Website accessed 18.04.2019)

[606] The analysis was carried out on the research programmes FP7 and H2020. Former research programmes were not considered, as rapid developments limit the relevance of older projects.

[607] CORDIS: Community Research and Development Information Service

[608] For each framework programme, the present set of projects was taken into account. For FP7 with all its various programmes this dataset comprised 25775 projects, for Horizon 2020, this dataset comprised 20 879 projects.

[609] The plausibility check was performed for all five technologies. Without this plausibility check, a significant overestimate was likely, as step 1.1 provides any project that shows links to the key words applied. For example, "software robotics", or "textile robotics" had to be excluded from the analysis, as these exceed the scope of the study. However, plausibility checks are not based on detailed assessments, thus there is a certain degree of uncertainty. This means that in the context of the study, emphasis was put on the completeness of the plausibility check, but not on the accuracy. However, when comparing along the timeline, the interpretability of trends is not questioned. Moreover, a deeper manual check was introduced for unmanned aerial vehicles and 3D printing, as for these technologies deeper checks were required to assure the relevance of the entries. E.g. for the UAV technology: certain projects simply *apply* the state of the art of available UAV technology for certain surface monitoring applications. By doing so, such a project *performs research by* UAV technology, but *without bringing innovation to the UAV technology*; in such a case it needed to be disregarded.

average intensity of labour. Moreover, it is expected that certain technologies show relevant research funded on national and regional levels, which are not covered by this analysis.

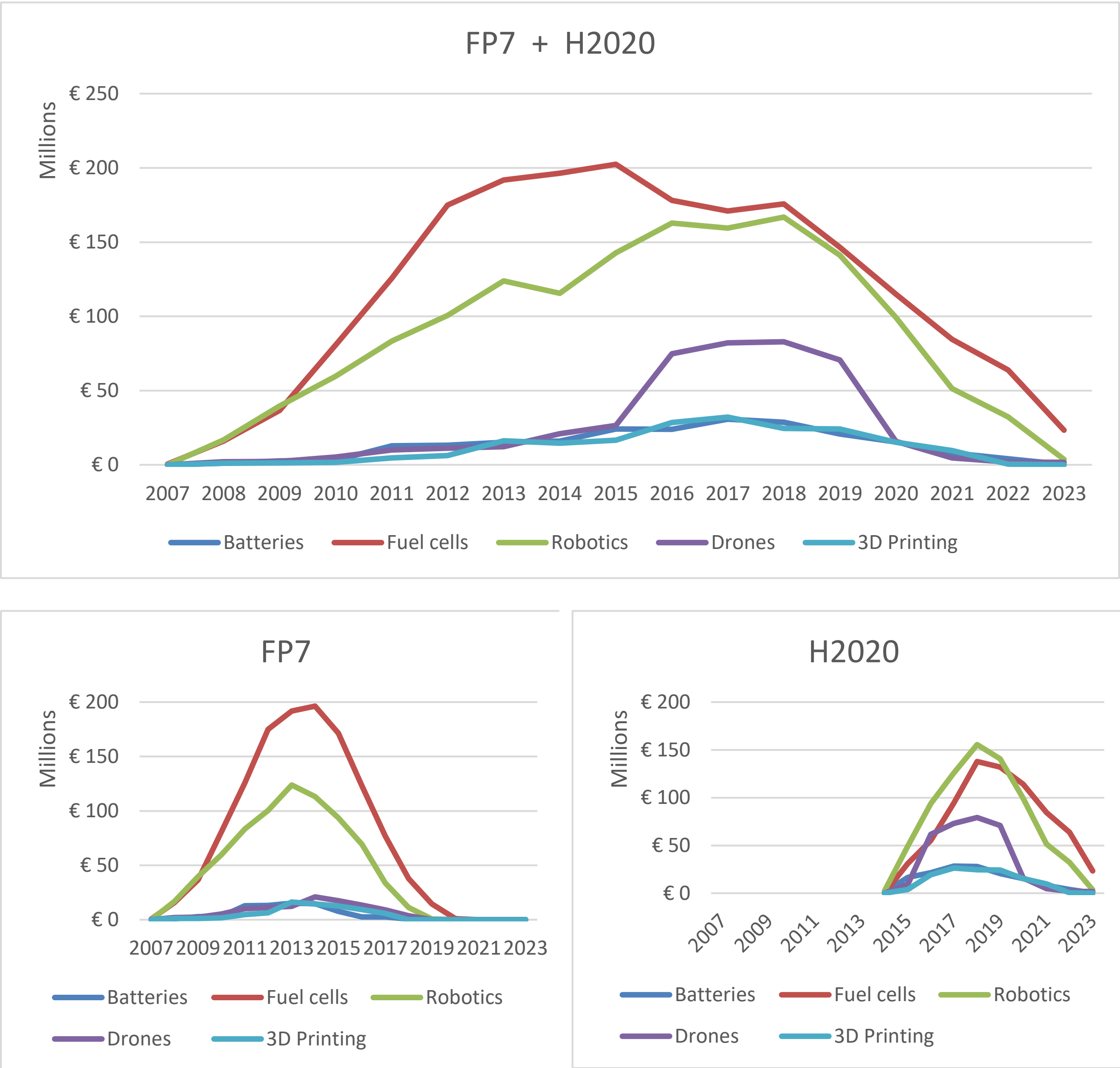
As the five technologies in this study are not defined in a strictly complementary way, they show certain overlaps, and a project can therefore be of relevance for more than one technology. Where attributable, the project was assigned to the technology showing a stronger linkage. A particular challenge was the overlap between robotics and unmanned vehicles, as the term 'robotics' is used with abundance in project descriptions. For the purpose of this analysis, we distinguish robotics from unmanned vehicles using the main design principles underlying the product, to which the research is related: if the design principle is related to the mobility of the final product, then the project was assigned to 'unmanned vehicles', for example where existing UAVs were used and adapted or advanced for the purpose of their final use. However, if the main research novelty is a new capability whose geographical scope and applicability was just amended by extended mobility, then the project was assigned to the technology field 'robotics'. For example, the development of a robot for tunnel inspection (FP7 ROBO-SPECT) was categorised as a robotics project, because its main novelty is the capacity to detect and assess tunnel deterioration (with simple mobility capacity as a side effect).

Figure 101 shows the total budget of FP7 and H2020 projects [610] related to the five technologies for the period 2007-2023. Predecessor and successor framework programmes are not considered in this analysis. The lower charts show the same data split by the two framework programmes. Fuel cells and robotics dominate the EU research efforts of the five technology fields to a significant degree. The FP budget for fuel cells and robotics exceeded EUR 100 million annually in 2011 and 2012 respectively, while the annual EU research efforts on batteries, drones and 3D printing stayed clearly below EUR 35 million annually, with the exception of drones, showing a distinct plateau between EUR 70 million and EUR 85 million annually for the period 2016 to 2019. All technologies apart from fuel cells experienced higher maximum research funding under H2020 when compared with FP7 funding.

The two framework programmes show a distinct funding overlap for the period 2015-2018, and to a lesser extent also for the adjacent years 2014, 2019 and 2020. Due to the fading out of the H2020 framework programme, research efforts (number of projects, funding volume) drop clearly from 2019 on, in particular for the more intensely funded technologies. The observations for the period 2019-2023 are seen as the lower limit of the research efforts, as further projects will be granted by H2020 and its successor framework programme. The preliminary character of the project overview for the years 2019-2023 is indicated in Figure 102 to Figure 106 by transparent bars.

[610] Predecessor and successor framework programmes are not considered in this analysis.

Figure 101 EU funding by framework programmes FP7 and H2020 for the five technologies in focus



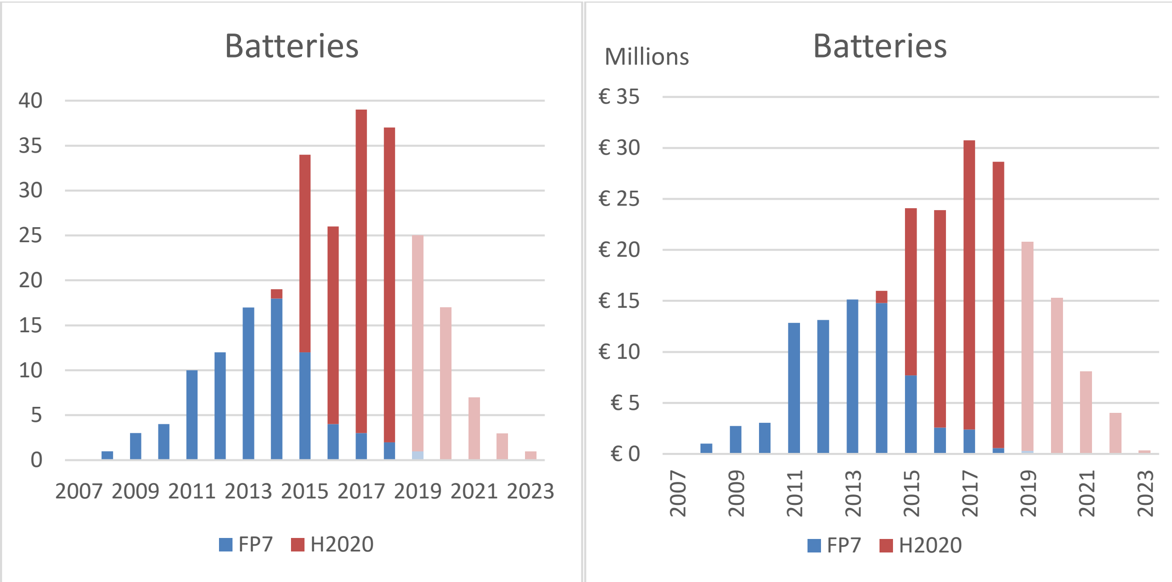
Source: JRC

7.1 R&D projects on batteries

The number of funded EU projects with focus on batteries peaked in 2017 (39 projects). The massive starting of new H2020 projects overcompensated the drop in FP7 projects after 2014. Accordingly, the peak in numbers of projects and total budgets spent on EU batteries research appeared only in 2017 (Figure 102). The histogram on the left shows the number of projects on this technology for each year, while chart on the right shows the annual volume of the related budgets. Preliminary data are presented in transparent colours.

Focus areas identified were the **improvements in charging performance, and increases in energy intensity** as demanded by several types of electronics that supplied the global market recently.

Figure 102 EU funding by framework programmes FP7 and H2020 for batteries



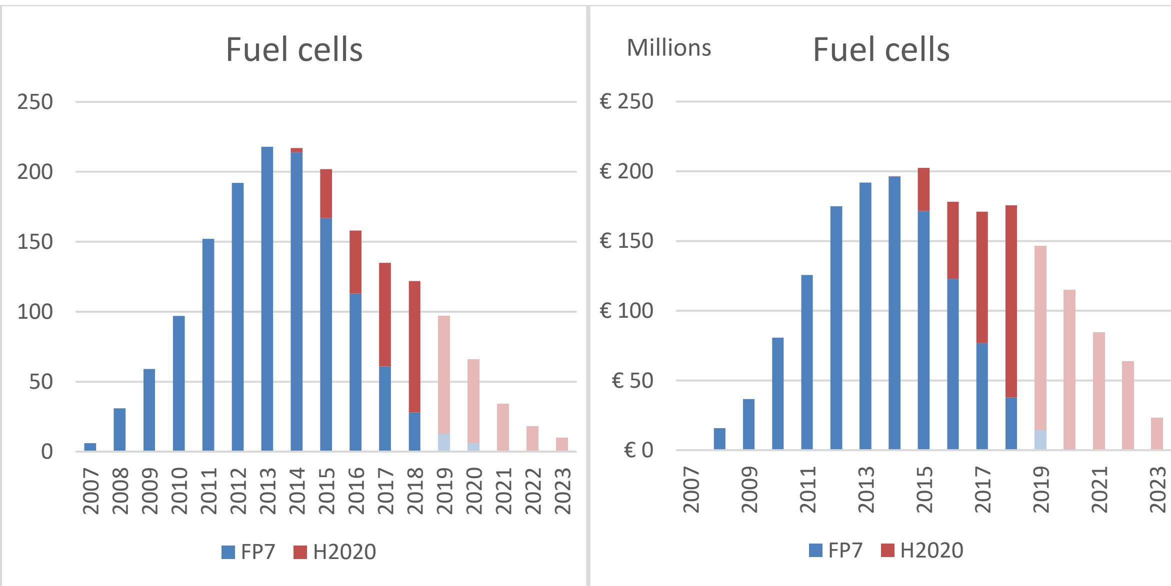
Source: JRC

7.2 R&D projects on fuel cells & hydrogen storage

The number of funded EU projects on fuel cells and hydrogen storage reached its maximum in 2013 (218 projects), while the funding volume peaked two years later, in 2015. This indicates an increase in the average budget size of the research projects.

In contrast with the other research areas, FP7 is clearly the dominating funding programme; H2020 cannot counterbalance the drop in number and volume of research projects (Figure 103). The left histogram on the left shows the number of projects on this technology for each year, while the chart on the right shows the annual volume of the related budgets. Preliminary data are presented in transparent colours.

Figure 103 EU funding by framework programmes FP7 and H2020 for fuel cells



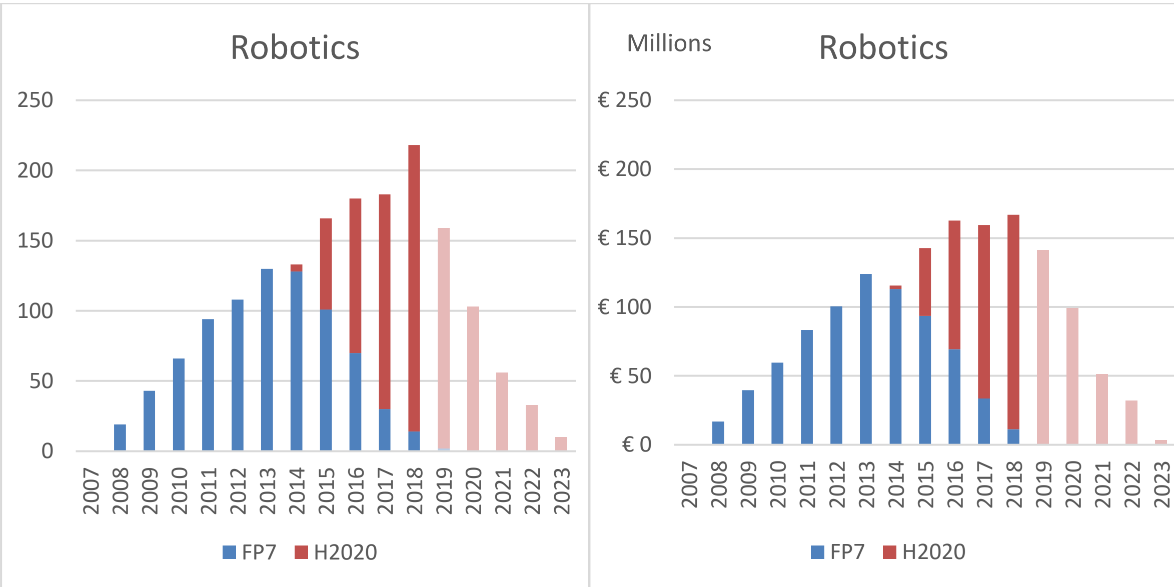
Source: JRC

Much of the effort in fuel cell technology has focused on the **technical improvement of the electrodes and electrolytes** and also on to the **systematic optimisation of fuel cell technology for intermediate storage of renewable energy**, along with the **required increase of energy conversion efficiency**. Some projects address the issue of technology upscaling and the commercialisation of fuel cell production, but more work is required in this area. A rise in new projects seems to be crucial in order to ensure a global role for EU fuel cell development. Areas of focus identified were the improvement of charging performance, and an increase in energy intensity as demanded by several types of electronics.

R&D projects on robotics

Across the five technologies, robotics and UAV are the most progressive, in the sense that the number and budget of projects have grown until 2018 and are thus clearly dominated by H2020 funding. For robotics this means that the research peak was not achieved before the midpoint of H2020. The three years with the highest annual research budgets are 2018, 2019 and 2017 (Figure 104). The left histogram shows the number of projects on this technology for each year, while the right chart shows the annual volume of the related budgets. Preliminary data are presented in transparent colours.

Figure 104 EU funding by framework programmes FP7 and H2020 for robotics



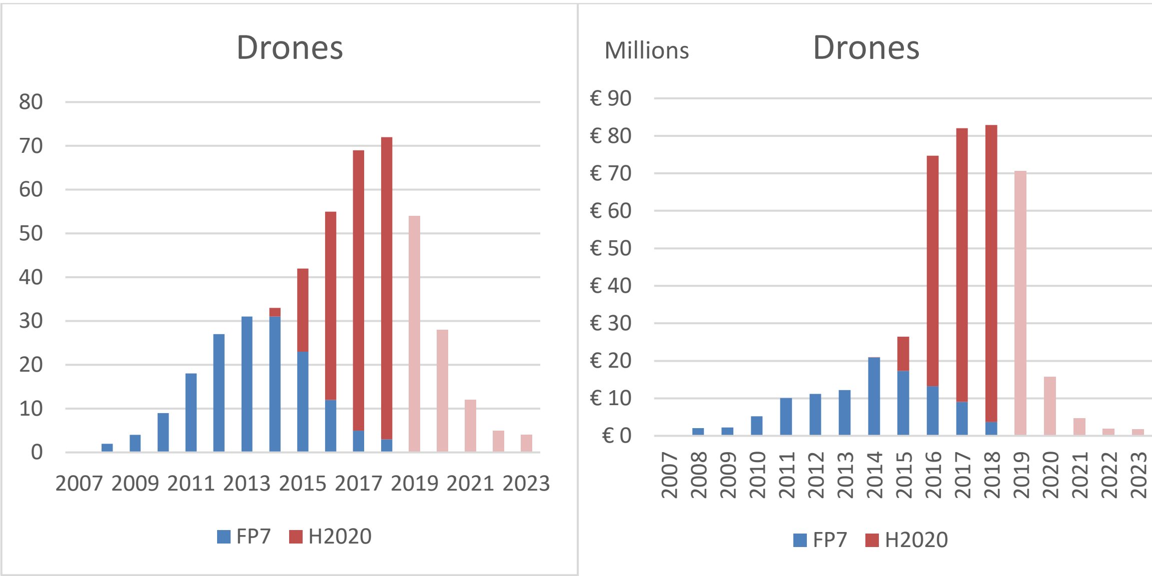
Source: JRC

The Robotics technology is very diverse and is related to numerous other electronic applications that integrate a certain level of smart control, autonomy, or artificial intelligence. Autonomy is also becoming a key issue for 'mobile robots' and unmanned vehicles with specialised capabilities. Key research topics identified are the **development of robotics software and the advancement of the human-robotics interface**. A high and increasing number of projects relate to the field of home care and elderly care robots, which support people in need of care. Such a care function is often related to physical support, but sometimes goes beyond that. Due to the strong influence of artificial intelligence, the **legal and moral responsibilities of robotics behaviour** is another field of research worth noting.

7.3 R&D projects on UVs

Unmanned aerial vehicles (UAV) are often considered as a special type of (mobile) robots, thus it comes as little surprise that also the research on the UAV technology, similar to robotics, has received a strong push in number and budget volume by the H2020 programme. In fact, when comparing H2020 with FP7, the maximum number of projects more than doubled to ca. 65 projects in 2018, and the maximum annual budget nearly quadrupled to almost €80 million in 2018 (Figure 105). The left histogram shows the number of projects on this technology for each year, while the right chart shows the annual volume of the related budgets. Preliminary data are presented in transparent colours.

Figure 105 EU funding by framework programmes FP7 and H2020 for drones



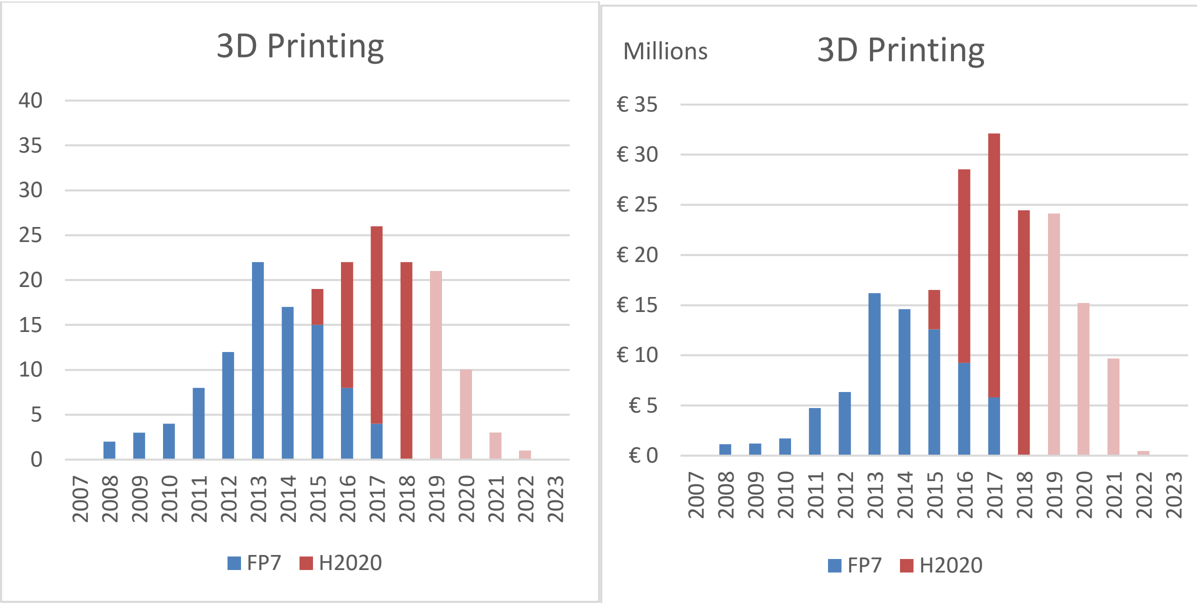
Source: JRC

The analysis detected R&D projects related to UAV issues, including technical solutions to increase the UAV performance, the required infrastructure, the integration of UAV in safety systems, as well as fostering tailor-made UAV based services, which are expected to push future UAV developments indirectly.

7.4 R&D projects on 3D printing

3D printing was already a common research field in FP7, with a peak of more than 20 active projects in 2013. This was followed by a slight drop, before research efforts rose again by the H2020 programme and peaked in 2017 for a second time. As the rise from the first to the second peak was modest for the number of projects, it is very sharp in budgetary terms (almost doubling to EUR 32 million per year). This development implies a massive rise in average project size (budget) (Figure 106). Altogether, the H2020 projects represent roughly EUR 100 million. It is noteworthy that half of the H2020 funds are destined for the M-ERA.NET 2, the ERA-NET for materials research and innovation. The histogram on the left shows the number of projects on this technology for each year, while the chart on the right shows the annual volume of the related budgets. Preliminary data are presented in transparent colours.

Figure 106 EU funding by framework programmes FP7 and H2020 for metal-based AM technology



Source: JRC

In parallel with the rapid commercialisation of metal AM processes, research activities in this area have grown. Much of the research assesses the potential benefits of AM regarding design, technical performance and the environment. The key disadvantages of metal AM are heavily researched, such as deposition speeds and surface quality issues, which had been hindering wider proliferation. The aerospace industry is a typical illustration of rapidly growing interest in metal AM-based volume production. In the area of improved surface finishing, much research is focussed on hybrid processes offering post-processing surface treatments in various forms. Several projects explicitly address the material level by characterising the material (AddMan, NANOTUN3D) and improving material performance (AlForAMA). Important research themes are the integration of 3D printing into classic production processes (forming by melting and casting etc., e.g. H2020 project AMOS). Other projects aim to optimise production at component level (e.g. FLOWCAASH on control actuators). According to the Wohlers report, a similar research focus is also observed in China, Singapore, Japan and the USA. [611] The KRAKEN project aims to propose an affordable solution for the production of parts up to 20 m long, whose applications range from waterproof covering modules for tunnels to mock-up car designs. [612]

7.5 Research options and outlook

As expected, the intensity of research (number of projects, budget) on the five technologies varies significantly across the technologies. Fuel cells lead EU research among these five, with up to EUR 200 million of EU funding in 2015. Robotics are in second position, exceeding robotics in the course of H2020 in terms of the number of active projects. The research volumes on batteries, drones and 3D printing are similar regarding budget volume, apart from the drones, which almost tripled in 2016.

The analysis in this sub-chapter shows trends in EU funding for the five technologies, and allows certain comparisons of funding patterns across these technologies. It should

[611] Wohlers Report 2018, 3D Printing and Additive Manufacturing State of the Industry, Annual Worldwide Progress Report, Wohlers Associates, Inc., 2018

[612] https://krakenproject.eu/#examples-of-application

be noted that a comprehensive R&D overview requires additional analyses on additional parts of technology funding like:

- national and regional public research programmes;
- military research and development (directly funded by ministries of defence, or branches of military services (army, navy, air-force).

Additional R&D funding: public sub-EU level and military research

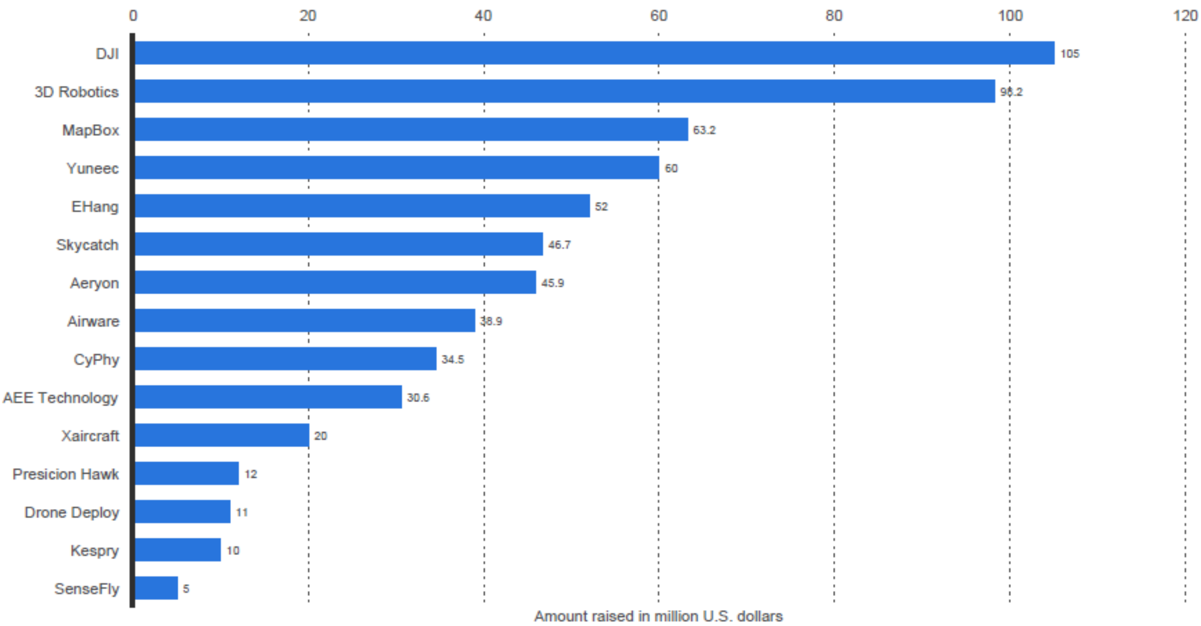
The availability of information on research for military applications is more constrained and anecdotal. Due to the strategic importance of systems autonomy, the unmanned feature has become a distinct R&D focus area for military operators. In the past, unmanned robotics and vehicles have been boosted significantly by military development. However, today, the civil applications have very much caught up, both in quality and quantity. Accordingly, there is significant R&D at national and sub-national level besides the EU funding described above.

For a more comprehensive overview, national and regional funding should also be monitored complementarily. The analysis in this chapter does not include national and sub-national levels, as a reasonably complete research project database on such levels does not yet exist. The H2020 project, ORAMA, envisaged the provision of information at EU, national and regional levels for raw-material related research. While not complete, the ORAMA database [613], and its successors, might support such deeper analyses.

Business sector: example of drones market

With the growth of the civil drones market, R&D funding has grown in the related business sectors. Due to the attractiveness of the drones market and its high potential for professional applications, drones companies have successfully raised R&D funds in the area of commercial UAV. By the beginning of 2016, these companies had together raised more than USD 500 million. It should be noted that funding volumes are highly concentrated on a group of less than 15 companies (Figure 107).

Figure 107 Estimated funds raised by selected firms in the area of commercial unmanned aerial vehicles as of January 2016.



Source: Statista Dossier "Commercial UAVs", November 2018

[613] https://orama-h2020.eu/about-the-project/

Most of these big players are not located in Europe; in fact, Chinese and USA companies dominate R&D in commercial UAVs. Given the dissatisfactory starting position of Europe in the global UAV market, along with the budgetary limitations, EU funds and related human resources should be carefully deployed in order to maintain or gain additional market share. As the UAV industry moves increasingly towards a service industry, we suggest the reinforcement of efforts in **software development**, which is still strong in the EU, rather than concentrating on pure hardware issues, which will prove increasingly difficult and potentially ineffective to fund. The shift of R&D funding from hardware to software and services that will make drones more useful is already in progress in the private sector and ought to increase overall funding efficiency.

In the mid-term, a healthy prospective UAV industry requires a balanced distribution of big players and small and medium-sized companies (SMEs). Due to the rapid rate of technology development in the UAV field, SMEs play an important role, as they are often better equipped than large companies to respond quickly and to adapt to changing environments. As the UAV sector is still an emerging market, the support of EU-based SMEs would be of strategic importance. The rapid rate of technological change in UAVs (and in the autonomous vehicle sector), supported by significant private investment, is also driving semiconductor advances and innovations. This includes improvements in obstacle avoidance, artificial intelligence, and context awareness, all of them making drones more effective across a range of industrial sectors like agriculture, construction, infrastructure and security, but also military, in which SMEs can specialise. However, research support mechanisms for SMEs in this field would need to be carefully designed to suit this rapid rate of change, including flexible work programmes, using front-runner approaches (e.g. by building on best practice in the USA and Europe).

From a supply chain perspective, R&D should support the closing of those gaps in the EU UAV supply chain, whose coherence and invulnerability are of strategic importance for next generation civil and defence applications. This includes components used for radars, communications and electronic warfare (EW) technologies, using gallium-nitride (GaN)-on-silicon-carbide (SiC) semiconductor technology.[614] The strategic importance of gallium-nitride to Europe is underlined by the fact that five consecutive/related EU projects have been run on this technology (KORRIGAN, MANGA, EuGaNIC, MAGNUS, MUSTANG). While KORRIGAN has developed a GaN HEMT technology in Europe, MANGA has successfully developed know-how and production processes for 100 mm SiC wafer production and GaN-on-SiC epitaxy, the EuGaNIC project will bring the technology to ful industrially maturity in Europe. MAGNUS has designed and developed multiple applications and demonstrators of enabling technologies such as monolithic microwave integrated circuits (MMICs) and highly integrable transmit and receive modules for phased array antennas to be used in radars, communications or EW systems from 2 to 18 GHz. The new MUSTANG project, currently in preparation, will extend the use of GaN technology in frequency terms.[615]

The vast majority of relevant projects push today's applications towards new areas at various levels. This means that although the projects addressing issues in the five technologies are numerous, only a minor share of them address the technologies at material level, as the focus is usually placed on the assembly or component levels (if not the product level). One project addressing the materials level is the Joint Technology Initiative HYPER[616], which advances fuel cell development, hydrogen storage and associated supply, and by doing so combines the technologies to extend the operational area, and thus also the field of application.

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[614] European Defence Agency, Towards Enhanced European Future Military Capabilities, European Defence Agency Role in Research and Technology 2016.
[615] https://www.eda.europa.eu/what-we-do/activities/activities-search/captech-components 5th February 2019.
[616] FP7 project "Integrated hydrogen power packs for portable and other autonomous applications"

Further methodological research is required on how to make best use of supply chain information to derive measures for strengthening material supply chains in general, and to address specific material supply bottlenecks. Of crucial importance here is the ability to combine supply chain information with other information, such as material system understanding. Although material system analyses [617] provide a complete overview of the life-cycle of materials, linkage to the data structure of supply chain analysis is not supported so far, as these analysis methodologies were developed by different research communities. There are potential synergies, which should be exploited in order to support raw material policy development. We therefore strongly recommend developing the capacity to better combine these methodologies.

[617] https://ec.europa.eu/jrc/en/scientific-tool/msa

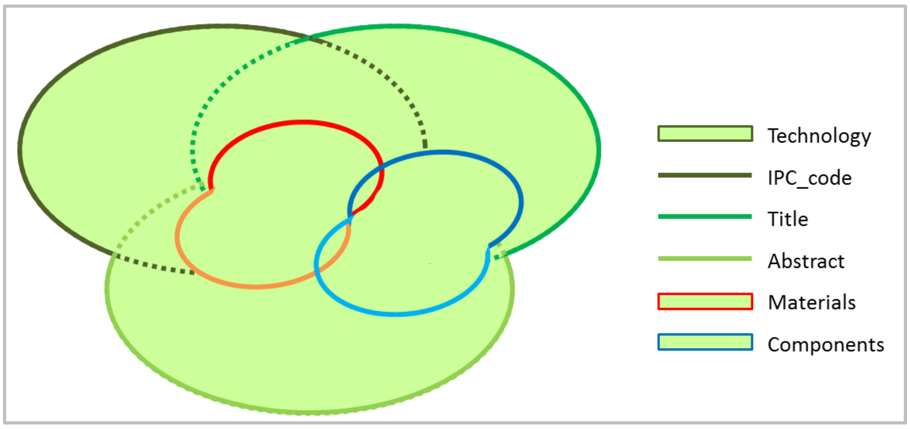
8 Patent application trend in selected dual-use technologies

Patent analysis is conducted with data retrieved from PATSTAT [618], spring 2018 version, the worldwide patent statistical database created and maintained by the European Patent Office (EPO).

Three different queries are run to each of the five technologies analysed in this study. The first one extracts all patent applications on the technology, while the second and the third concern the subsets of these patent applications related to specific materials and components, respectively, identified as key for the development of the technology itself.

Due to the recent development of the five technologies, the International Patent Classification (IPC) does not provide yet a thoughtfully codification, but it accommodates patent searches based on groups of codes. Therefore, technologies are defined through a mix of IPC codes and keywords, the latter searched in both the title and the abstract of patent applications, as summarised in Figure 108.

Figure 108 Overview of the patent searching approach



Source: JRC

The two subsets of patent applications on materials and components, which may or may not overlap, are identified through additional keywords, either in the title or in the abstract. An additional set of bibliographic information is extracted for each patent application, as summarised in Table 28.

Table 28 Set of bibliographic information extracted per patent application

Patent application			Applicant			Fractional
Code	Year	IPC_code	Name	Country	Sector	
P_1	Y_1	IPC_111	A_1	C_1	S_1	1/6
P_1	Y_1	IPC_111	A_2	C_1	S_2	1/6
P_1	Y_1	IPC_111	A_3	C_2	S_1	1/6
P_1	Y_1	IPC_222	A_1	C_1	S_1	1/6
P_1	Y_1	IPC_222	A_2	C_1	S_2	1/6
P_1	Y_1	IPC_222	A_3	C_2	S_1	1/6

[618] https://www.epo.org/searching-for-patents/business/patstat.html#tab-1

Based on this panel of information, the fractional count technique was applied to take into account the proportional contribution to patent applications. [619] Before the fractional count, data were cleaned in order to increase data accuracy and completeness. [620] Table 29 reports IPC codes and key words used for the patent search for the five technologies.

Table 29 List of IPC codes and keywords per technology

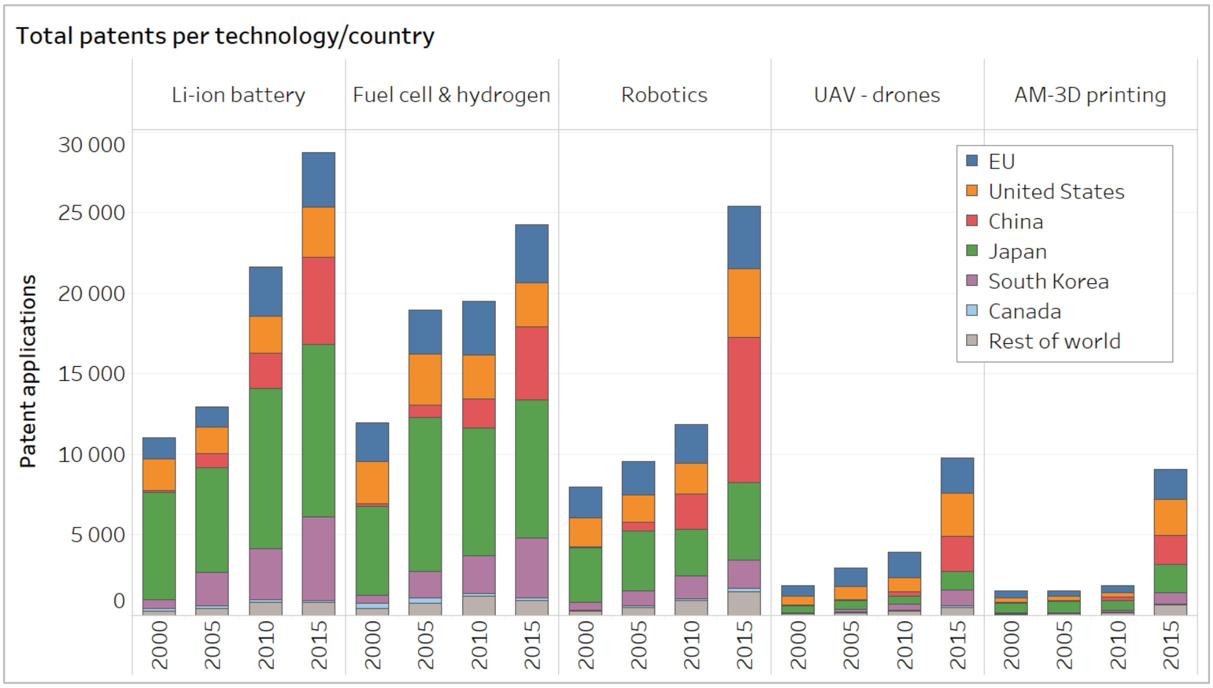
Technology	IPC codes	Keywords		
		Technology	Component	Material
Lithium-ion battery	H01M 2/00; H01M 4/00; H01M 10/00	Li-ion battery; Lithium-battery pack; Lithium-ion battery; Lithium-ion cell	Anode electrode; Cathode electrode; Electrolyte; Separator	Aluminium; Cobalt; Copper; Graphite; Lithium; Manganese; Nickel
Fuel cell and hydrogen storage	C01B 3/00; F17C; H01M 4/00; H01M 8/00; H01M 16/00	Fuel cell; Fuel-cell; Hydrogen storage; Hydrogen tank	Bipolar plate; Gas diffusion layer; Membrane electrode assembly	Carbon fibre composite; Cobalt; Magnesium; Metal hydride; Metal; Nickel; Palladium; Platinum; Polymer; Porous carbon; Precious metal; Rare earth; Rare-earth; Rhodium; Silver; Yttria-stabilised zirconia
Robotics	A61B 34/00; B25J; G05B 19/00	Exoskeleton; Robot	Actuator; Battery; Fuel cell; Fuel-cell; Gear; Graphical processing unit; Microprocessor; Sensor	Aluminium; Antimony; Arsenic; Bismuth; Boron; Cadmium; Carbon fibre composite; Carbon nanotubes; Ceramic; Chromium; Cobalt; Copper; Gallium; Glasses; Gold; Indium; Kevlar; Lead; Lithium; Magnesium; Manganese; Mercury; Molybdenum; Nano-material; Nano-powders; Nickel; Palladium; Platinum; Polymers; Rare earth; Rare-earth; Refractory; Semiconductor; Silicon; Silver; steel; Strontium; Tellurium; Titanium; Vanadium; Zinc; Zirconium
Drones	B64C 1/00; B64C 3/00; B64C 27/00; B64C 39/00; G05D 1/00	Drone; Unmanned aerial	Actuator; Controller; Fuel cell; Fuel-cell; Gear; Inertial Measurement Unit; Li-ion battery; Lithium-battery pack; Lithium-ion battery; Lithium-ion cell; Microprocessor; Sensor	Aluminium; Antimony; Aramid; Cadmium; Carbon fibre reinforced polymer; Carbon fibres; Cobalt; Composite material; Composites; Copper; Ferroniobium; Hafnium; High-performance alloys; Iron; Magnesium; Mercury; Molybdenum; Nickel; Niobium; refractory metals powder; Semiconductors; specialty steel; Synthetic

[619] Fiorini, A., Georgakaki, A., Pasimeni, F., & Tzimas, E. (2017). Monitoring R&I in Low-Carbon Energy Technologies. EUR 28446 EN, JRC105642. Available at: https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/monitoring-ri-low-carbon-energy-technologies.
[620] Pasimeni, F. (2019). SQL query to increase data accuracy and completeness in PATSTAT, World Patent Information, 57, 1-7. Available at: https://www.sciencedirect.com/science/article/pii/S0172219018300875.

				fibres; Tellurium; Titanium; Tungsten; Vanadium; Zinc; Zirconium
3D printing	B22F 3/00; B29C 64/00; B33Y	3D Print; 3-D Print; 3D-Print; 3-D-Print; Additive Manufacturing; Additive-Manufacturing; Three dimensional print; Three-dimensional print	Binder jetting; cladding; Direct Metal Deposition; Directed Energy Deposition; Electron Beam Melting; Laser Sintering; metal deposition; metal printing; nozzle systems; Powder Bed fusion; Selective Laser Melting; wire feed	Alloy; Aluminium; Chromium; Cobalt; Hafnium; Magnesium; Metal; Nickel; Niobium; Powder metallurgy; Scandium; Stainless steel; superalloy; Titanium; Vanadium; Zirconium

An overview of the evolution of patent applications globally, between 2000 and 2015, is given in Figure 109. Patents were sifted per technology and country. More detailed patent analysis for each dual-use technology, including global key players, is shown in Figure 111 to Figure 115.

Figure 109 Overview of total patent applications per technology and country in the period 2000-2015



Source: JRC based on EPO

Lithium-ion battery

A significant increase in global patenting activity related to Li-ion batteries is observed in the period 2010-2012 (Figure 111). The activity is kept relatively constant in the later years. Most patents (around two thirds) are related strictly to technology improvements, and a much smaller number of patent applications deal with materials and components issues for batteries. Japan is by far the leading patenting country with a peak in the number of patents in 2011-2012. Other countries that have registered a significant number of patents are the USA, China, South Korea and the EU. Europe looks strong in know-how and innovation-based activities, but lacks manufacturing capacities for batteries. The three key companies active in patenting are LG Chemical, Samsung (South Korea) and Toyota Motor (Japan). There are three European companies among the top 20 global players, namely Robert Bosch (Germany), Li Tec Battery (Germany) and Daimler Ag (Germany). Companies based in Germany, France, Belgium and the UK are among the top 20 European companies.

Fuel cells and hydrogen storage

The patent activates in fuel cells and hydrogen storage have been growing steadily in the last 15 years, with the exception of 2008 and 2009 (Figure 112). Like in Li-ion batteries, most of the patents (around 2/3) are related to technology improvements. A smaller part (around 1/3) of the patents can be associated with materials development. Very few patents could be identified as related to components. Also here Japan is the absolute leader in patenting – far above the other countries registering patents – USA, China, South Korea, the EU and Canada. The EU is well represented, being the third player globally in terms of number of patents regardless the marginal manufacturing of fuel cells in Europe. Two countries in particular are showing increasing activities in patenting in the last years – China and South Korea.

Toyota Motor Corporation (Japan), LG Chemicals (South Korea) and Nissan Motor Co (Japan) are the leading companies globally in patenting activities related to fuel cells and hydrogen storage. There are 4 European companies among the top 20 global players, namely Robert Bosch (Germany), Daimler (Germany), Air Liquide (France) and BMW AG (Germany). Companies based in Germany, France, Netherlands, Belgium, Denmark, UK and Luxembourg are among the top 20 European companies.

Robotics

Patenting activities in robotics showed a rapid increase from 2011 onwards (Figure 113). The majority of the patents are related to technological improvements, around one fifth have components relevance and a very few are materials-related. Japan is the country recording the biggest number of robotics related patents globally, followed by China, the EU, the USA and South Korea. China became very active in robotics patenting from 2011 onwards.

Seiko Epson Corporation (Japan), Siemens Ag (Germany) and Mitsubishi Electric Corporation (Japan) are the leading companies, globally, in patenting activities related to robotics. There are two European companies among the top 20 global players, namely Siemens Ag (Germany) and KUKA Roboter (Germany). Companies based in Germany, France, Netherlands, Sweden and the UK are among the top 20 European companies.

Drones

The patent activates related to drones have shown rapid increase from 2012 onward (Figure 114). The majority of the patents are related to technological improvements, around 1/4 of the patents have components' relevance and less than 10% of the patents are materials related. The EU is the global leader in terms of cumulative number of patents related to drones, very closely followed by USA, Japan, China and South Korea. The biggest growth rate in patens in the last years is observed for USA and China, also registered the highest number of patents in 2015.

Boeing Company (USA), Airbus Operations Gmbh (Germany) and Airbus Operations Sas (France) are the leading companies globally in patenting activities related to 3D printing. There are 8 European companies among the top 20 global players, namely Airbus Operations Gmbh (Germany), Airbus Operations Sas (France), Airbus Helicopters (France), Eurocopter (France), Airbus Operations Ltd (UK), Robert Bosch Gmbh (Germany), Airbus Operations S.L. (Spain) and Thales SA (France). Companies based in Germany, France, Sweden, Spain and UK are among the top 20 European companies for drones.

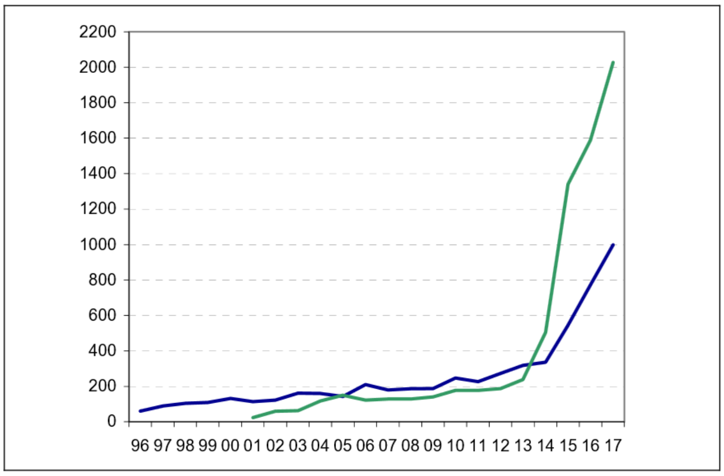
3D printing

Patenting activates related to 3D printing have shown a rapid increase since 2013 (Figure 115). The majority of patents are related to technological improvements. In the past, around half of patents were related to materials. In recent years, patents related to technology alone are in the majority, accounting for around three quarters of all patents in 2015. Japan is the global leader in terms of the cumulative number of patents related to 3D printing, followed by the EU, the USA, China and South Korea. The biggest growth rate in patents in recent years is observed for the USA, China, the EU and Japan. In 2015, the USA registered the most patents in 3D printing globally.

Hewlett-Packard Development (USA), United Technologies Corp. (USA) and Seiko Epson Corp. (Japan) are the leading companies globally in patenting activities related to 3D printing. There are five European companies among the top 20 global players, namely Siemens Ag (Germany), Snecma (France), Sandvik Intellectual Property AB (Sweden), EOS Electro-Optical Systems (Germany) and MTU Aero Engines AG (Germany). Companies based in Germany, France, Sweden UK, Italy, Netherlands and Austria are among the top 20 European companies for 3D printing.

The rapid increase in the number of patent applications related to AM since 2013 is also confirmed by the USA patents office [621] (Figure 110). The following graph, extracted from Wohlers, indicates the rapid growth of AM-related patents issued since 1995, according to the USA patents office (blue curve – patents issued; green curve – published applications).

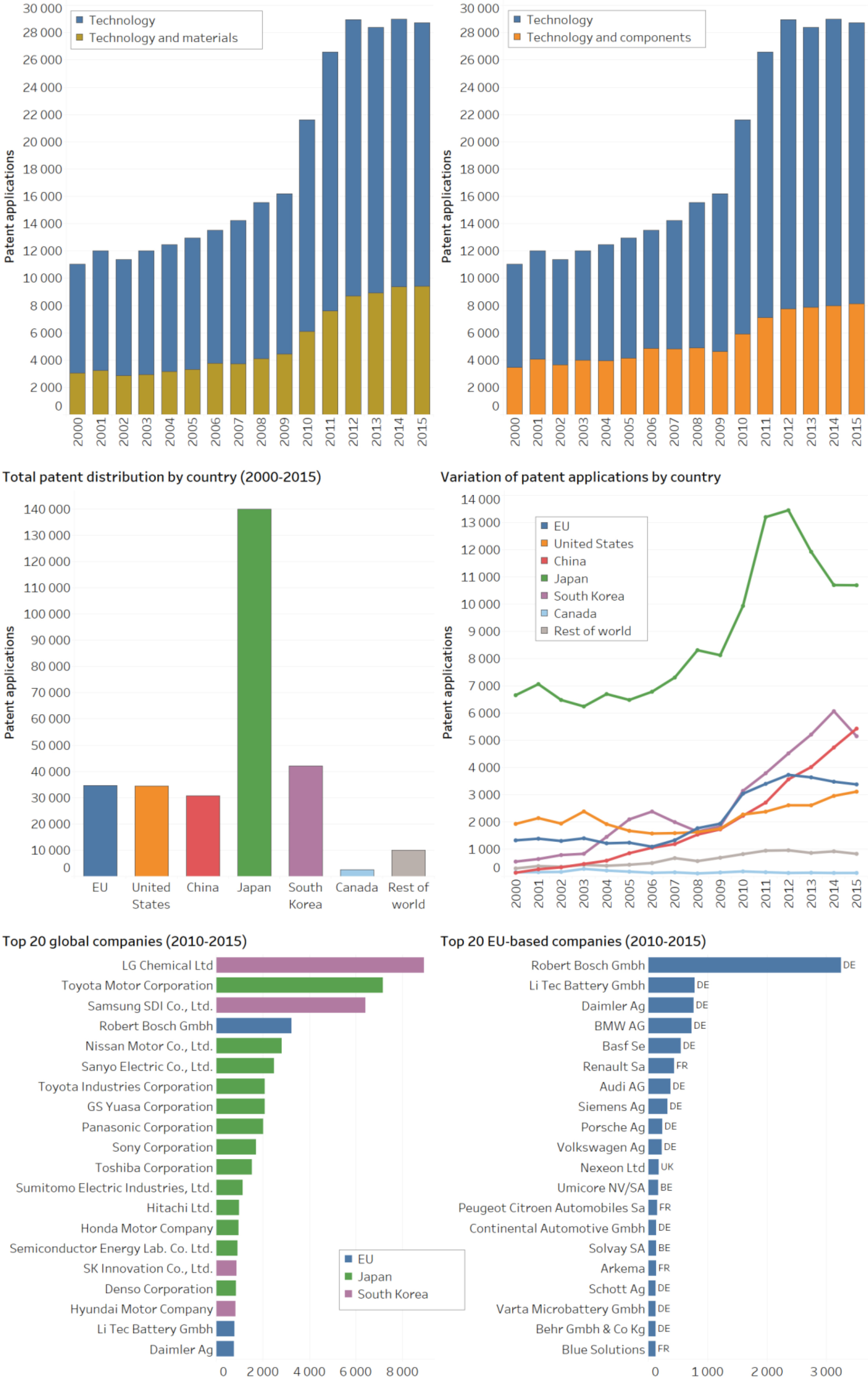
Figure 110 AM-related patents, source: Wohlers/ USA Patents and Trademark Office



Source: Wohlers Report 2018 and the U.S. Patent and Trademark Office

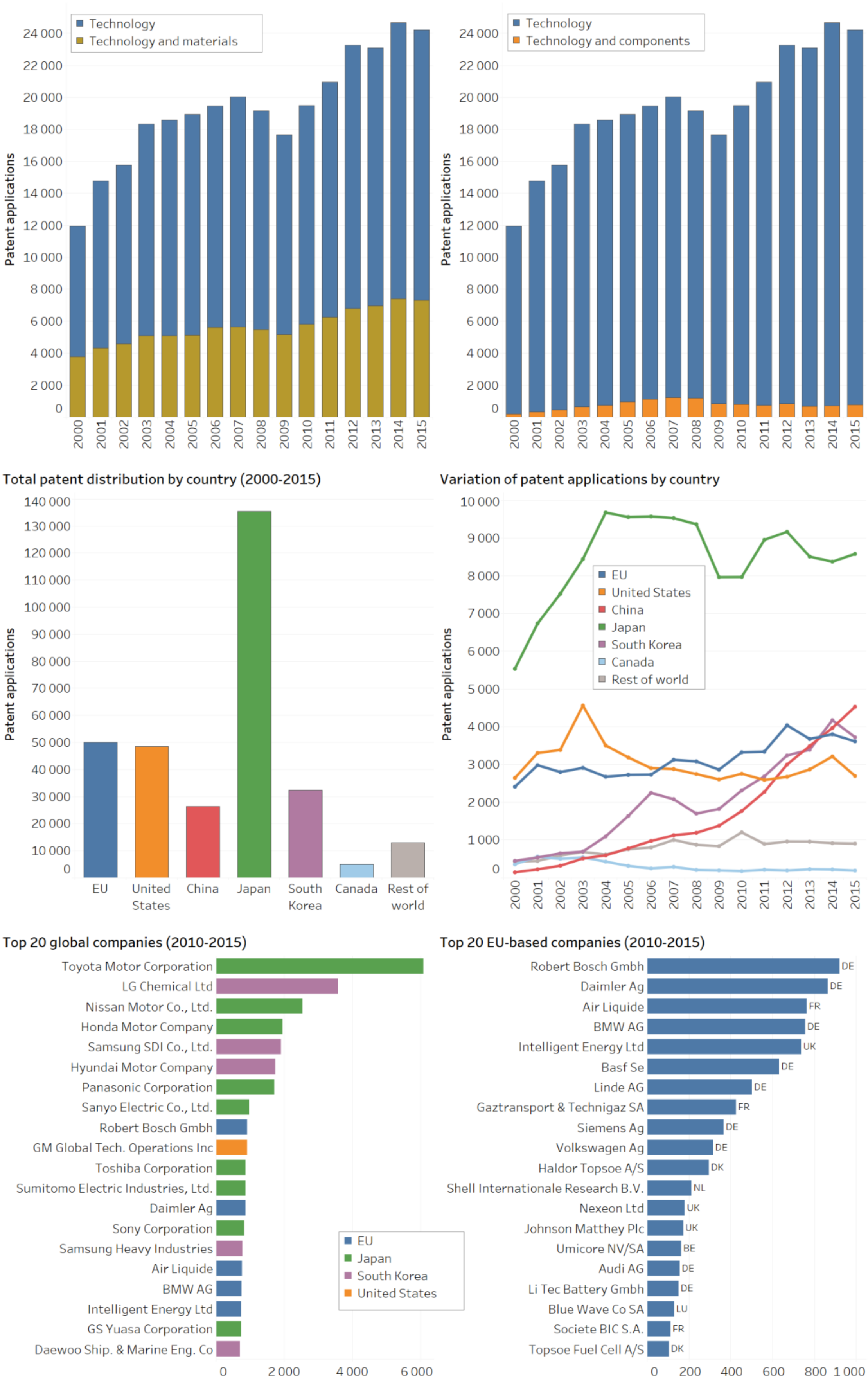
[621] Wohlers Report 2018, 3D Printing and Additive Manufacturing State of the Industry, Annual Worldwide Progress Report, Wohlers Associates, Inc., 2018

Figure 111 Patent applications variation related to Li-ion battery technology



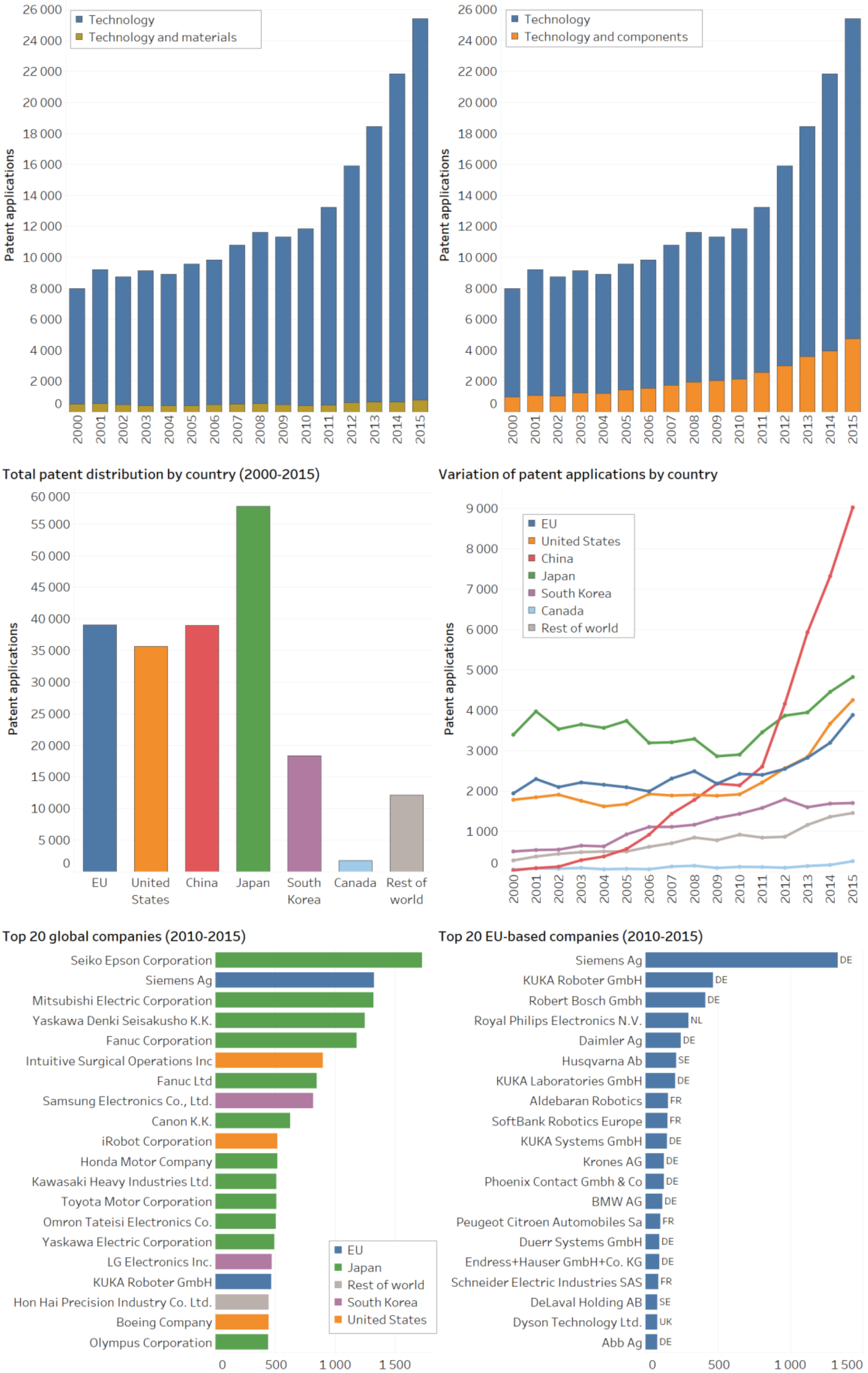
Source: JRC based on EPO

Figure 112 Patent applications variation related to fuel cells and hydrogen storage technology



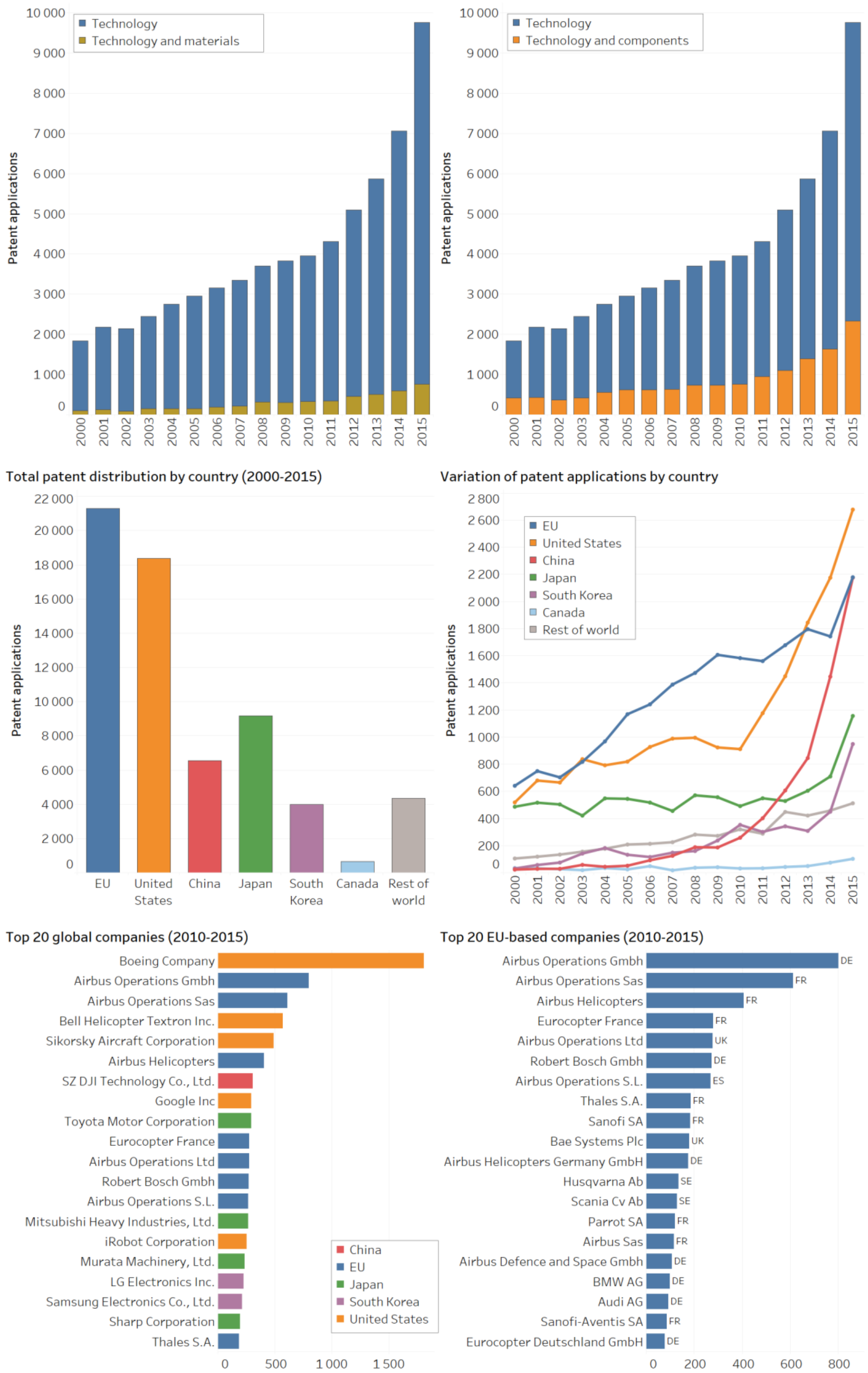
Source: JRC based on EPO

Figure 113 Patent applications variation related to robotics technology



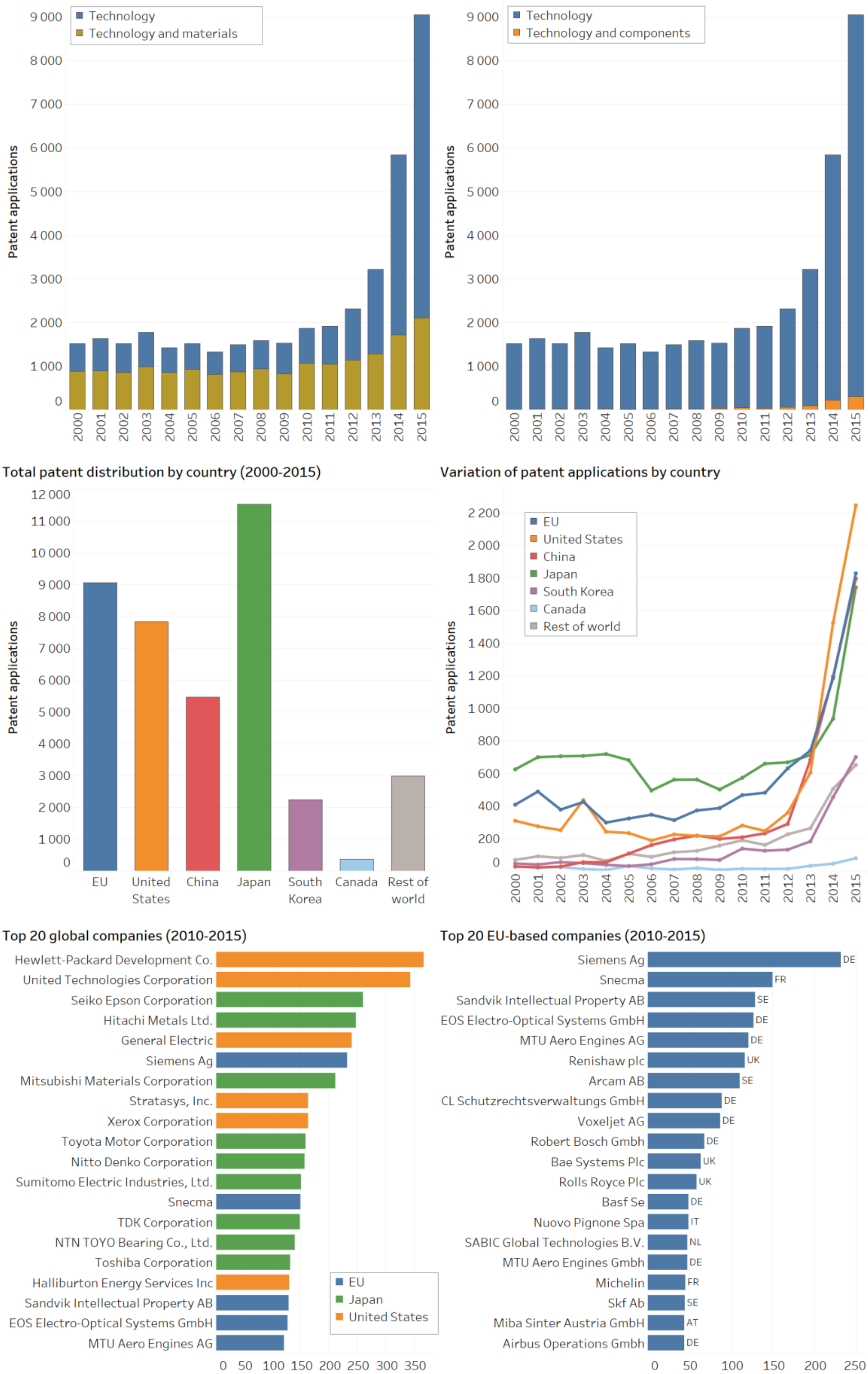
Source: JRC based on EPO

Figure 114 Patent applications variation related to UAV (drones) technology



Source: JRC based on EPO

Figure 115 Patent applications variation related to additive manufacturing (3D printing) technology



Source: JRC based on EPO

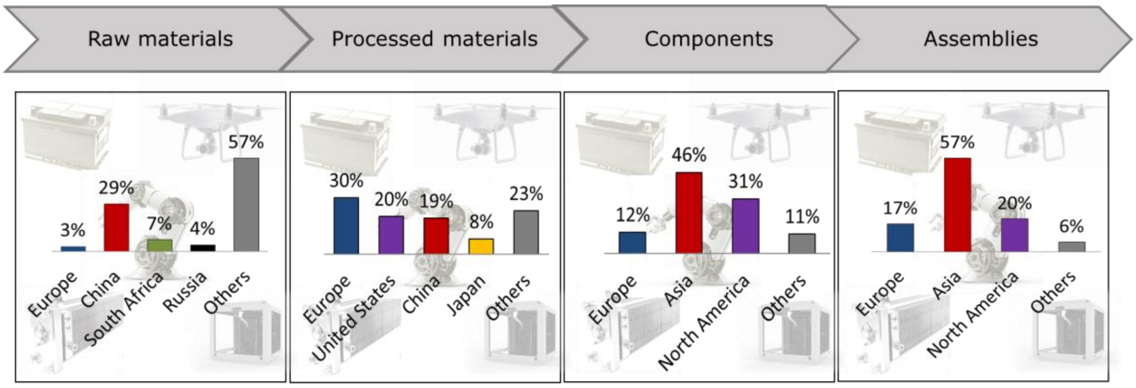
9 Conclusion

Study findings

Rapid growth in demand of between 10 % and more than 30 % is expected over the short and medium term for the five technologies examined here. Securing adequate and continuous access to raw and processed materials, and components, is of the utmost importance for the competitiveness of European industry.

The dependence of Europe on the supply of raw materials for the five analysed technologies is extremely high. Europe produces on average around 3 % of the overall raw materials required in Li-ion batteries, fuel cells, robotics, drones and 3DP technologies (Figure 116). China dominates global production, supplying around one third of the raw materials. Other key suppliers are South Africa (7 %) and Russia (4 %). Brazil, Australia and Chile are also shown to be key suppliers for 3DP and Li-ion batteries. More than half of the raw materials are produced by numerous small suppliers with minor shares of global production (< 4 %).

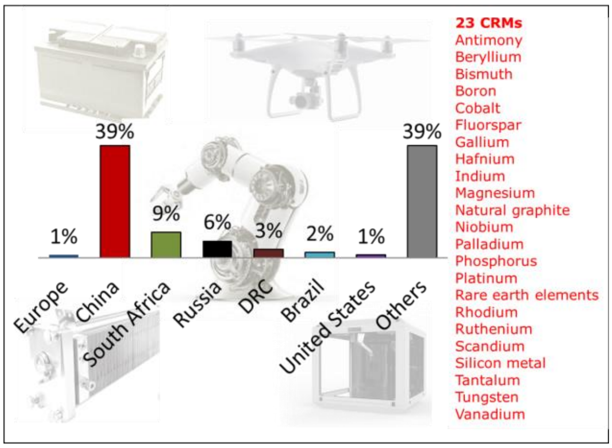
Figure 116 Key suppliers of raw materials, processed materials, components and assemblies for Li-ion batteries, fuel cells, robotics, UAVs and additive manufacturing (3DP)



Source: JRC

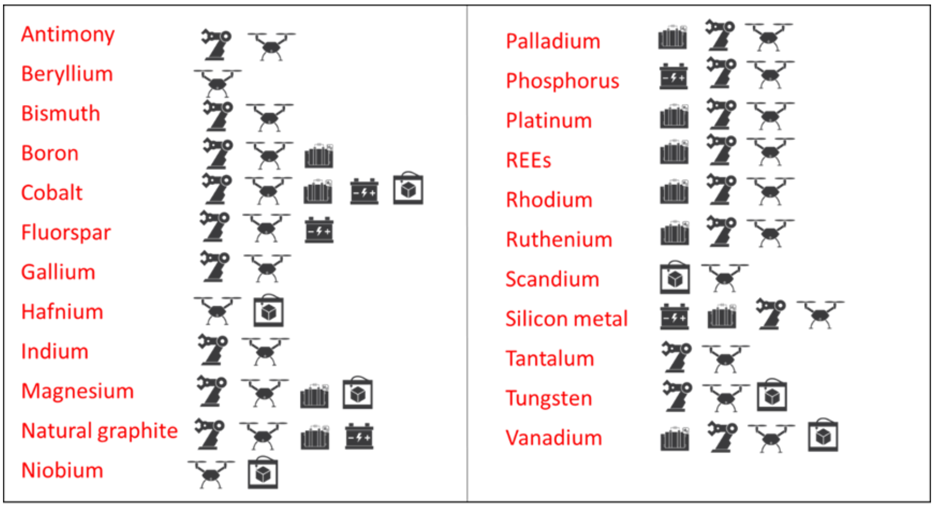
Europe supplies only 1 % of the CRMs required in the five technologies in question. The major supplier is China, with a share of almost 40 %, followed by South Africa (9 %), Russia (6 %) and many smaller suppliers (Figure 117).

Figure 117 Key suppliers of CRMs for Li-ion batteries, fuel cells, robotics, UAVs and 3D printing



Source: European Commission, 2017, Study on the review of the list of critical raw materials

Figure 118 Critical materials required in Li-ion batteries, fuel cells, robotics, UAVs and additive manufacturing (3DP)



Source: JRC

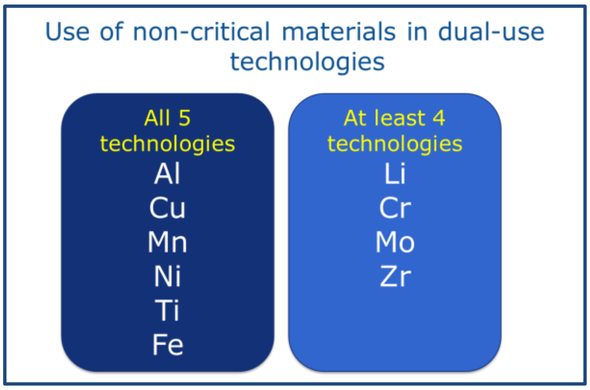
In total, 23 CRMs have been identified as necessary for Li-ion batteries, fuel cells/hydrogen technologies, robotics, drones and 3DP technologies. The main CRMs at risk are cobalt, used in all five technologies, and natural graphite, magnesium, silicon metal and vanadium, used in four of the five technologies. Most of the critical materials are used in three of the technologies (Figure 118).

Critical Materials and REACH: nine of the CRMs are registered in REACH, namely Antimony (Sb), Beryllium (Be), Cobalt (Co), Graphite, Magnesium (Mg), Niobium (Nb), Cerium (Ce), Neodymium (Nd) and Tungsten (W). [622] These substances of concern need to be progressively replaced by suitable alternatives in future. The enforcement of REACH is a Member State obligation and therefore they are taking care of this. Member States may allow for exemptions from REACH in specific cases for certain substances, on their own, in a mixture or in an article, where necessary in the interest of defence (Article 2.3 of REACH). The European Defence Agency is also working on this issue. [623] The line between defence and civil protection (e.g. police, fire fighters) is sometimes difficult to draw and goods used for defence are used for civil purposes. But civil protection material may also be used for defence purposes. Another piece of chemical legislation (Classification, Labelling and Packaging) is following the same route as REACH in the defence sector.

With regard to the use of non-critical materials that might merit further attention in future, the study has found that 6 materials are extensively used in all five technologies, namely Al, Cu, Mn, Ni, Ti and Fe; while four materials, namely Li, Cr, Mo and Zr are required in at least 4 of the examined technologies (Figure 119).

[622] ECHA, 2013. Chemicals risk management and Critical Raw Materials under REACH and CLP, European Chemicals Agency, Joint Raw Materials Supply Group and ECHA information session on Critical Raw Materials and REACH, 2013, URL https://echa.europa.eu/documents/10162/22816078/2_info_session_reach_and_crm_vainio_echa_en.pdf/80fd2cc3-52ee-4e31-a674-8ce951dc77dc
[623] European Defence Agency, REACH, 2019, URL https://www.eda.europa.eu/what-we-do/activities/activities-search/reach

Figure 119 Non-critical materials required in at least four of the five technologies: Li-ion batteries, fuel cells, robotics, UAVs and additive manufacturing (3DP)



Source: JRC

With the exception of Li-ion batteries, Europe is generally an important supplier of processed materials for the five technologies, providing, on average, about one third. Other key suppliers are the United States (20 %), China (9 %) and Japan (8 %). Canada, India and South Korea are shown to be key suppliers for 3DP, robotics and Li-ion batteries.

Though a strong player in the production of processed materials, Europe is highly dependent on the supply of certain materials such as aramid fibre, semiconductors, ferroniobium (main supplier Brazil; used in drones) and processed materials for Li-ion batteries (main supplier China). Such dependencies apply to both the civil and the defence sectors. Europe also relies, to a lesser degree, on the supply of nanomaterials, specific Al alloys, and speciality steels.

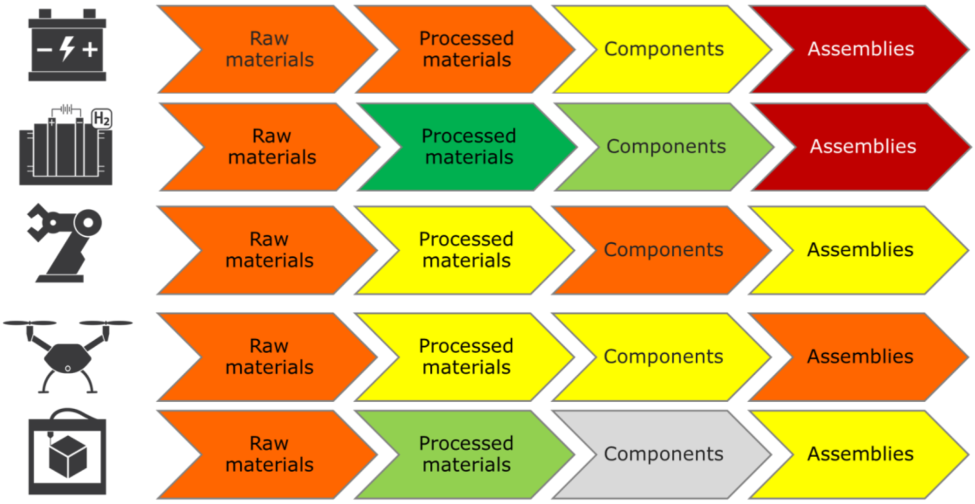
In terms of component supply, **with the exception of fuel cell technology, Europe's domestic production of components is relatively low. Europe produces, on average, around 12 % of the components required in Li-ion batteries, fuel cells, robotics and drones** (Figure 116). A key issue for batteries is the lack of EU capacity in Li-ion cell component manufacturing (cathodes, anodes, electrolytes and separators) and in cell manufacturing itself. There is high dependence on China for both. Although the European share in Li-ion cell production is expected to increase, thanks to the European Strategic Action Plan for Batteries adopted in 2018, Li-ion batteries for common military applications are still assembled from commercial cells manufactured in Asia. China is also a major supplier (80 %) of the REE magnets used in robots and drones for both civil and defence applications. The main concern of EU industry for robotics and UAVs is the lack of EU component manufacturers, with the United States leading the supply of actuators, controllers (processors), GPUs and IMUs, while Japan dominates the supply of high precision gears. Overall, the key suppliers of components resulting from the analysis are the United States (fuel cells, robotics, drones), China (Li-ion batteries, robotics, drones), Japan (Li-ion batteries, fuel cells, robotics, drones), Canada (fuel cells) and South Korea (Li-ion batteries).

Europe produces, on average, around 17 % of Li-ion batteries, fuel cells, robotics, drones and 3D metal systems globally (Figure 116). **Europe is a strong player in the production of robots and 3D metal systems**. It has some production of drones, though not enough to satisfy its needs (assuming European demand is around 20-25 % of global demand as observed for other established technologies). **Europe is very weak as regards the supply of Li-ion, LiPo batteries and fuel cells, which are predominantly provided by Asia (China, Japan and South Korea) and North America (United States and Canada).** Japanese manufacturers dominate industrial robotics, while USA manufacturers dominate non-industrial robotics, UVs and artificial intelligence. Manufacturers in the United States are also the key players for military exoskeletons. The United States and China dominate UAV assembly and UAV manufacturing. Regarding 3D printers for industrial use, the United States leads in polymer-based technologies, with Europe strongly present in metal AM. For aerospace applications, the United States and the EU are equally present in the top 15 system integrators, exploring and driving the development of 3DP on a large scale.

The role of China as a key supplier in the supply chains is worthy of note. It has acquired and continues to expand its dominant position in the Li-ion battery and drone supply chains, and has ambitious plans in the fields of robotics, fuel cells and 3DP.

The analysis shows that the weakest step in the supply chain for the five technologies under investigation is the supply of raw materials. Furthermore, the supply of assemblies appears to be very critical for three of the technologies, namely Li-ion batteries, fuel cells and drones. The supply of processed materials is shown to be critical for Li-ion batteries, though some supply risks are also detected for robotics and drones. At components level, though some supply risks are detected for Li-ion batteries and drones, robotics seems to be the most vulnerable technology (Figure 120).

Figure 120 Supply risks identified for Europe in the supply chains of Li-ion batteries, fuel cells, robotics, UAVs and 3DP



Source: JRC

Some general cross-cutting issues identified in the analysis are related to **sensors** and **software development skills**. Sensors will become ever more important, and their development and the processing of their data should receive close attention. Software development skills will be a key enabler for the development of robotic and autonomous systems for both European military forces and civil applications.

General policy recommendations

It is important that European industry is preserved, organised and supported in order to reduce Europe's strategic dependency and increase **security of supply via diversification**, especially with regard to the supply of raw materials and components, both of which are shown as weak links in the supply chains. **Besides increasing domestic production, other suggested strategies include the substitution of critical materials, recycling and finding alternative suppliers.** In addition to reducing the demand for primary materials of limited supply, recycling can also reduce production costs, save energy, lessen resource consumption and diminish our environmental impact. However, it remains a challenge to develop a cost-effective, environmentally friendly recycling process with high recycling efficiency, [624] which produces cleaner, higher quality recycled materials. This needs attention, in terms of both research and policymaking.

Another important aspect is that the **security of supply with regard to material dependence should be always examined in a value-chain approach,** taking into account the linkages between various value chain steps. The study advances this point by investigating the raw materials, processed and advanced materials, components and assemblies required for five strategic emerging technologies. The collection of reliable data for processed materials and often for components has been identified as an issue that merits further attention.

The EU's dependency on raw materials goes beyond physical access to the individual minerals and is affected by other economic conditions related to mining conditions, ownership, trade restrictions, environmental permitting and other uneven conditions. Industries outside the EU are typically less concerned with responsible sourcing, potentially causing an uneven playing field. This is undermining social and environmental conditions in developing countries. **Securing sustainable access to the right quantity and quality of raw materials** will be key to future responsible EU industry developments.

The study also highlights the **need for more effective action on (critical) raw materials in Europe.** Such actions can tackle supply risks at any step in the supply chain, such as **joint procurement, promoting recycling and substitution,** among others. **Supply diversification**, via trade agreements or tailor-made trade contracts with different supplier countries, could decrease the threat of supply shortages. Such a contract would secure the supply from a certain country, giving the supplying country planning reliability (a win-win situation). **Stockpiling** could be one of the options to mitigate short- to medium-term supply disruptions in the event of a crisis. Different stockpiling options could be examined at EU or Member State level, supporting corporate strategies to mitigate risks. A dedicated study could be commissioned to evaluate and analyse in more depth the potential of stockpiling materials essential to the development of certain technologies, along with the environmental, social and economic impacts, taking into account the expected technological developments of the future.

In order to tackle the extremely **high dependence of Europe on the supply of raw materials** this study identified the need for more cooperative and effective action on securing the supply of (critical) raw materials. In order to do so, distinct measures are identified by this report, which require as a basis the **permanent monitoring of raw materials markets and (strategic) value chains.** It also puts in evidence the need for industry and policymakers to work together and to **ensure access to up-to-date reliable information for the Member States and stakeholders** (e.g. as done in the Raw Materials Information System) in relation to the most critical CRMs. The **exchange of data and information, and international cooperation should be supported in an integrated manner at the EU, Member State and corporate levels**. The above could be of great support to strategic sectors, including the dual-use and defence sectors, thus supporting the development of a coherent EU CRM policy.

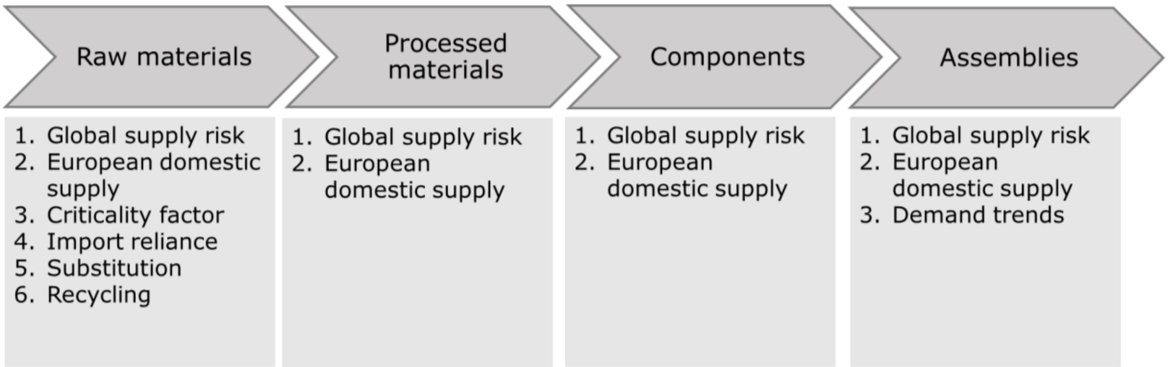
Lastly, inclusive, **strategic and comprehensive discussions are needed on the role and future competitiveness of these emerging technologies** – particularly on material availability, sustainability, IPR protection, software development and digital security for key military and civil supply chains.

[624] CHROMIC EU project will develop new processes to recover chromium, vanadium, molybdenum and niobium from industrial waste.

Annex 1 Methodology

In order to identify forthcoming bottlenecks in the supply chains of the five technologies selected for this study, a tailored methodology was developed and applied. In this dedicated methodology, the materials supply issues and potential bottlenecks in the supply chain for the five dual-use technologies (Li-ion battery cells, fuel cells, robots, drones and AM systems) are assessed using several parameters for each step of the supply chain: raw materials, processed materials, components and assemblies. For each step, several parameters were taken into account that might weaken or jeopardise sustainable supply in Europe (Figure 121).

Figure 121 Parameters used in assessing the potential bottlenecks in the supply chain



Source: JRC

Six parameters are used to evaluate the potential supply issues at the level of raw materials, namely: (1) global supply risk; (2) European production (domestic supply); (3) criticality factor (whether a material is flagged as critical in the 2017 CRM list); (4) import reliance of Europe for a particular raw material; (5) substitution and (6) recycling. The import reliance, substitution and recycling parameters are assessed using data from the 2017 CRM study. For steps 2, 3 and 4 in the supply chain, two parameters are used: (1) global supply risk, and (2) European production (domestic supply). The global supply risk for all steps has been determined using the Herfindahl-Hirschman Index (HHI), based on concentration of supply. The European domestic supply corresponds to the European shares determined during the supply chain analysis. An additional parameter – demand trends – is considered at the last step in the supply chain, indicating demand increases forecast for the future.

The indicators are normalised in the range of 0 to 1; lower values indicate a relatively higher degree of supply risk. The results are presented visually in the form of a traffic-light matrix. The following two marginal cases are distinguished:

- **Red area** (corresponding to value 0), indicating a **very high supply risk** and the presence of substantial supply issues combined with a limited ability to adapt or tackle them due to the nature of the impact/risk.
- **Green area** (corresponding to value 1), indicating the **best case scenario**, or no detectable supply issues.

Intermediate values, represented by yellow, orange or various intensities of green, indicate that a potential supply issue/risk is detectable with medium confidence. The relationship between colour, score scale, risk scale and bottlenecks is shown in Table 30.

Table 30 Relationship between given scores, colours and bottlenecks

Colour	Score	Risk scale	Bottlenecks
	0 - 0.2	Very high (VH)	Existence of severe bottlenecks in the supply chain and the presence of other significant factors, negatively influencing the supply combined with limited ability to adapt due to the nature of the supply risk
	0.2 – 0.4	High (H)	Presence of severe and widespread bottlenecks in the materials supply chain
	0.4 – 0.6	Medium (M)	Bottlenecks are detectable which can affect the supply at medium confidence
	0.6 – 0.8	Low (L)	Bottlenecks are hardly perceptible and if they exist, they have low impact on the supply risk
	0.8 - 1	Undetectable (U)	No bottlenecks are detectable which would weaken the security of supply

The materials identified for each technology contribute to each parameter with an equal weight through an arithmetic mean before being combined and scaled from 0 to 1.

More details about the parameters used for evaluation of the potential bottlenecks and materials supply issues are given in Table 31.

Table 31 Definition of the parameters used in the bottlenecks assessment

Indicator	Description	Supply chain step
Global supply risk	Calculated using a metric of market concentration (known as the Herfindahl-Hirschman Index)	All four steps in the supply chain
European domestic supply	Estimated European supply as a share of the global supply, scaled from 0 to 1*.	All four steps in the supply chain
Criticality factor	Whether or not a raw material is flagged as a critical material in the 2017 CRM list. The score given is 0 if critical and 1 if non-critical.	Step 1: raw materials
Import reliance	The European import reliance as estimated in the 2017 CRM study, scaled from 0 to 1.	Step 1: raw materials
Substitution	Represents substitution index in relation to the supply risk (SISR) as defined in the 2017 CRM study.	Step 1: raw materials
Recycling	Refers to the end-of-life recycling input rate (EOL-RIR) as provided by the 2017 CRM study, scaled from 0 to 1.	Step 1: raw materials
Demand trends	Takes into account the technology uptake forecast in the short and medium term (by 2030); lower values correspond to high expected uptake rates.	Step 4: assemblies

** it is assumed that 30 % domestic production could satisfy European needs, considering that European demand is around 20-25 % of global demand (assumption based on data from different energy sectors). Therefore, European production of 30% or higher is considered safe (=1); production shares of less than 30 % are scaled down accordingly.*

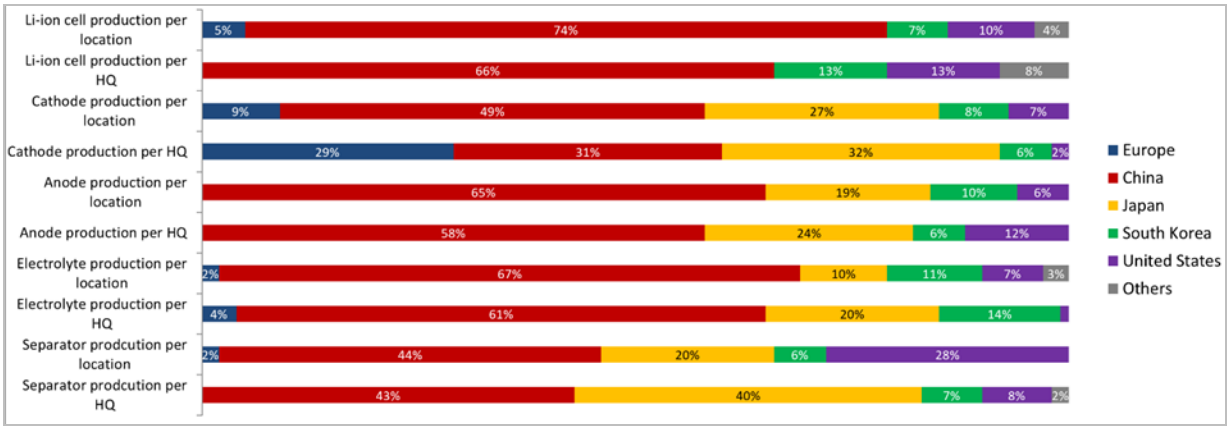
This methodology is meant to give an indication of whether or not the selected dual-use technologies are susceptible to supply bottlenecks and where in the supply chain these shortages might be expected. Thus, it allows us to identify where in the supply chain intervention is needed.

Methodology robustness check regarding using companies' headquarter location

The calculation of the supply shares for the raw materials step is rather straightforward using data from the criticality assessment (European Commission, 2017, Study on the review of the list of critical raw materials — Final report). This is not however the case for the other steps of the supply chain. Often big companies own production facilities and sales offices in multiple countries for which the supply shares are not normally known. This makes it very challenging and often impossible to collect pertinent data specifically for processed materials and components and sometimes for the final product (assembly). Therefore, a simplified approach of using headquarters location to assess country supply shares was adopted. Such an approach, however, could introduce some form of discrepancy into the calculation of the final supply chain shares, since they can differ from the supply shares calculated using the geographical location where actual production takes place. The possible discrepancy introduced due to this approach was assessed for battery technology where data are available for the last two steps - components and Li-ion cell production. Figure 122 shows country supply shares calculated using headquarters approach and the geographical location of the production facility. Figure 123 illustrates the comparison between final supply-chain shares for Li-ion components and Li-ion cells using both approaches. With the exception of Europe regarding Li-ion cells production where a large discrepancy is observed, the deviation for the other countries is estimated to be between '-50%' and '+44%'.

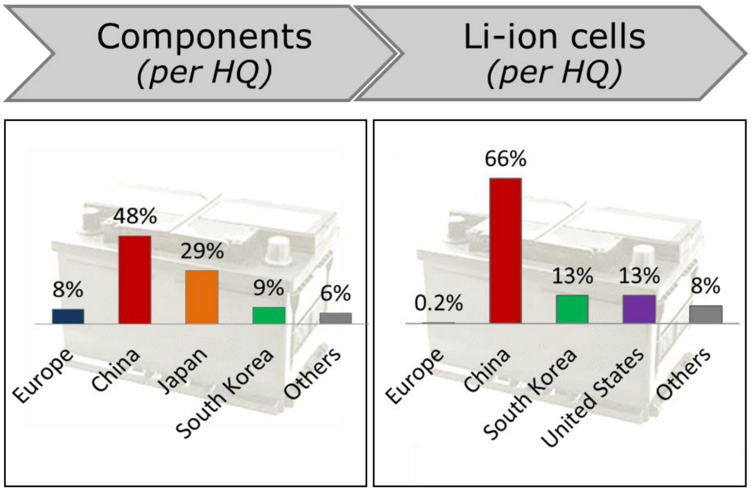
Conclusion: in spite of this deviation, the fact that China is the major supplier in the supply chain in both cases is evident. The shares of other suppliers also show relatively small differences. It is assumed that similar conclusions can be also drawn for the other technologies in the study.

Figure 122 Comparison between country supply shares based on headquarters and on the geographical location of production facilities for Li-ion components (cathodes, anodes, electrolytes and separators) and Li-ion cells

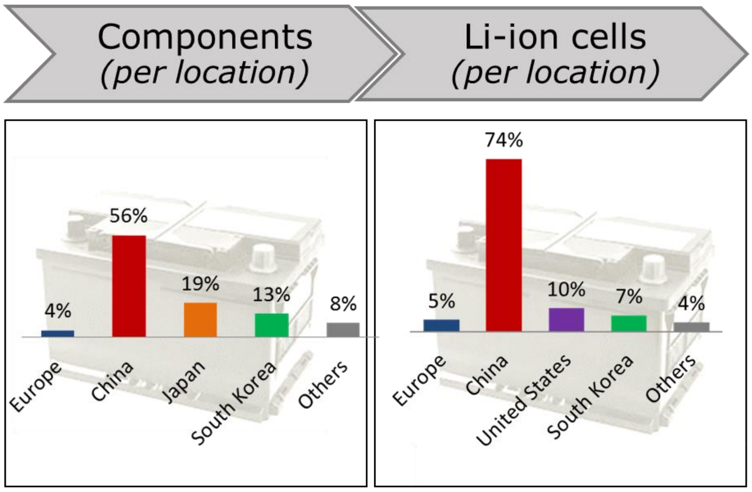


Source: BNEF, 2019. Bloomberg New Energy Finance, Battery Manufacturing database, retrieved March 2019.

Figure 123 Overall country supply chain shares for Li-ion components and Li-ion cells: comparison between (a) headquarters location and (b) geographical location of production facilities



(a)



(b)

Source: BNEF, 2019. Bloomberg New Energy Finance, Battery Manufacturing database, retrieved March 2019.

Annex 2 Data used in the analysis

Public open sources such as Statista, USGS, Europages and European Commission reports, etc. were used for the analysis to the greatest possible extent. Market/consultancy reports, commercial (companies') websites, associations' reports and websites were also used.

Data on raw materials were taken from the 2017 study on critical raw materials: Study on the review of the list of critical raw materials — Final report, European Commission, 2017.

Data on processed materials, components and assemblies (e.g. batteries, fuel cells, robots, drones, AM systems) were taken from various sources. Shares were calculated preferably using production data/capacity or market/sales data whenever possible. Otherwise data on revenues were used. If no other data were available, the number of companies per country was used to estimate country shares.

All data used in the technologies supply chain analysis are summarised in Table 32.

As a rule, the location of a company's headquarters was taken into account in order to allocate a company to a specific country. If a company with its headquarter in Europe has production facilities in other non-European countries, for instance, it still counts as a European company in the analysis and vice versa.

The following countries are considered to be 'Europe' in the report: the EU-28, Belarus, Norway, Switzerland and Ukraine. Cross-continental countries such as Russia and Turkey are not considered to be 'Europe' in this study.

Table 32 Overview of key country suppliers along the identified value chains for Li-ion batteries, fuel cell & hydrogen production & storage, robotics, UAVs and 3D printing technologies

	Batteries	**Fuel cells & hydrogen storage**	**Robotics**	**UAVs**	**3D printing**
Raw materials	**Aluminium** CN-45% RU-8% CA-6% EU-4% US-4% AU-4% RoW-29% **Iron** CN-44% AU-18% BR-13% IN-5% RoW-20% **Copper** CL-32% CN-9% PE-8% US-7% AU-5% RoW-39% **Titanium** CA-21%	**Aluminium** CN-45% RU-8% CA-6% EU-4% US-4% AU-4% RoW-29% **Iron** CN-44% AU-18% BR-13% IN-5% RoW-20% **Copper** CL-32% CN-9% PE-8% US-7% AU-5% RoW-39% **Chromium** ZA-48%	**Aluminium** CN-45% RU-8% CA-6% EU-4% US-4% AU-4% RoW-29% **Iron** CN-44% AU-18% BR-13% IN-5% RoW-20% **Chromium** ZA-48% KZ-21% TR-13% IN-12% RoW-6% **Cobalt** CD-64% CN-5%	**Aluminium** CN-45% RU-8% CA-6% EU-4% US-4% AU-4% RoW-29% **Iron** CN-44% AU-18% BR-13% IN-5% RoW-20% **Chromium** ZA-48% KZ-21% TR-13% IN-12% RoW-6% **Cobalt** CD-64% CN-5%	**Aluminium** CN-45% RU-8% CA-6% EU-4% US-4% AU-4% RoW-29% **Iron** CN-44% AU-18% BR-13% IN-5% RoW-20% **Chromium** ZA-48% KZ-21% TR-13% IN-12% RoW-6% **Copper** CL-32% CN-9%

	Batteries	Fuel cells & hydrogen storage	Robotics	UAVs	3D printing
	AU-15% ZA-12% CN-9% RoW-43% **Cobalt** CD-64% CN-5% CA-5% AU-4% ZM-4% RoW-18% **Silicon** CN-61% BR-10% Europe-7% US-6% RoW-16% **Lithium** CL-44% AU-32% AR-11% CN-5% RoW-8% **Manganese** CN-29% ZA-20% AU-14% GA-8% RoW-29% **Natural graphite** CN-69% IN-12% BR-8% RoW-11% **Nickel** PH-15% CA-12% RU-11% NC-10% AU-10% ID-9% RoW-32% **Fluorspar** CN-64% MX-6% MN-5% RoW-15% **Phosphorus** CN-44% US-13% MA-13%	KZ-21% TR-13% IN-12% RoW-6% **Boron** TR-38% US-23% AR-12% CL-9% RoW-18% **Cobalt** CD-64% CN-5% CA-5% AU-4% ZM-4% RoW-18% **Magnesium** CN-87% US-5% IL-3% RoW-5% **Nickel** PH-15% CA-12% RU-11% NC-10% AU-10% ID-9% RoW-32% **Palladium** RU-46% ZA-36% CA-7% RoW-11% **Platinum** ZA-71% RU-16% ZW-6% RoW-7% **REE** CN-95% US-2% RoW-3% **Silver** MX-21% PE-14% CN-14% AU-7% Europe-7% RoW-37% **Strontium**	CA-5% AU-4% ZM-4% RoW-18% **Molybdenum** CN-42% USA-23% CL-15% PE-6% RoW-14% **Silicon** CN-61% BR-10% Europe-7% US-6% RoW-16% **Natural graphite** CN-69% IN-12% BR-8% RoW-11% **Titanium** CA-21% AU-15% ZA-12% CN-9% RoW-43% **Nickel** PH-15% CA-12% RU-11% NC-10% AU-10% ID-9% RoW-32% **Magnesium** CN-87% US-5% IL-3% RoW-5% **Vanadium** CN-53% ZA-25% RU-20% RoW-2% **Copper** CL-32% CN-9% PE-8% US-7% AU-5%	CA-5% AU-4% ZM-4% RoW-18% **Molybdenum** CN-42% USA-23% CL-15% PE-6% RoW-14% **Silicon** CN-61% BR-10% Europe-7% US-6% RoW-16% **Natural graphite** CN-69% IN-12% BR-8% RoW-11% **Titanium** CA-21% AU-15% ZA-12% CN-9% RoW-43% **Nickel** PH-15% CA-12% RU-11% NC-10% AU-10% ID-9% RoW-32% **Magnesium** CN-87% US-5% IL-3% RoW-5% **Vanadium** CN-53% ZA-25% RU-20% RoW-2% **Copper** CL-32% CN-9% PE-8% US-7% AU-5%	PE-8% US-7% AU-5% RoW-39% **Titanium** CA-21% AU-15% ZA-12% CN-9% RoW-43% **Nickel** PH-15% CA-12% RU-11% NC-10% AU-10% ID-9% RoW-32% **Cobalt** CD-64% CN-5% CA-5% AU-4% ZM-4% RoW-18% **Magnesium** CN-87% US-5% IL-3% RoW-5% **Vanadium** CN-53% ZA-25% RU-20% RoW-2% **Molybdenum** CN-42% USA-23% CL-15% PE-6% RoW-14% **Manganese** CN-29% ZA-20% AU-14% GA-8% RoW-29% **Zirconium** AU-38% ZA-25% CN-9% ID-8%

	Batteries	Fuel cells & hydrogen storage	Robotics	UAVs	3D printing
	RU-5% RoW-25% **Tin** CN-45% ID-19% MY-10% PE-8% RoW-18%	Europe-45% MX-28% CN-25% RoW-2% **Zirconium** AU-38% ZA-25% CN-9% ID-8% RoW-21% **Gold** CN-14% AU-9% US-8% RU-8% ZA-6% PE-6% RoW-49% **Rhodium** ZA-53% ZW-28% RU-13% US-5% CA-1% **Manganese** CN-29% ZA-20% AU-14% GA-8% RoW-29% **Silicon** CN-61% BR-10% Europe-7% US-6% RoW-16% **Natural graphite** CN-69% IN-12% BR-8% RoW-11% **Molybdenum** CN-42% USA-23% CL-15% PE-6% RoW-14% **Ruthenium** RU-50% South America-30%	RoW-39% **Lead** CN-49% AU-14% US-7% PE-5% MX-5% RoW-20% **Silver** MX-21% PE-14% CN-14% AU-7% Europe-7% RoW-37% **Tin** CN-45% ID-19% MY-10% PE-8% RoW-18% **Antimony** CN-78% RU-4% RoW-18% **Bismuth** CN-82% MX-11% JP-7% **Gold** CN-14% AU-9% US-8% RU-8% ZA-6% PE-6% RoW-49% **Manganese** CN-29% ZA-20% AU-14% GA-8% RoW-29% **Zinc** CN-35% AU-12% PE-10% Europe-7% US-6% RoW-30% **REE** CN-95%	RoW-39% **Lead** CN-49% AU-14% US-7% PE-5% MX-5% RoW-20% **Silver** MX-21% PE-14% CN-14% AU-7% Europe-7% RoW-37% **Tin** CN-45% ID-19% MY-10% PE-8% RoW-18% **Antimony** CN-78% RU-4% RoW-18% **Bismuth** CN-82% MX-11% JP-7% **Gold** CN-14% AU-9% US-8% RU-8% ZA-6% PE-6% RoW-49% **Manganese** CN-29% ZA-20% AU-14% GA-8% RoW-29% **Zinc** CN-35% AU-12% PE-10% Europe-7% US-6% RoW-30% **REE** CN-95%	RoW-21% **Hafnium** AU-38% ZA-25% CN-9% ID-8% RoW-21% **Tungsten** CN-84% RU-4% RoW-12% **Scandium** CN-66% RU-26% UA-7% **Niobium** BR-95% RoW-5%

	Batteries	Fuel cells & hydrogen storage	Robotics	UAVs	3D printing
		ZA-7% US-7% CA-6% **Titanium** CA-21% AU-15% ZA-12% CN-9% RoW-43% **Limestone (Ca)** CN-25% US-18% Europe-21% RoW-36% **Feldspar** TR-26% Europe-39% CN-8% RoW-27% **Kaolin** Europe-27% US-17% IN-11% CN-9% RoW-36% **Vanadium** CN-53% ZA-25% RU-20% RoW-2% **Lithium** CL-44% AU-32% AR-11% CN-5% RoW-8% **Soda ash (Na)** US-40% TR-7% RoW-53% **Potash (K)** CA-29% RU-17% BY-15% CN-15% RoW-24%	US-2% RoW-3% **Lithium** CL-44% AU-32% AR-11% CN-5% RoW-8% **Palladium** RU-46% ZA-36% CA-7% RoW-11% **Platinum** ZA-71% RU-16% ZW-6% RoW-7% **Strontium** Europe-45% MX-28% CN-25% RoW-2% **Zirconium** AU-38% ZA-25% CN-9% ID-8% RoW-21% **Boron** TR-38% US-23% AR-12% CL-9% RoW-18% **Indium** CN-57% KR-15% JP-10% RoW-18% **Gallium** CN-53% US-11% UA-9% KR-8% RoW-19% **Arsenic** CN-68% MA-20% RoW-12% **Mercury**	US-2% RoW-3% **Lithium** CL-44% AU-32% AR-11% CN-5% RoW-8% **Palladium** RU-46% ZA-36% CA-7% RoW-11% **Platinum** ZA-71% RU-16% ZW-6% RoW-7% **Strontium** Europe-45% MX-28% CN-25% RoW-2% **Zirconium** AU-38% ZA-25% CN-9% ID-8% RoW-21% **Boron** TR-38% US-23% AR-12% CL-9% RoW-18% **Indium** CN-57% KR-15% JP-10% RoW-18% **Gallium** CN-53% US-11% UA-9% KR-8% RoW-19% **Arsenic** CN-68% MA-20% RoW-12% **Mercury**	

	Batteries	Fuel cells & hydrogen storage	Robotics	UAVs	3D printing
			CN-80% RoW 20% **Cadmium** CN-36% KR-16% JP-10% CA-7% RoW-31% **Tellurium** US-35% JP-28% RU-21% RoW-16% **Ruthenium** RU-50% South America-30% ZA-7% US-7% CA-6% **Rhodium** ZA-53% ZW-28% RU-13% US-5% CA-1% **Limestone (Ca)** CN-25% US-18% Europe-21% RoW-36% **Fluorspar** CN-64% MX-6% MN-5% RoW-15% **Feldspar** TR-26% Europe-39% CN-8% RoW-27% **Soda ash (Na)** US-40% TR-7% RoW-53% **Potash (K)** CA-29% RU-17% BY-15% CN-15%	CN-80% RoW 20% **Cadmium** CN-36% KR-16% JP-10% CA-7% RoW-31% **Tellurium** US-35% JP-28% RU-21% RoW-16% **Ruthenium** RU-50% South America-30% ZA-7% US-7% CA-6% **Rhodium** ZA-53% ZW-28% RU-13% US-5% CA-1% **Limestone (Ca)** CN-25% US-18% Europe-21% RoW-36% **Fluorspar** CN-64% MX-6% MN-5% RoW-15% **Feldspar** TR-26% Europe-39% CN-8% RoW-27% **Soda ash (Na)** US-40% TR-7% RoW-53% **Potash (K)** CA-29% RU-17% BY-15% CN-15%	

	Batteries	**Fuel cells & hydrogen storage**	**Robotics**	**UAVs**	**3D printing**
			RoW-24% **Kaolin** Europe-27% US-17% IN-11% CN-9% RoW-36% **Phosphorus** CN-44% US-13% MA-13% RU-5% RoW-25% **Tungsten** CN-84% RU-4% RoW-12% **Tantalum** CD-39% RW-28% NG-8% CN-7% BR-6% AU-5%	RoW-24% **Kaolin** Europe-27% US-17% IN-11% CN-9% RoW-36% **Phosphorus** CN-44% US-13% MA-13% RU-5% RoW-25% **Tungsten** CN-84% RU-4% RoW-12% **Tantalum** CD-39% RW-28% NG-8% CN-7% BR-6% AU-5% **Niobium** BR-95% RoW-5% **Hafnium** AU-38% ZA-25% CN-9% ID-8% RoW-21% **Beryllium** US-75% JP-25% **Scandium** CN-66% RU-26% UA-7%	
Processed materials	**Anode material (Processed natural graphite)** CN-57% JP-29% KR-4% RoW-10%	**Porous carbon** Europe-43% CN-29% JP-14% US-14% **YSZ** Europe-39% US-56%	**Aluminium alloys** US-43% IN-57% **Nickel alloys** Europe-45% CN-23% IN-22%	**Aluminium alloys** US-41% Europe-40% JP-4% IN-4% CA-1% **Aluminium-magnesium**	**Aluminium alloy powders** Europe-41% US-41% CA-11% JP-4% IN-3% **Nickel alloy powders**

	Batteries	Fuel cells & hydrogen storage	Robotics	UAVs	3D printing
	Anode materials (Artificial graphite) CN-76% JP-18% RoW-6% **Cathode material (NCA)** JP-79% KR-15% CN-4% RoW-2% **Cathode material (NMC)** CN-47% Europe-18% JP-9% KR-9% RoW-17% **Cathode material (LCO)** CN-59% KR-16% Europe-15% JP-8% RoW-2%	JP-5% **Polymers (PFSA)** Europe-20% US-60% CN-20% **Carbon fibres (CFC)** US-30% JP-18% Europe-16% CN-12% RoW-24% **Graphene** Europe-38% US-31% CN-8% AU-6% KR-3% IN-3% RoW-11% **Carbon cloth/paper** Europe-20% CA-20% US-20% JP-40% **Polyamide Ultramid** Europe-87% SG-6% US-5% CN-2% **Stainless steel** Europe-57% US-27% JP-3% IN-3% CA-7% TR-3% **Scrap and flake mica** Europe-22% TR-13% US-11% CN-8% CA-7% RoW-39% **Nano materials & Carbon**	RoW-10% **Ni-Ti alloys** Europe-36% CN-33% IN-22% RoW-9% **Mg alloys** Europe-42% CN-47% RoW-11% **Carbon fibre composites** US-30% JP-18% Europe-16% CN-12% RoW-24% **Aramid fibre (Kevlar)** US-50% JP-25% CN-10% RoW-15% **Special steels** IN-60% CN-27% US-7% Europe-6% **Polymers** US-54% Europe-37% RoW-9% **Nano materials & carbon nanotubes** US-43% Europe-19% IN-16% CN-9% RoW-13% **Advanced ceramics & glasses** Europe-49% JP-41% US-10% **Semi-conductors** US-55% KR-36% JP-5%	**alloys** CN-30% Europe-61% TR-6% IN-3% **Magnesium alloys** Europe-42% CN-47% RoW-11% **Nickel alloys** Europe-45% CN-23% IN-22% Row-10% **Nickel-titanium alloys** Europe-36% CN-33% IN-22% RoW-9% **Titanium alloys** Europe-51% US-30% CA-10% RoW-9% **Specialty steels** IN-60% CN-27% US-7% Europe-6% **High performance alloys** Europe-55% CN-29% US-7% RoW-9% **Refractory metals** Europe-42% CN-22% US-20% IN-8% RoW8% **Composites (CFC)** US-30% JP-18%	Europe-55% US-29% CA-10% JP-3% IN-3% **Stainless steel powders** Europe-57% US-27% CA-7% RoW-9% **Special alloy powders** Europe-70% US-19% CA-7% RoW-4% **Titanium alloy powders** Europe-50% US-30% CA-10% RoW-10%

	Batteries	Fuel cells & hydrogen storage	Robotics	UAVs	3D printing
		nanotubes US-43% Europe-19% IN-16% CN-9% RoW-13% **Boron Nitride powder** Europe-67% CN-17% US-8% IL-8% **Metal hydrides** Europe-50% CN-17% US-33%	RoW-4% **LIB proc materials** *(aggregated data)* CN-48% JP-29% KR-9% Europe-7% RoW-7% **Magnets proc. materials** CN-80% RoW-20% **FC proc. materials** *(aggregated data)* Europe-40% US-28% CN-10% JP-7% RoW-15%	Europe-16% CN-12% RoW-24% **Aramid fibres (kevlar)** US-50% JP-25% CN-10% RoW-15% **Semi-conductors** USA-55% KR-36% JP-5% RoW-4% **Magnets proc. materials** CN-80% RoW-20% **Ferro-niobium** BR-90% CA-10%	
Components	**Anode** CN-58% JP-24% US-12% KR-6% **Cathode** JP-32% CN-31% Europe-29% KR-6% RoW-2% **Electrolyte** CN-61% JP-20% KR-14% Europe-4% RoW-1% **Separator** CN-43% JP-40% KR-8% RoW-9%	Aggregated data used for components	**Gears** JP-85% RoW-15% **Actuators** US-78% Europe-11% IL-11% **Sensors** JP-25% US-23% Europe-23% CN-10% KR-11% RoW-8% **Magnets** CN-80% RoW-20% **Micro-processors** US-83% KR-8% RoW-9% **GPUs** US-95%	**Gears** JP-85% RoW-15% **Actuators** US-78% Europe-11% IL-11% **Sensors** JP-25% US-23% Europe-23% CN-10% KR-11% RoW-8% **Micro-processors** US-83% KR-8% RoW-9% **Magnets** CN-80% RoW-20% **GPUs** US-95%	Cannot be quantified

	Batteries	Fuel cells & hydrogen storage	Robotics	UAVs	3D printing
			RoW-5% **LIB cells** CN-66% US-13% KR-13% Europe-0.2% RoW-8% **Fuel cells** Asia-51% North America-48% Europe-1%	RoW-5% **Inertial measu-rement units** US-58% Europe-31% CA-7% RoW-4% **LiPo batteries** CN-60% US-20% KR-10% JP-10% **Fuel cells** Asia-51% North America-48% Europe-1% **Communica-tion systems** Europe-56% US-22% IL-11% CA-11% **Navigation and control systems** US-64% Europe-24% CA-8% RoW-4%	
Assemblies	**Battery cell** CN-66% US-13% KR-13% Europe-0.2% RoW-8%	**Fuel cell system** Asia-51% North America-48% Europe-1%	**Robots** JP-47% Europe-41% US-11% RoW-1%	**Drones** CN-77% Europe-9% US-5% IL-3% RoW-6%	**Metal 3D-printer systems** Europe-34% US-24% CN-23% JP-6% RoW-13%

Source: JRC compilation with data from various sources. Data on raw materials were mainly taken from the 'Study on the review of the list of critical raw materials – factsheets' published by the European Commission in 2017. The values represent the average between 2010 and 2014. The critical raw materials are given in red colour. Production data from USGS (2018) are used for materials not evaluated in the 2017 EC study on criticality. Various sources are used for processed materials, components and assemblies, referenced in the body of the report.

NOTE: Country abbreviations correspond to the ISO 3166-2 codes.

Table 33 Porous carbon manufacturers (used in Fuel cells supply chain)

Company	Country (HQ)
SGL Group	Germany
Fangda Carbon New Material Co., Ltd	China
Toyo Tanso Co. Ltd	Japan
Mersen	France
Schunk	Germany
Sinosteel Corporation	China
UCR	USA

Table 34 YSZ manufacturers (used in Fuel cells supply chain)

Company	Country (HQ)
Zircomet Ltd	UK
Inframat Advanced MaterialsTM	USA
LLC	USA
Elan Technology	USA
Sunfire GmbH	Germany
Delphi Automotive PLC	USA
Hexis AG	Germany
Rolls-Royce Plc	UK
FuelCell Energy Inc.	USA
Elcogen AS	Estonia
Ceres Power Limited	UK
FuelCell Energy Inc.	USA
Bloom Energy Corporation	USA
Topsoe Fuel Cell A/S	Denmark
Acumentrics SOFC	USA
Protonex Technology Corporation	USA
Versa Power Systems, Inc.	USA
Toto Ltd.	Japan

Table 35 Polymers (PFSA) manufacturers (used in Fuel cells supply chain)

Company	Country (HQ)
DuPont	USA
Solvay	Belgium
Dongyue	China
Chemours	USA
3M	USA

Table 36 Metal hydrides manufacturers (used in Fuel cells supply chain)

Company	Country (HQ)
McPhy Energy	France
MBN Nanomaterialia S.p.A.	Italy
GKN Powder Metallurgy	Germany
Alfa Aesar	USA
American Element	USA
Changsha Easchem Co.	China

Table 37 Boron nitride powder manufacturers (used in Fuel cells supply chain)

Company	Country (HQ)
SHENZHEN CHINARY CO., LTD.	China
Sigma Aldrich Corp.	USA
Henze Boron Nitride Products AG	Germany
HENGE Baustoff GmbH	Germany
ESK Ceramics GmbH & Co. KG	Germany
H.C. Carbon GmbH	Germany
Boron Compounds Ltd.	Israel

CeramTec AG	Germany
CERATONIA GmbH & Co. KG	Germany
Henan Suntek International Co.,Ltd	China
H. C. Starck GmbH	Germany
Saint-Gobain Ceramics	France

Table 38 Nano materials suppliers including carbon nanotubes (used in Fuel cells, Robotics and Unmanned vehicles supply chains)

Company	**Country (HQ)**
Adnano Technologies	India
Advance Nanopower Inc.	Taiwan
Alfa Aesar	USA
American Elements	USA
Arknano	China
Arry International Group Limited	China
AVANSA Technology & Services	India
Bottom Up Technology Corporation	India
Canatu	Finland
Carbon Nanomaterials Technology	South Korea
Carbon Nanotechnologies Incorporated	USA
Carbon Solution Inc.	USA
Catalytic Materials LLC	USA
CHASM Advanced Materials	USA
Cheap Tubes Inc	USA
Chengdu Alpha Nano Technology	China
Chengdu Organic Chemistry Co.	China
FutureCarbon GmbH	Germany
Glonatech	Greece
Haydale	UK
Heji Inc.	China
Hubron	UK
Hyperion Catalysis	USA
Klean Carbon	Canada
Litmus Nanotechnology	USA
Marion Technologies	France
Mer Corporation	USA
Mkano	Canada
Modern Synthesis Technology	Latvia
MP Biomedicals	USA
Nano-C	USA
Nanocomp Technologies	USA
Nanocs	USA
Nanografi	Turkey
Nanocyl S.A.	Belgium
NanoIntegris	USA
NanoLab	USA
Nanomics Technologies	India
NanoResearch Elements	India
Nanoshel	India
Nanostructured & Amorphous Materials Inc.	USA
NanoTechLabs	USA
Nanothinx S.A.	Greece
NoPo Nanotechnologies	India
OCSiAI	Russia
Plasma X	USA
Plasmachem GmbH	Germany
Platonic Nanotech	India
Polytech & Net GmbH	Germany
Quantum Corporation	India
Reade Advanced Materials	USA
Reinste Nano Ventures	India
SES Research	USA

Sigma-Aldrich	USA
Sisco Research Laboratories	India
Stanford Advanced Materials	USA
Stanford Materials	USA
Sun Innovations Nanomaterials Store	USA
Sun Nano	USA
Sun Nanotek Ltd.	China
TCI Europe	Belgium
TDA Research	USA
Texas Biochemicals	USA
Thomas Swan	UK
Tokyo Chemical Industry	Japan
XinNano Materials	Taiwan
Xintek Inc.	USA
Zeon Corporation	Japan

Table 39 Carbon cloth/paper manufacturers (used in Fuel cells supply chain)

Company	**Country (HQ)**
AvCarb Material Solutions	USA
Toho Tenax	Japan
Toray	Japan
Ballard	Canada
SGL Carbon	Germany

Table 40 Polyamide Ultramid (used in Fuel cells supply chain)

Company	**Country (HQ)**
Ecu Line Nv	Belgium
Ecu Line GmbH	Germany
Basf Se	France
BASF South East Asia Pte., Ltd.	Singapore
Basf Se	Germany
Ecu Worldwide Belgium Nv	Belgium
And Pantai	USA
Ac Container Line GmbH	Germany
Panalpina Welttransport GmbH	Germany
Basf Ltd. (HK)	Hong Kong

Table 41 Polymers' manufacturers (used in Robotics supply chain)

Company	**Country (HQ)**
Dow Chemical	USA
Lyondell Basell	Netherlands
Exxon Mobil	USA
SABIC	Saudi Arabia
INEOS	Switzerland
BASF	Germany
ENI	Italy
LG Chem	South Korea
Chevron Phillips	USA
Lanxess	Germany

Table 42 Semiconductors' manufacturers (used in Robotics and Unmanned vehicles supply chains)

Company	**Country (HQ)**
Broadcomm	USA
Intel	USA
Micron	USA
Nvidia	USA
NXP	Netherlands
Qualcomm	USA

Samsung	South Korea
SK Hynix	South Korea
Texas Instruments	USA
Toshiba	Japan

Table 43 Advanced ceramics, glasses and refractories manufacturers (used in Robotics supply chain)

Company	Country (HQ)
Saint-Gobain	France
Kyocera Corp.	Japan
Asahi Glass Co.	Japan
Murata Manufacturing Co.	Japan
Corning Inc.	USA
NSG Group	Japan
Morimura Group	Japan
SCHOTT AG	Germany
RHI Magnesita	Austria
Vesuvius plc	UK
Morgan Advanced materials	UK
Materion Corp.	USA
CeramTec Holding	Germany

Table 44 Major Aramid fibres manufacturers (Unmanned vehicles supply chains)

Company	Country (HQ)
DuPont	USA
Teijin	Japan
Yantai Tayho Advanced materials	China
X-FIPER New Materials	China
Kolon	South Korea
Hyosung	South Korea
Kamenskvolokno	Russia

Table 45 Gears manufacturers (used in Robotics and Unmanned vehicles supply chains)

Company	Market share	Country (HQ)
Nabtesco	60%	Japan
Harmonic Drive	16%	Japan
Others	24%	

Table 46 Actuators manufacturers (used in Robotics and Unmanned vehicles supply chains)

Company	Country (HQ)	Relevance to defence
Advanced motion controls	USA	NO
Beaver Aerospace and Defence	USA	YES
CDA Intercorp	USA	YES
Harmonic drive LLC	USA	NO
HFE International LLC	USA	NO
Marotta Controls	USA	YES
MTC Industries and Research	Israel	YES
Northwest UAV	USA	NO
Volz Servos	Germany	NO

Table 47 Microprocessors' manufacturers (used in Robotics and Unmanned vehicles supply chains)

Company	Country (HQ)
Intel	USA
Qualcomm	USA
Samsung	South Korea
Advanced Micro Devices	USA

Freescale Semiconductor	USA
Texas Instruments	USA
MediaTek	Taiwan
Nvidia	USA
Spreadtrum	China
Broadcom	USA

Table 48 IoT sensors manufacturers (used in Robotics and Unmanned vehicles supply chains)

Company	**Country (HQ)**
Analog Devices	USA
ARM Holdings Plc	UK
Broadcom Limited (Avago)	USA
Digi International Inc	USA
Ericsson	Sweden
Fujitsu	Japan
Honeywell International Inc	USA
IBM	USA
Infineon Technologies AG	Germany
InvenSense Inc	USA
Libelium	Spain
Linear Technology	USA
LORD Corp	USA
Microsemi	USA
Millennial Net	USA
NXP Semiconductors	Netherlands
OMRON Corporation	Japan
Renesas	Japan
Robert Bosch GmbH	Germany
Semtech	USA
Sensirion AG	Switzerland
Silicon Laboratories	USA
SmartThings Inc	USA
STMicroelectronics	Switzerland
Texas Instruments	USA

Table 49 CMOS image sensors manufacturers (used in Robotics and Unmanned vehicles supply chains)

Company	**Country (HQ)**
Sony	Japan
Samsung	South Korea
Omnivision	USA
On semiconductor	USA
Canon	USA
Toshiba	Japan
Panasonic	Japan
5K Hynix	South Korea
Galaxycore	China
STMicroelectronics	Switzerland
Pixart imaging	Taiwan
Pixelplus	South Korea
Hamatsu	Japan

Table 50 Hyperspectral imaging sensors /cameras manufacturers (used in Robotics and Unmanned vehicles supply chains)

Company	**Country (HQ)**
Admesy BV	Europe
Photon Etc	Canada
Teledyne DALSA	Canada
ABS GmbH	Europe

Adimec Electronic Imaging Inc.	USA
American Infrared Solutions (AIRS)	USA
Bodkin Design & Engineering LLC	USA
Brimrose Corp. of America	USA
Camlin Photonics	Europe
Cosine measurement systems BV	Europe
Delta Commercial Vision LLC	USA
Diaspective Vision GmbH	Europe
Entwicklungsbuero Stresing	Europe
EVK DI Kerschhaddl GmbH	Europe
FluxData Inc., A Halma Group Co	Europe
GIGAmacro	USA
Headwall BVBA, Sub. Of Headwall Photonics Inc.	Europe
Headwall Photonics Inc.	Europe
HinaLea Imaging, Bus. Unit of TruTag Tech. Inc.	USA
Hindsight Imaging Inc.	USA
HORIBA Scientific, Unit of HORIBA Int. Corp.	USA
INFAIMON Brasil, Member of INFAIMON GROUP	Brazil
ITRES Research Ltd.	Canada
MG Optical Solutions GmbH	Europe
MK Photonics Inc.	USA
Mountain Photonics GmbH	Europe
Optical Support Inc.	USA
PerkinElmer	USA
QuantaSpec Inc.	USA
Resonon Inc.	USA
SciTech Pty. Ltd.	Australia
Senop Oy	Europe
Spectral Imaging Ltd. (SPECIM)	Europe
Stream Technologies Inc.	Canada
Surface Optics Corp.	USA
Telops Inc.	Canada
TruTag Technologies Inc.	USA
Vrmagic Imaging GmbH	Europe

Table 51 Major exoskeleton companies, considered in the analysis (Robotics chapter)

Exoskeleton Company	**Country (HQ)**	**Application**
20KTS+ (20 Knots Plus Ltd)	UK	industrial & defence
Againer	Latvia	consumer
AlterG	US	medical
AxoSuit	Romania	medical
BAMA TEKNOLOJI	Turkey	medical
Bionic Power	Canada	energy
Bionik Laboratories	Canada	medical
Bioservo Technologies AB	Sweden	medical
B-Temia	Canada	defence & medical & industrial
CYBERDYNE	Japan	medical & industrial
Daiya Industry Co	Japan	medical & industrial
DSMY	South Korea	industrial
Ekso Bionics Holdings	USA	medical & defence
Exhauss	France	industrial
ExoAtlet	Russia	medical & defence
Focal Meditech BV	The Netherlands	medical
Fourier Intelligence	China	medical
Gobio Robot	France	industrial
GOGOA Mobility Robots	Spain	medical
GoXtudio	USA	consumer
Hocoma	Switzerland	medical
Honda	Japan	medical & industrial
Hyundai Motor Company	South Korea	industrial & medical
Indego	USA	medical
Innophys	Japan	industrial

Intercative Motion Technologies	USA	medical
Japet	France	others
Kinetek Wearable Robotics	Italy	medical
Kinetic Innovations LtD	UK	consumer
Laevo	The Netherlands	industrial
Lockheed Martin	USA	defence
Marsi-Bionics	Spain	medical
MedEXO Robotics	Hong Kong	medical
MediTouch	Israel	medical
Mitsubishi Heavy Industries	Japan	disaster management
Motorika Medical	Israel	medical
Myomo Inc	USA	medical
Noonee AG	Switzerland	industrial
Otherlab Orthotics	USA	medical
Ottobock	Germany	medical
P&S Mechanics Co. Ltd.	South Korea	medical
Panasonic-Activelink	Japan	disaster relief & industrial & medical
Parker Hannifin	USA	medical
PhaseX AB	Sweden	medical
RB3D	France	industrial
Reha Technology	Switzerland	medical
Rehab-Robotics	Hong Kong	medical
ReWalk Robotics	USA	medical
Rex Bionics	New Zealand	medical
Roki Robotics	Mexico	medical
Rotbod Systems	Israel	industrial
Sarcos LC	USA	others
Sarcos/Raytheon	USA	defence
Spring Active	USA	medical & others
SRI International	USA	others
StrongArm Tech	USA	others
Toyota	Japan	medical & others
Tyromotion GmbH	Austria	medical
US Bionics/SuitX	USA	others
Wandercraft-Exoskeleton	France	medical

Table 52 Major Industrial Robotics Companies

Company	**Country (HQ)**
Mitsubishi Electric	Japan
ABB (ASEA Brown Boveri)	Switzerland
B+M Surface Systems GmbH	Germany
Comau Robotics	Italy
Denso Corporation	Japan
Durr	Germany
Epson robots	USA
FANUC Robotics	Japan
IGM	USA
Kawasaki	Japan
KUKA Robotics	Germany
Nachi-Fujikoshi	USA
Omron Adept Technologies	Japan
Rethink Robotics	USA
Schunk	Germany
Siasun Robot and Automation	China
Staubli	Switzerland
Universal Robots	Denmark
Wittmann Battenfeld Group	Austria
Yamaha	Japan
Yaskawa	Japan

Table 53 The word's most innovative robotic companies in 2018

Company	Application	Country (HQ)
Open Robotics	IT	USA
Anki	consumer	Japan
Marble	supply chain	USA
Fetch Robotics	supply chain	USA
Whill	medical	Japan
Zume Pizza	supply chain	USA
Blue River Technology	agriculture	USA
ReWalk Robotics	medical	USA
Knightscope	security	USA
Standard Cognition	IT	USA

Table 54 Robotic companies related to defence

Companies	Country (HQ)
Ekso Bionics	USA
Energid Technologies	USA
MRX Technologies	UK
M-Tecks Robotics	France
Neptec Technologies	Canada
Neya Systems	USA
Qinetiq	UK
Robo-Team	USA
Silent Falcon	USA
SRI International	USA

Table 55 Companies providing robotic systems to military

Company	Country (HQ)
AAR Corp	USA
AeroVironment	USA
Agilent	USA
Airware	USA
API Technologies	UK
BAE Systems	UK
Boeing	USA
Boston Dynamics	USA
CAE Inc	Canada
Clearpath Robotics	Canada
CyPhy Works	USA
Dassault Aviation	France
Ekso Bionics	USA
Elbit Systems	Israel
Energid Technologies	USA
European Aeronautics Defense and Space	France
Exponent Inc.	USA
Finmeccanica Spa	Italy
FLIR Systems Inc	USA
General Dynamics	USA
Honeywell International	USA
Inrob Tech Ltd	USA
iRobot Corp	USA
ITT Exelis	USA
L3 Communication	USA
Lockheed Martin Corp	USA
MacDonald, Dettwiler and Associates	Canada
Moog Inc.	USA
MRX Technologies	UK
M-Tecks Robotics	France
Neptec Technologies	Canada
Neya Systems	USA

Northrop Grumman Corp	USA
Qinetiq Group	UK
Raytheon Company	USA
Robo-Team	USA
Rockwell Collins	USA
SARCOS RESEARCH CORP.	USA
Shield AI	USA
Silent Falcon	USA
SKYWATCH	Denmark
SRI International	USA
Teledyne Technologies Inc	USA
Textron Inc	USA
Thales Group	France
Thermo Fisher Scientific	USA
United Technologies Corp	USA
Velodyne	USA

Table 56 Communication systems manufacturers for unmanned systems (used in Unmanned vehicles supply chain)

Company	**Country (HQ)**
Unmanned System Source	USA
Commtact	Israel
Marshall	UK
Silvus Technologies	USA
Dynautics Ltd	UK
Sonardyne International	UK
Domo Tactical Communications	UK
Microdrones	Germany
Microhard	Canada

Table 57 Control and navigation systems manufacturers for unmanned systems (used in Unmanned vehicles supply chain)

Company	**Country (HQ)**
Advanced Navigation	Australia
Dynautics Ltd	UK
Emcore Corporation	USA
Gladiator Technologies	USA
Inertial Sense	USA
Lord MicroStrain	USA
Moog	USA
NavCom Technology	USA
Memsense	USA
Nemsic Inc	USA
NovAtel	Canada
Oxford Technical Solutions	UK
Polynesian Exploration Inc	USA
Rovotics	UAE
SBG Systems	France
Sonardyne	UK
Sparton NavEx	USA
Systron Donner Inertial	USA
Uavos Inc.	USA
Unmanned System Source	USA
VectorNav Technologies	USA
Xsens	Netherlands
Inertial Labs	USA
Applanix	Canada
Spirent	UK
uAvionix Corporation	USA

Table 58 Global UGVs manufacturers – key players

Company	Country (HQ)
General Dynamics	USA
Northrop Grumman	USA
Lockheed martin	USA
Clearpath Robotics Inc.	Canada
Israel Aerospace Industries	Israel
ECA Group	France
QinetiQ Group plc	UK
Oshkosh Corporation	USA
John Bean Technologies Corporation	USA
KION Group	Germany
Swisslog Holding AG	Switzerland
iRobot Corp	USA
Cobham	UK
SEEGRID Corporation	USA
Endeavor Robotics (FLIR Systems)	USA

Table 59 Global UAVs' manufacturers (used in Unmanned aerial vehicles supply chain)

Company	Country (HQ)
3D Robotics	USA
Aeronautics Defence Systems Ltd.	Israel
Aero-Sentinel Ltd.	Israel
AeroVironment	USA
Aeryon (belongs now to FLIR)	Canada
AGAT Control Systems	Belarus
Ambarella	USA
Beihang University	China
BirdsEyeView Aerobotics	USA
Blue Bear Systems Research Ltd.	United Kingdom
BlueBird Aerosystems	Israel
Chengu Aircraft Industry Group	China
China Aerospace Science and Industry Corporation	China
China Aerospace Science and Technology Corporation	China
CybAero	Sweden
Delair	France
Deltadrone	France
Denel SOC Ltd.	South Africa
DJI Innovations	China
DroneDeploy	USA
ECA Group	France
Ehang	China
Elbit Systems	Israel
EMT Ingenieurgesellschaft	Germany
ENICS JSC	Russia
FLIR Systems Inc. (incl. Prox Dynamics AS)	USA
FLYABILITY SA	Switzerland
Flying Production Ltd.	Israel
Global Industrial & Defence Solutions	Pakistan
GoPro	USA
ideaForge Technology Pvt.Ltd.	India
Innocon Ltd.	Israel
INSITU (100% owned by Boeing)	USA
Israel Aerospace Industries	Israel
Izhmash-Unmanned Systems LLC	Russia
JSC "558 Aircraft Repair Plant"	Belarus
Kaman	USA
KB Independent Development Laboratory LLC	Belarus
Korea Aerospace Industries LTD.	South Korea
Korean Air	South Korea
Leonardo	Italy

MapBox	USA
Northrop Grumman Corporation	USA
Paramount Group	South Africa
Parrot SA	France
senseFly	Switzerland
Piaggio Aerospace	Italy
Precision Hawk	USA
Safran (incl. Sagem)	France
Schiebel Elektronische Geraete GmbH	Austria
Sky-Watch	Denmark
Special Technology Center Ltd.	Russia
Syma Toys	China
TEKEVER	Portugal
The National Academy of Sciences Belarus	Belarus
UAV Factory Ltd.	Latvia
UAVision	Portugal
UCONYSYSTEM CO. LTD.	South Korea
Ukrspecsystems	Ukraine
Ultimate Unmanned Systems (PTY) Ltd.	South Africa
UMS Skeldar	Switzerland
Unmanned Systems	Russia
WB Electronics S.A.	Poland
Xi'an Aisheng Technology Group	China
Xiaomi	China
YUNEEC	Hongkong
ZALA AERO GROUP	Russia
ZeroZero (Hover)	China

Table 60 GPUs manufacturers (used in Robotics and Unmanned vehicles supply chains)

Company	**Country (HQ)**
nVIDIA	USA
Advanced Micro Devices (AMD)	USA
Intel	USA
S3 Graphics	USA
Matrox	Canada
Qualcomm	USA
Imagination Technologies	UK
ARM Holdings	UK

Table 61 IMUs manufacturers (used in Unmanned vehicles supply chains)

Company	**Country (HQ)**
Advanced Navigation	Australia
Analog Devices Inc.	USA
Applanix	Canada
ASC GmbH*	Germany
Bosch Sensortec GmbH	Germany
EMCORE CORPORATION	USA
Epson Electronics America, Inc	USA
Gladiator Technologies	USA
Honeywell International Inc.	USA
Inertial Labs	USA
Inertial Sense LLC	USA
InnaLabs Ltd	Ireland
KVH Industries Inc.	USA
LORD Sensing	USA
Memsense	USA
MEMSIC, Inc	USA
NovAtel Inc.	Canada
NXP semiconductors	NL
Oxford Technical Solutions Ltd	UK
SBG Systems S.A.S.	France

SENODIA SEMICONDUCTOR CO. LTD.	China
Sensonor AS	Norway
Sparton Navigation and Exploration	USA
Systron Donner, Inc.	USA
Vectornav LLC	USA
Xsens Technologies B.V.	Netherlands
Texas Instruments	USA
TTTech	Austria

Annex 3 Policy and research actions 3D printing

The following actions are retrieved from the AM motion roadmap and clustered under the topics of raw material supply bottlenecks, technology development, standardisation and certification, digital Security and the protection plus valorisation of IPR

Raw material supply bottlenecks

AM Motion – Technical cross-cutting action 11 - **Availability of high quality, environmentally friendly and cost-effective materials**

- The AM community relies on a limited selection of conventional feedstock materials. The availability of high quality, environmentally friendly and economically feasible raw materials or feedstocks should be fostered. The range of available materials needs to be expanded (e.g. high-class titanium powders); it is important to understand safe transport and handling of these materials and to study the whole life cycle impacts; strategic support is needed for European powder/material for AM supply chain and growth.
- Proposed activities are: Developing new ultra-high temperature materials (refractory, composite, others) and new alloys with high temperature capability; research into materials suitable for printing of multifunctional components, novel materials resulting in fewer undesirable by-products and less waste; reinforce collaboration between designers, material producers and AM machine manufacturers; increase awareness on existing powder metallurgy solutions; life cycle analyses approach to ensure material economic and environmental sustainability and recyclability.

Technology development

AM Motion – Technical cross-cutting action 8 - **Role of AM in circularity for resources**

- There is a need for recycling of parts made with AM and for using recycled materials to produce AM components. From one hand, there is a shortage of material recycling services and means for reusing AM materials.
- Proposed research activities include better environmental, economic and social assessment; development of feedstock recycling process and regulatory requirement for recycling of metal powders; Need for standard validation procedures for material properties in parts produced with feedstock that has been subjected to re-use/ recycling, as well as guidelines for acceptable material properties and actions that restore the material properties to the original target values.

AM Motion – Technical cross-cutting action 9 - **Building a knowledge repository of materials and process parameters**

- Databases of process parameters and material properties need to be developed to enable determination of product design and establishment of material design allowances for specific processes.
- Proposed activities include knowledge generation for the effect of AM parameters (including waste streams), to the energy consumption and environmental footprint (activity connected with life cycle analysis approaches); AM material information database to enable the correct choice of AM materials and; a library of industry cases (successful and failed).

AM Motion – Aerospace action 3 – **Quality and consistency of powder production**

- There is a need for identification of powder properties that are critical to obtain a "good" part during processing in AM machines. Moreover, having the right requirement for powder batch acceptance is required for certification compliance.
- Proposed activities are: Research about material quality, shape for powder and size in order to have a well-controlled material for the 3D process, including feedstock management and handling; quality and consistency of powder production. Improve processes for powder production with better distribution size control; define powder testing and validation criteria which can depend on each machine.

AM Motion – Aerospace action 4 – **New sustainable materials and processes** and related characterisation in the field of multifunctional materials, multi-materials and materials with highly improved functionality for aerospace applications.

- There is a need for improved reliability of AM produced parts during their life time, high performance materials (light weight, strong, high temperature, reliable) and special materials (ceramic/metal) or materials that include multifunctional capabilities on the materials (e.g. sensoring conductivity).

- Proposed activities are: development of shape memory alloys (thermal and magnetic), piezoelectric actuators and electro active polymers, lightweight materials (e.g. titanium alloys); extreme operating temperature super-alloys for turbine components; improved dynamic (fatigue) materials properties: development of new alloys with improved dynamic properties and the development of advanced composites including high mechanical resistance ceramic particles in metal matrix; development of materials with improved creep and oxidation resistance; development of new routes for powder production to enable cheaper powders; development of wire feedstock value chain with chemistry tailored for AM applications; welding filler metal suppliers; development of 'smart' parts by embedding sensors and/or effectors; development of new machine concepts and the development of modelling tools to support this activity.

AM Motion – Aerospace action 13 – **Production of larger airframe structures** through AM technologies

- There is a need for increasing the size of envelopes mean increases the productivity of the 'printers' including DED processes with wire, at a reasonable cost with the same quality. Also, methods to perform quality control/NDT on large AM parts are to be investigated further.
- Proposed activities are: the development of new machines with larger build envelopes, high deposition rate for higher productivity and integrated post-processing; assembly operations to be reduced towards the end of the production line.

Standardisation and certification

AM Motion – Technical cross-cutting action 3 - **Design guidelines**

- There is a need for AM process, material and application specific guidelines. Solid progress has been recently made in standardisation, like in form of ISO International standards. However, there is need for process; material, application specific guidelines as well as design standards for AM (such as for light weight structures and low vibration). In parallel there is also need for specific training and educational activities.
- Proposed actions are: Establishment of a set of generic AM design not-binding recommendations; design guidelines should also include the entire manufacturing aspects of AM in combination with pre- and post-processing; development of non-binding recommendations for addressing topology optimization; creation of a central European data bank as base reference; collection of best practices and application-specific Design Guidelines in mature industry environments.

AM Motion – Technical cross-cutting action 10: Increased industry engagement on **standards development** and **decrease fragmentation of AM standardization initiatives**

- There is a need to accelerate AM market take up, industry should be further engage in CEN, ASTM, and ISO standards development (e.g. in process certification.
- Proposed activities include: To promote the use of AM standards, including the use of a consistent AM terminology in all important documents and communications, including education on AM; promote the ongoing activities on standardization at a wider level; to boost truly collaborative environments and networks among the regions and Member States; Support further engagement via EC funded projects or other relevant projects with central focus on standardisation.

AM Motion – Technical cross-cutting action 12 - **Quality management systems**

- There is a need for definition of key quality affecting parameters for various AM systems& applications.
- Proposed actions are: Development of AM-process chain monitoring solutions, protocols and data systems; development of statistically based knowledge about the influence of AM-processing-chain parameters on the final part quality; development of specific 'AM-quality management' standards; definition of quality at several levels; setup of a qualification label for AM service providers; experimentally-validated databases containing standard sets of process parameters per process/machine/material; standard materials databases and standard post-processing (especially heat treatment) temperature profiles.

AM Motion - Technical cross-cutting action 15 – **Convergence among Artificial Intelligence, Robotics, Sensing Technologies and 3D Printing**

- AI can make 3D printing more productive by for example enabling more people to be designers and improving co-creation opportunities in different environments. Robots and disruptive software may enhance 3D printing speed and properties including quality by introducing artificial intelligence algorithms such as computer vision algorithms for in line quality control. Development of new AM technologies that can print in more complex spaces is also important.
- Proposed actions are: Development of novel AM technologies, integrating mechatronics, robotics and software development; integrate artificial intelligence in 3D printing design process, promoting co-creation and enhancing design opportunities by involving users and different stakeholders; increase automation, manufacturing speed and in line quality control in 3D printing through robotics and artificial intelligence.

AM Motion – Non - technical cross-cutting action 4 - **Safety issues of AM**

- There is a need for safety assessment, safety management and guidelines and education on EHS challenges with AM. In relation with protection of Machine Operators. Typical hazards to be addressed include: guarding from moving parts that are not protected from contact; the chemical handling; air emissions (dusts, vapours, fumes); noise; electrical; flammable/combustible cleaning materials; solid waste; laser use; and UV light.
- Proposed actions are: Adopt safer-by-design approaches; creating a standard addressing EHS issues relative to additive machines, incl. physical measurement of operator exposure to AM materials is one of the most critical needs and can be leveraged from existing industry standards and guidelines; in case of use of nano-materials during the AM process safe by design approaches are relevant; understanding the potential of the operation to generate fine powders, the exposure and the effect of volatile powders on the individual and surrounding environment during the life cycle; develop sufficient protective equipment around AM; development of technical solutions to minimize contact between operator and material; exploring the potential for charging powders into Flammable Atmospheres.

AM Motion – Aerospace action 12 – **Develop NDT and inspection criteria**

- There is a need for assessing whether the 'classic' NDT methods applied in the aerospace valid and sufficient also for AM.
- Proposed activities are: networking, coordination and research activities in the following aspects: defect classification, analysis of influence on static and fatigue performance, analysis and measurement of residual stresses, defect detection techniques, acceptance criteria.

Digital Security and the protection plus valorisation of IPR

AM Motion – Non-technical cross-cutting action 7 – **Developing and promoting effective intellectual properties strategies in AM** and better awareness of IP issues.

- There is a need for review of intellectual property implications of AM to avoid that it hinders innovation. Short term key IPR issues relate to AM designs and copyrights. Designs could be stolen and thus, reproduced. Open innovation strategies should be further exploited. There should be greater awareness in the IP law community on how AM is impacting client´s business models; among current challenges there are also a need for digitalization of patent law, digitalization of design rights and trademarks; territoriality of IPRs vs. global nature of digitalization; protection of information included in CAD files via exclusive rights; IPR protection of new materials; limits to apply patent law due to possible ethical issues involved; enforcement issues; use of technical protection measures to increase efficiency of enforcement of IPRs.
- Proposed activities are: development of a strategy to identify possible IP rights and issues that may arise taking into account the interests of all stakeholders; new forms of protection mechanisms; clearer guidance on defining whether a CAD file could have IPR protection; involvement of IPR related entities as EPO (European Patent Office); learn lessons from the past; look at past digitisation waves and avoid doing the same mistakes; joint tech/non-tech actions aiming at raising awareness; solving IP issues by implementing new business models.

AM Motion – Non-technical cross-cutting action 8 – **Promoting the creation of a suitable IP framework**

- There is currently no case law about AM/ 3D-Printing in Europe. Knowing the real implications of AM will take some time to develop, it is important to understand how the existing IP framework can be used in a suitable manner. On the other hand, the IP system might need to shape itself to be able to meet the needs of AM technology.

- Proposed activities are: To explore aspects that might be further regulated or regulated differently and liability aspects; to explore the need of regulating AM separately; to assess applicability and efficiency of current protection tools: copyright, patents, design rights, utility models, trade secrets; research is needed to address challenges and understand: What field of IPRs can currently apply to CAD Files; IPR Helpdesk workshops focusing on IP challenges related to AM.

List of abbreviations and definitions

3DP	3D Printing
AFC	Alkaline Fuel Cell
AI	Artificial Intelligence
AM	Additive Manufacturing
AMC	Acceptable Means of Compliance
APAC	Asia-Pacific
APU	Auxiliary Power Unit
ASTM	American Society of Testing and Materials
ATEC	Army Test and Evaluation Command
BMS	Battery Management System
BOP	Balance-of-Plant
CAD	Computer Aided Design
CAGR	Compound Annual Growth Rate
CBRN	Chemical, Biological, Radiological and Nuclear
CCM	Catalyst Coated Membrane
CFC	Carbon Fibre Composites
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CMOS	Complementary Metal—Oxide–Semiconductor
CNT	Carbon nanotubes
COE	Common Operating Environment
COTS	Commercial Off-The-Self
CRM	Critical Raw Material
C-RPAS	Counter Remotely Piloted Aircraft System
CSIR	Council for Scientific and Industrial Research South Africa
CTQ	Critical to Quality
DARPA	Defence Advanced Research Projects Agency
DED	Directed Energy Deposition

DG	Directorate General
DLA	US Defence Logistics Agency
DMD	Direct Metal Deposition
DMFC	Direct-Methanol Fuel Cell
DMLS	Direct Metal Laser Sintering
DOD	Department of Defence
EASA	European Aviation Safety Agency
EBM	Electron Beam Manufacturing
EDA	European Defence Agency
EDTIB	European Defence Technological and Industrial Base
EMEA	Europe, the Middle East and Africa
EOD	Explosive Ordnance Disposal
EPO	European Patent Office
ESM	Electronic Countermeasure
ESS	Energy Storage Systems
EU	European Union
EV	Electric Vehicle
FC	Fuel Cell
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FoF	Factories of the Future
GDE	Gas Diffusion Electrode
GDL	Gas Diffusion Layers
GM	Guidance Material
GPS	Global Positioning System
GPU	Graphics Processing Unit
HALE	High-Altitude Long Endurance
HIP	Hot Isostatic Pressing
HT-PEMFC	High-temperature Polymer Electrolyte Membrane Fuel Cell

IEA	International Energy Agency
IED	Improvised Explosive Device
IFR	International Federation of Robotics
IIoT	Industrial Internet of Things
IPR	Intellectual Property Right
IR	Infrared
ISO TC	International Organization for Standardization Technical Committee
ITAR	International Traffic in Arms Regulations
JARUS	Joint Authorities for Rulemaking on Unmanned Systems
JAUS	Joint Architecture for Unmanned Systems
JIT	Just-in-Time
KET	Key Enabling Technology
LACE	Low Altitude Short Endurance UAV
LALE	Low-Altitude Long Endurance
LCO	Lithium Cobalt Oxide
LENS	Laser Engineering Net Shaping
LIDAR	Light Detection And Ranging of Laser Imaging Detection And Ranging
LMD	Laser Metal Deposition
LT-PEMFC	Low-temperature Polymer Electrolyte Membrane Fuel Cell
MALE UAV	Medium-Altitude Long Endurance UAV
MAV	Micro UAV
MAVLink	Micro Air Vehicle Link
MCFC	Molten Carbonate Fuel Cell
MCS	Mobile Camouflage System
MEA	membrane electrode assembly
MH	Metal Hydride
MIG	Metal inert Gas welding

MMIC	Monolithic Microwave Integrated Circuit
MRL	Manufacturing Readiness Level
MS	Member States
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NAV	Nano UAV
NCA	Nickel Cobalt Aluminum
NDT	Non-Destructive Testing
NIST	National Institute of Standards and Technology
NMC	Nickel Manganese Cobalt Oxide
NPA	Notice of Proposed Amendment
nvSRAM	Non-volatile Static Random-Access Memory
OEMs	Original equipment manufacturer
P.S.S.	Public Safety and Security
PAFC	Phosphoric Acid Fuel Cells
PATSTAT	Patent Statistical Database
PBF	Powder Bed Fusion
PET	Polyethylene Terephthalate
PFSA	Perfluorinated Sulfonic Acid
PGM	Platinum Group Metal
PTFE	Polytetrafluoroethylene
PVC	Polyvinylchlorate
R&D	Research and Development
R&I	Research and Innovation
RAM	Radar Absorbing Materials
RAS	Radar Absorbing Structures
REEs	Rare Earth Elements
RFID	Radio-frequency identification

RMFC	Reformed Methanol Fuel Cell
ROS	Robot Operating System
RPAS	Remotely Piloted Aircraft System
RTO	Research Technology Organization
SBIR	Small Business Innovation Research
SCADA	Supervisory Control And Data Acquisition
SLC	Selective Laser Cladding
SLI	Starting Lighting & Ignition
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SME	Small and medium-sized enterprise
SOC	Special Operation Command
SOFC	Solid Oxide Fuel Cell
SORA	Specific Operations Risk Assessment
SRL	System Readiness Level
STANAG	STANdardization AGreement
TALOS	Tactical Assault Light Operator Suit
TCP	Technology Collaboration Programme
TIG	Tungsten Inert Gas welding
TOW	Tube-launched, Optically-tracked, Wire-guided
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle
UGS	Unmanned Ground System
UGV	Unmanned Ground Vehicle
UMS	Unmanned Maritime System
UMV	Unmanned Maritime Vehicle
UPC	Uninterruptible Power Supply

USFRL	USA Air Force Research Lab
USGS	The United States Geological Survey
USV	Unmanned Surface Vehicle
UTM	Unified Threat Management
UUV	Unmanned Undersea / Underwater Vehicles
UV	Unmanned Vehicle
UXO	UneXploded Ordnance
VTOL	Vertical take-off and landing
WAAM	Wire and Arc Additive Manufacturing
WW1	World War 1
YSZ	Yttria-Stabilized Zirconia

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KJ-1A-29889-EN-N

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Publications Office of the European Union

doi:10.2760/977597

ISBN 978-92-76-16658-0