European
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Addressing European Research and Innovation Challenges for System Transitions in Energy and Mobility

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Addressing European Research and Innovation Challenges for System Transitions in Energy and Mobility

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Manuscript completed in November 2024
1st edition

PDF	ISBN 978-92-68-18848-4	doi:10.2777/45191	KI-02-24-747-EN-N

Luxembourg: Publications Office of the European Union, 2024

EUROPEAN COMMISSION

Addressing European Research and Innovation Challenges for System Transitions in Energy and Mobility

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2024 Directorate-General for Research and Innovation

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FOREWORD

In 2019, the European Green Deal was introduced as the new European growth strategy, marking a significant step towards transforming the EU into a sustainable, fair and prosperous society. Since then, the European Commission has remained steadfast in its commitment to this transformation, steering a course through various crises while establishing the regulatory framework to tackle the climate crisis, accelerate the energy transition, and bolster the EU's economy.

The energy sector accounts for around 75% of GHG emissions, meaning massive efforts are required to reach net zero by 2050. The same is true of the transport sector, which must reduce its GHG emissions by 90% by 2050. This is why initiatives such as REPowerEU, the Green Deal Industrial Plan, and the Net-Zero Industry and Critical Raw Materials Acts, which have already been set in motion, must be pursued relentlessly.

A successful transformation can limit the existential risks and impacts of the climate and biodiversity crises, strengthen the EU's open strategic autonomy and security, and bolster the EU's long-term competitiveness and social model. Such a transformation entails addressing and navigating trade-offs that affect our society while identifying and seizing the opportunities this epochal change is opening. In this context, research and innovation (R&I) will be crucial to Europe's competitiveness. The reports of Enrico Letta on the future of the Single Market and of Mario Draghi on the future of European competitiveness also share this conclusion – R&I must be at the forefront of the EU's efforts if we are to succeed.

This reflection paper, prepared by four independent experts, offers recommendations and ideas on challenges and priorities for R&I in clean energy and mobility. It sets out a vision for future energy and mobility systems aligned with the EU's long-term ecological, economic, and social objectives, particularly reaching climate neutrality by 2050.

To bring about its vision, the paper explores nine innovation pathways for energy and mobility systems, selected based on their expected impact to achieve the vision. The pathways are assessed against four contemporary challenges affecting energy and mobility systems: low-carbon transitions, competitiveness, security, and social acceptance and justice. The experts also provide broader policy recommendations, acknowledging that R&I policy alone will not enable the necessary transitions but is at the core of a systemic and whole-of-government approach to achieving the EU's objectives.

This reflection paper is, therefore, both timely and prescient. It offers an exciting and thought-provoking set of ideas and recommendations for future R&I work in clean energy and mobility. It will also help to stimulate the debate on the next Framework Programme for Research and Innovation.

Marc LEMAÎTRE
Director-General for Research and Innovation (DG RTD)

EXECUTIVE SUMMARY

The world is rapidly changing and European research and innovation (R&I) policy must change with it. This Reflection Paper focuses on energy and mobility systems. Chapter 1 identifies four macro-level contextual changes. Chapter 2 elaborates on how these changes engender four contemporary challenges in energy and mobility systems. Chapter 3 articulates a vision of future energy and mobility systems that could address these changes and challenges. Chapter 4 explores how the four challenges play out in nine selected 'innovation pathways' and sets out recommendations for future R&I actions in each pathway. Chapter 5 provides broader recommendations for European R&I policy.

The four macro-level contextual changes outlined in Chapter 1 are, firstly, that low-carbon transitions have entered the diffusion and deployment stage in electricity and auto-mobility systems, which offers some hope for climate mitigation. This also means that European R&I and industrial policy should adapt to better support deployment and diffusion. Secondly, low-carbon and clean energy innovations have become part of a global innovation race, in which Europe is falling behind peers such as China and the United States, giving rise to concerns about European competitiveness. Thirdly, there has been a marked rise in global geopolitical tensions, resulting in greater security concerns. Fourthly, the low-carbon transition is increasingly the subject of societal contestation, with growing concerns about social acceptance, equity, justice, and inclusion.

Chapter 2 discusses in more detail how the four macro-level contextual changes have created four corresponding contemporary challenges in energy and mobility systems. While Europe has reduced its greenhouse gas (GHG) emissions by 31% between 1990 and 2022, and 24% between 2005 and 2022, it is not currently on track to meet future GHG reduction targets (at least 55% by 2030, 90% by 2040, and net-zero by 2050). The acceleration of low-carbon transitions challenge is particularly salient for energy systems (which include energy supply, industry, and buildings and agricultural energy) and mobility systems because these respectively account for 63% and 24% of GHG emissions. Regarding the competitiveness challenge, Europe is falling behind peers such as the United States and China, in terms of R&I activities, manufacturing and deployment of major low-carbon technologies. The security challenge entails not only the vulnerabilities and risks associated with over-reliance on a single supplier for materials or technologies, but also military defence, as well as climate change impacts. As the low-carbon transitions enter the diffusion and deployment stage, concerns about distributional effects, affordability and social justice implications, both within the EU and globally, have increased, and it is important not to underestimate the social acceptance and justice challenge.

According to the vision set forth in Chapter 3, taking into account both the contextual changes and the resulting challenges, by 2040-2050 future energy and mobility systems should have the following characteristics: (1) be low-emission, cost-competitive, energy- and resource-efficient, integrated and flexible; (2) involve significant degrees of European manufacturing in order to support employment and maintain economic vitality; (3) reduce security risks and, in line with the concept of 'open strategic autonomy', rely on diversified international supply chains and science, technology and innovation networks, and increased domestic manufacturing of low-carbon technologies; and (4) offer societal benefits such has cleaner air and improved affordability.

Chapter 4 discusses how the challenges for energy and mobility systems play out in nine 'innovation pathways', selected on the basis of their expected impact on achieving the vision for future energy and mobility systems proposed in this paper. Therefore, each pathway *proposes a series of forward-looking policy recommendations for concrete R&I actions, addressing basic and applied research, and deployment. The selected pathways are:*

1. *System integration, focusing especially on digital technologies and how they can act as the 'glue' in aligning multiple innovations.*

2. *Infrastructural innovations in mobility and energy, including street redesign, electricity grids (comprising enablers of greater flexibility, including storage technologies) and hydrogen infrastructures.*

3. *The decarbonisation of electricity production, particularly through solar photovoltaic and wind that will be critical for Europe's economic competitiveness and industrial development.*

4. *Heat pumps, which enable the electrification of buildings and industry, to be effectively paired with electrothermal energy storage, and to bring significant energy efficiency enhancements that reduce primary energy demand.*

5. *Electric vehicles, which enable the electrification of road transport, to offer opportunities for synergies with grid flexibility thanks to battery storage, and that will also bring energy efficiency improvements.*

6. *Biofuels in transport, which have climate mitigation and security benefits, but may struggle to scale up and achieve cost parity.*

7. *Hydrogen and its derivatives with regard to the overall energy system, including transport applications; despite potential benefits, this innovation pathway may also struggle to scale up and achieve cost parity.*

8. *Social innovations, which can improve the sustainability and resilience of energy and mobility systems.*

9. *Mobility-as-a-Service, which is a particular social innovation intertwined with digital innovations that involves deeper behavioural changes and social innovations in mobility systems, including a shift from private ownership towards more shared mobility.*

Chapter 5 offers wider policy recommendations that, taking into account the contextual changes and their associated challenges, go beyond the selected innovation pathways and address R&I policy more generally. These recommendations are:

1. *Increase public R&I support strategically, with a focus on achieving price/performance parity to leverage the power of markets.*

2. *Find a new balance between the protection of existing assets and the creation of new assets for growth, taking a forward-looking approach.*

3. *Align basic research for disruptions, applied R&I as a key enabler of change, and deployment actions to scale up resilient innovations.*

4. *Take specific R&I actions to reduce supply chain over-dependency, in conjunction with other policies with the same objective.*

5. *Align R&I actions with other strategic, infrastructure-related choices, correcting market failures, targeting better competitiveness.*

6. *Take specific R&I actions regarding social innovations and better understanding of the dynamics of system transitions.*

7. *Consider institutional changes to leverage large-scale opportunities, including better EU/Member State coordination.*

8. *Foster the contributions of new stakeholders, moving the attention beyond incumbents, to better leverage the potential of startups.*

1. Introduction – Four contextual changes in a changing world

The European Green Deal (European Commission, 2019) aimed for transitions in energy, mobility, industrial, and food systems to address persistent environmental problems and develop a '*new growth strategy*' (p.2) for Europe. This focus on system transitions explicitly built on the Intergovernmental Panel on Climate Change's (IPPC, 2018) 1.5C report and the European Environmental Agency's (EEA, 2019) State and Outlook of the European Environment report, with the former calling for '*rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems*' (IPCC, 2018: 21) and the latter calling for transformations in production-consumption systems in energy, mobility, and food, which require changes in the constituting system elements, including technologies, infrastructures, industry, markets, user practices, policy, values, and knowledge (EEA, 2019: 345).

Innovations and innovation policies are widely acknowledged to play a central role in system transitions (OECD, 2015, 2023; European Commission, 2018; EEA, 2019; Geels et al., 2023), although sectoral policies (e.g. transport, energy, food) and cross-cutting policies (e.g. fiscal, education, industrial) are also important, especially for diffusion and deployment. There are many promising innovations that can reconfigure existing systems in more sustainable directions, while also offering new growth opportunities and societal benefits (Table 1).

	Energy (electricity, heat)	**Mobility**	**Agri-food**
Technical innovation	Renewable electricity (wind, solar, biomass, hydro), heat pumps, passive house, whole-house retrofit, smart meters	Battery-electric vehicles, electric bikes and micromobility, autonomous vehicles, alternative fuels (e.g. biofuels, hydrogen, ammonia) for trucks, ships and planes	Permaculture, agroecology, alternative proteins (e.g. plant-based meat and milk), manure digestion
Infrastructural innovation	Smart grids, electricity storage, grid extensions and reinforcements, district heating system, bio-methane in reconfigured gas grid	Intermodal transport systems (including smart cards for payment), revamped urban transport systems (tram, light-rail, metro, cycle lanes), compact cities	Efficient irrigation systems, agroforestry, rewilding, multi-functional land-use
Grassroots and social innovation	Community energy, 'prosumers' (households generating and using their own electricity), demand-side response	Car-sharing, bike sharing, modal shifts (from coals to bicycles or public transport), Mobility as a Service (Maas), tele-working, tele-conferencing	Alternative food networks, organic food, less-meat initiatives, urban farming

	Energy (electricity, heat)	Mobility	Agri-food
Business model innovation	Energy service companies, capacity markets, vehicle-to-grid electricity provision	Mobility services, car-sharing, bike sharing	Alternative food networks, organic food

Table 1. Examples of promising innovations in mobility, agri-food and energy domains (adapted from Geels, 2019: 190).

In recent years, several major contextual changes have occurred that create new challenges for Europe's unfolding system transitions. We discuss four contextual changes here and elaborate the related new challenges in Chapter 3 for energy and mobility, which are the focus of this Reflection Paper.

- One important change is that some technical innovations such as renewable electricity technologies (e.g. solar-PV, wind turbines, heat pumps) and electric vehicles have entered the diffusion and deployment stage of low-carbon transitions, which offers some hope for climate mitigation, despite rising greenhouse gas emissions at the global scale. The preface to the 2023 State of Climate Action report therefore notes not just the worsening climate emergency, but also states that 'we are seeing spectacular gains that are surprising even optimists' (Boehm et al., 2023: vii), referring in particular to solar-PV, wind turbines, electric vehicles, and heat pumps. Likewise, the preface of the 2023 World Energy Outlook (IEA, 2023c: 6) states that: 'Clean energy deployment is moving faster than many people realise. And it can and should go faster still for us to meet our shared energy and climate goals.' Many other innovations are in earlier developmental stages (e.g. hydrogen, smart grids, carbon capture and storage (CCS), mobility as a service), which poses acceleration challenges as we elaborate in Chapter 3. Once these other innovations start accelerating, they also need to be combined, which means that system integration becomes more important (European Commission, 2020), creating possibilities that digital technologies, low-carbon innovations, social innovations, and business model innovations work together in new ways.

- A second change is that low-carbon and clean energy innovations have become a part of global innovation races between major powers, with industrial policy rising to the top of the agenda for policymakers in the world's three largest economies: the United States, China, and the European Union (EU) (Johnston, 2023). China has achieved a global lead in many energy technology areas (IEA, 2024a), to the point that clean energy was a key driver of its economic growth in 2023 (Myllyvirta et al., 2023). Both the United States and Europe started to respond, triggering a global race. In the United States, key responses include the Bipartisan Infrastructure Law (US Congress, 2021), which includes major investments aimed at modernising the electricity grid, building a nationwide network of electric vehicle chargers, strengthening battery supply chains, expanding public transit and passenger rail and investing in new clean energy and emissions reduction technologies. The US response also include the Inflation Reduction Act in 2022 (US Congress, 2022), which offered significant financial support for the domestic production and use of many low-carbon technologies and the Chips and Science Act, which aims to support a diversification of supply chains for digital technologies (White House, 2022). As shown also by recent tariff increases (White House, 2024), the US policy response also creates new barriers for imports (especially from China).

In the EU, key responses include the NextGenerationEU recovery instrument, responding to COVID-19 and including major infrastructure investments (similar to the US BIL), funded for the first time by joint borrowing and dedicating a significant portion of its budget to climate change mitigation (European Commission, 2022). They also include: the 'Fit for 55 package', first proposed in 2021, currently almost entirely converted into EU law (European Commission, 2023), and including a significant reform of the Emission Trading Scheme, the establishment of a Carbon Border Adjustment Mechanism and several regulatory tools aiming to provide clear signals to stimulate clean energy demand. In addition, the Green Deal Industrial Plan (European Commission, 2023), proposed in 2023 aims to provide a more supportive environment to scale up EU manufacturing capacity for net-zero technologies, including the supply of required materials. Aiming to bolster Europe's competitiveness and resilience in semiconductor technologies, while also supporting the digital transition, the EU also finalised, in 2023, the European Chips Act (European Union, 2023). Despite these and earlier policy efforts, the EU has fallen behind China in several areas of the clean tech innovation and manufacturing race and it also risks being behind the United States (Karagianni and Besnainou, 2024), exacerbating concerns about Europe's competitiveness generally and more specifically, in clean and digital tech markets.

- A third contextual change is the marked increase of global geopolitical tensions and rising risks to European security. Russia's full-scale invasion of Ukraine and its weaponisation of gas exports to Europe in 2022 and 2023 increased security concerns over reliance on dominant suppliers, leading to the development of the REPowerEU plan (European Commission, 2022) and the ratcheting up of the ambition of the 'Fit for 55' package to reduce the EU's dependence on Russian fossil fuels, while continuing to tackle the climate crisis and stimulate an industrial transformation. Increasing tensions with China have also heightened concerns about the country's advantage in digital and low-carbon supply chains (for technologies, minerals, and materials). To reduce potential vulnerabilities associated with over-dependency, but also in light of the importance of global trade and economic interdependence for global peace and prosperity (Okonjo-Iweala, 2023), European policymakers introduced the new concept of 'open strategic autonomy'. The increasing security risks have also resulted in many EU member states to push up their defence budgets (European Defence Agency, 2023), with potential implications on funds available for other purposes, such as R&I and new discussions on previously avoided topic of dual use technologies for military and other societal uses (European Commission, 2024).

- A fourth change is the increase in societal contestation of environmental policies and low-carbon innovations in many European countries, despite significant efforts to alleviate equity-related challenges such as the Just Transition Mechanism (European Commission, 2021) and the Social Climate Fund (European Union, 2023), and an articulated set of tools in the framework of the European cohesion and just transition policy with significant funds (European Commission, n.d.). Protests and heated debates about changes in farming, home heating, and electricity grids highlight the challenge of bringing society along in system transitions, and the need to better listen and address the concerns of multiple stakeholders and pay specific attention to vulnerable groups in society (e.g. children, youth, the elderly, low-income households, indigenous people).

- After years of relative complacency, in which many EU policy documents proclaimed and self-congratulated Europe's green leadership, emphasising (correctly, but also insufficiently) the comparatively lower GHG emissions intensity of the EU economy in comparison with China and the United States, the EU has woken up to acknowledge the serious challenges posed by recent context changes. For example, former Italian Prime Minister and President of the European Central Bank, Mario Draghi, delivered a speech on 16 April 2024 (Groupe d'Etudes Politiques, 2024), in which he presented ideas for his commissioned report on Europe's competitiveness, diagnosing that European policymakers have '*had the wrong focus*', '*have not looked outwards enough*', and are '*lacking a strategy for how to keep pace in an increasing cutthroat race for leadership in new technologies*'. He therefore argues that '*radical change is what is needed*' and sets out various directions.

- In his report 'The future of European Competitiveness' (Draghi, 2024), published on 9 September 2024, Draghi concluded that declining European competitiveness now poses an 'existential challenge' (p.1) because it would hamper future growth and the ability to maintain Europe's social model. The report therefore called for radical change and disruptive innovation in three main areas, aimed at: (1) '*closing the innovation gap with the US and China, especially in advanced technologies*' (p.2), including digital and clean technologies; (2) accelerating decarbonisation, which offers growth opportunities in clean technologies (where the EU still holds some leading positions, especially in battery technologies) and opportunities to reduce energy costs, which are much higher than in the US and China. But the report also warns that: '*It is not guaranteed that Europe will seize this opportunity. Chinese competition is becoming acute in industries like clean tech and electric vehicles*' (p.3) and that '*despite the EU's ambition to maintain and develop clean tech manufacturing capacity, there are multiple signs of an evolution in the opposite direction*' (p.42); (3) increasing security and reducing dependencies' (p.3) because Europe relies strongly on a handful of suppliers of digital technology, microchips, critical raw materials, and clean technology components. To address the new challenges and achieve the stated aims, the Draghi report proposes a new industrial strategy for Europe that focuses centrally on innovation policy (to accelerate the development, diffusion, and commercialisation of new technologies) and greater alignment with fiscal policies (to drive domestic production and demand), trade policies (to protect against countries with anti-competitive policies), and foreign economic policies (to secure supply chains) but with a mixed strategy that combines different policy approaches for different industries.

- Former Italian Prime Minister, Enrico Letta, recently delivered a report on Europe's single market (Letta, 2024), which similarly acknowledges that '*the international scenario has profoundly changed*' (p.3), that the international order has '*entered a phase marked by the resurgence of power politics*' (p.4), and that Europe faces '*strong global competition*' which requires it to '*step up its efforts to develop a competitive industrial strategy*' (p.12), while also recognising and better communicating '*the extensive benefits that this transition offers to citizens, businesses, and workers*' (p.12). Importantly, this report also includes a proposal to add a '*fifth freedom*' to the free movement of goods, services, people, and capital characterising the European single market. The proposal aims to foster an '*ecosystem where knowledge diffusion propels both economic vitality, societal advancement and cultural enlightenment*'. The Letta report also proposes to add energy – alongside finance and electronic communications – to the perimeter of the Single Market, moving beyond its exclusion from the EU integration process (as they were considered too strategic for their operation and regulation to extend beyond national borders). It also calls for a further leap in interconnectivity between energy and mobility infrastructures.

These contextual changes imply that European R&I policy should also adapt to help address the new challenges. This Reflection Paper aims to articulate these strategic adaptations with regard to both R&I priorities (Chapter 4) and policies (Chapter 5), with a particular focus on mobility and energy (although not nuclear power, which is beyond the remit of this Reflection Paper). Chapter 2 describes the new challenges that the four contextual changes pose for energy and mobility systems, with Chapter 3 setting forth a vision of European energy and mobility systems towards 2050 that addresses these challenges and which is quite feasible based on current development trajectories. One reason for focusing on energy and mobility systems is that both systems are essential for climate change mitigation, with transport accounting directly[1] for 24.1% of European greenhouse gas (GHG) emissions in 2022, and energy supply, industry, and buildings and agriculture energy accounting for 62.9% of emissions (ESABCC, 2024). Another reason is that energy and mobility account for significant European manufacturing capacity, employment, and exports - especially for transport vehicles (including cars, trucks, aircraft and their parts), machines (including heavy industrial equipment, turbines, engines and electric motors) and chemicals (such as refined products and tyres) (OEC, 2024). Job opportunities in clean energy (including electric vehicles, low-emission electricity grids and storage, end-use efficiency, raw materials and low-emission fuels) are expected to outweigh job losses in fossil fuel sectors (IEA, 2023d). This means that the economic and social stakes are high in the global innovation and manufacturing races, mentioned above. A third reason is that energy and mobility are directly relevant for people's daily lives and experiences, and that the associated infrastructures offer the potential for creating more robust and efficient Europe-wide systems, accompanied by opportunities for job creation.

2. Key challenges for energy and mobility systems and associated European R&I policies

Energy and mobility system transitions towards the long-term vision set out in Chapter 3 will encounter four key challenges in the next 10-15 years that are highly relevant for European R&I policy.

2.1. The acceleration of low-carbon transitions challenge

The first challenge is to reach the European climate mitigation goals. Europe has made significant progress in the past, reducing GHG emissions by 31% between 1990 and 2022 and 24% between 2005 and 2022 (Figure 1). Most emission reductions between 2005 and 2022 were achieved in energy supply (-30%), especially through demand reduction and a shift from coal to renewables in electricity generation, industry (-30%) and buildings (-28%). Less progress was made in transport (-5%) and agriculture (-5%). Some emission reductions (especially in industry) relate to structural changes such as deindustrialisation due to the outsourcing of energy-intensive activities, which means that the EU is importing higher amounts of energy and GHG emissions embodied in goods and services (Moreau et al., 2019).

[1] I.e. excluding vehicle manufacturing and infrastructure construction and maintenance, and only including tailpipe emissions due to fuel combustion.

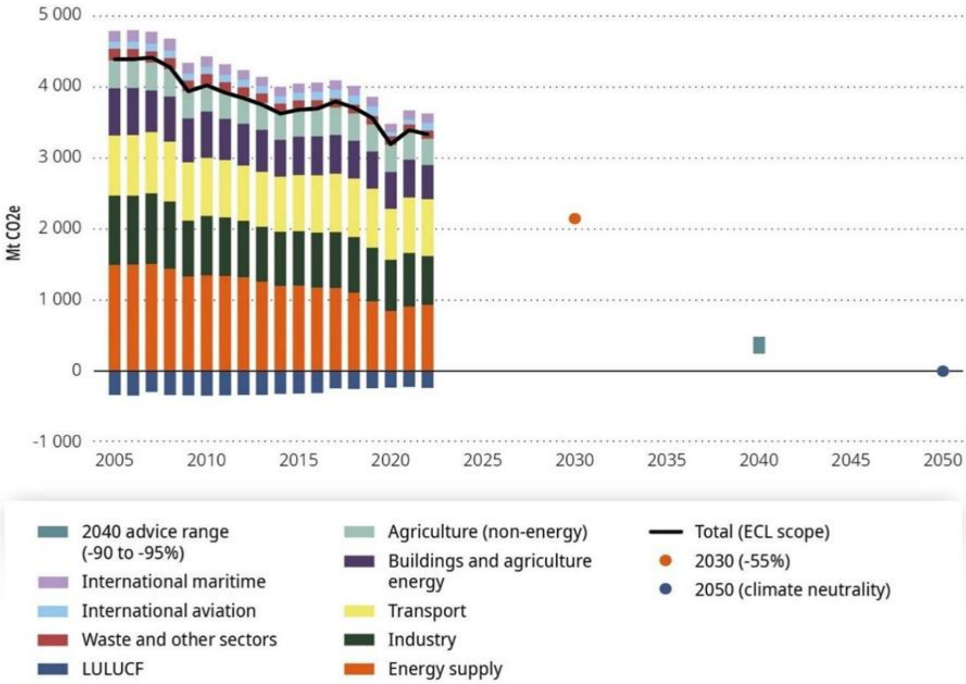

Figure 1. European greenhouse gas emissions in different sectors (ESABCC, 2024: 40).

The latest report by the IPCC concluded that insufficient progress has been made in national plans to limit the global temperature rise to 1.5 degrees (IPCC, 2023). The IPCC synthesis report also notes that '*Urban infrastructure, including transportation, water, sanitation and energy systems have been compromised by extreme and slow-onset events*' (IPCC, 2023, p. 6), meaning that energy and mobility systems not only need to be developed to further reduce greenhouse gas emissions, but also make them more resilient against the impacts of climate change. It also noted that many mitigation options (e.g. solar, wind, electrification, demand-side management), are increasingly cost effective and supported by the public. Further, the report emphasised the interdependence of climate with ecosystems, biodiversity and human societies. For instance, maladaptation, e.g. via increasing resource exploitation, '*can worsen existing inequities especially for Indigenous Peoples and marginalised groups and decrease ecosystem and biodiversity resilience*' (IPCC, 2023, p. 19)

Although moving in the right direction, the European Scientific Advisory Board on Climate Change's recent assessment report also concludes that: '*the observed trends are not sufficient to indicate that the EU is on track to meet its climate targets*' (ESABCC, 2024: 18). Europe should thus accelerate the low-carbon transition in energy and mobility systems, which requires both the diffusion and deployment of more developed innovations that can help reduce emissions in the near term and the development and commercialisation of new innovations that can help reduce emissions in the longer term.

2.2. The competitiveness challenge

The second challenge is that Europe is falling behind competitors, especially China, in the deployment, manufacturing, and research and innovation of major low-carbon technologies. While this is partly influenced by structural deindustrialization dynamics in the EU (Moreau et al., 2019), it is also the result of a proactive approach on industrial policy for clean technologies adopted in China in the past decade, with renewable energy equipment, EVs and battery technology as key success stories (Garcia Herrero and Schindowski, 2024).

In terms of deployment, cumulative installed capacity of solar and wind, for example, quadrupled in Europe from 110GW in 2010 to 405GW in 2022, increased 7-fold in the United States from 43GW to 254GW, and increased 24-fold in China from 31GW in 2010 to 759GW in 2022 (https://ourworldindata.org/renewable-energy). This has created a large domestic market for Chinese manufacturers, enabling them to benefit from scale economies, learning-by-doing, and cost reduction. China has also raced ahead in the deployment of plug-in and battery electric vehicles, with annual sales increasing from 1.1 million in 2020 to 8.1 million in 2023. European annual sales in that period increased from 1.4 million to 3.36 million, while US annual sales increased from 294,000 to 1.4 million (IEA, 2024b).

In terms of manufacturing, the gap between Europe and China is even larger. Because of years of strategic investments in production facilities and other forms of policy support, China has very dominant positions in the manufacturing (and global exports) of solar-PV, onshore and offshore wind, electric vehicles and batteries, and also leads the manufacturing of heat pumps and electrolysers (Figure 2).

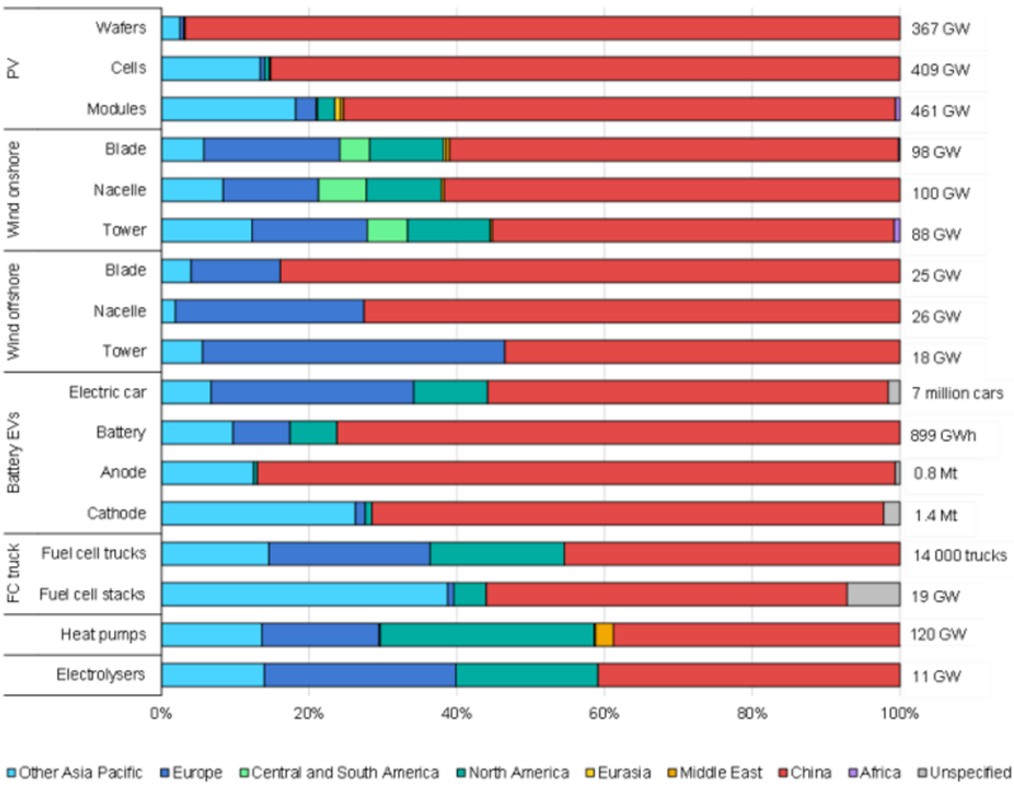

Figure 2. Regional shares of manufacturing capacity for selected clean energy technologies and components in 2021 (IEA, 2023a: 96) (FC refers to Fuel Cell).

Europe still has some presence in the manufacturing of (components for) onshore and offshore wind, electric vehicles, fuel cell trucks, heat pumps, and electrolysers (Figure 6), which thus offers a potential basis for stronger future participation in global low-carbon innovation and manufacturing races. However, realising that potential will require stronger policy action to promote R&I, create demand and mobilise private investments. It will also require the growth of new industrial capacity (e.g. for the recycling of battery materials, wind turbines and solar panels), especially in the context of a progressive development towards increased economic circularity.

That said, China's recent and planned investments in new manufacturing facilities are exacerbating competitive pressures on Europe because output exceeds domestic demand, which has led China to increasingly export electric vehicles and wind power equipment, often at cheaper prices that threaten to undercut European producers in the automotive and wind energy industries. Based on current installed capacity (in 2022) and announced manufacturing capacity additions (for 2030), the IEA projects that China will maintain its dominance in solar PV, and wind, somewhat reduce its share in batteries (as Europe and the United States increase their domestic production), and significantly reduce its manufacturing shares in electrolysers and heat pumps, while Europe expands its share in these technologies (Figure 3).

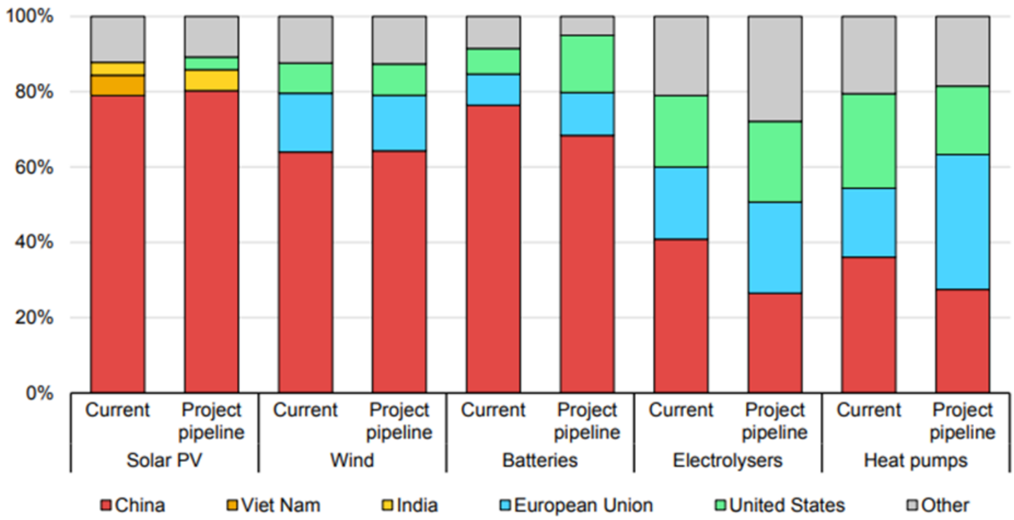

Figure 3. Current (2022) and projected (2030) geographical concentration for clean technology manufacturing operations (IEA, 2023b: 14).

In terms of research and innovation, Europe is also increasingly lagging behind both the US and China, both generally and with regard to energy and transport. In terms of overall research inputs, Europe has slightly improved its R&D funding from 2.0% to 2.3% of GDP between 2012 and 2022 (Figure 4) but continues to struggle to meet the 3% target from the Lisbon agenda agreed in 2000. European R&D funding intensity also continues to lag the United States and Japan and has recently been overtaken by China (Figure 4). In terms of absolute R&D spending, however, China already overtook Europe in 2014 and is rapidly approaching the United States (Figure 5). One of Europe's long-standing problems is the relative paucity of private R&D funding (Fagerberg et al., 2015), which partly relates to the sectoral composition of Europe's economy (Veugelers and Cincera, 2015), where mid-tech industries (like automobiles, parts, chemicals, and machine tools) with relatively low R&D intensities are more prevalent than high-tech industries (like software, IT hardware, electronics, pharmaceuticals, biotechnology) (Clemens et al., 2024).

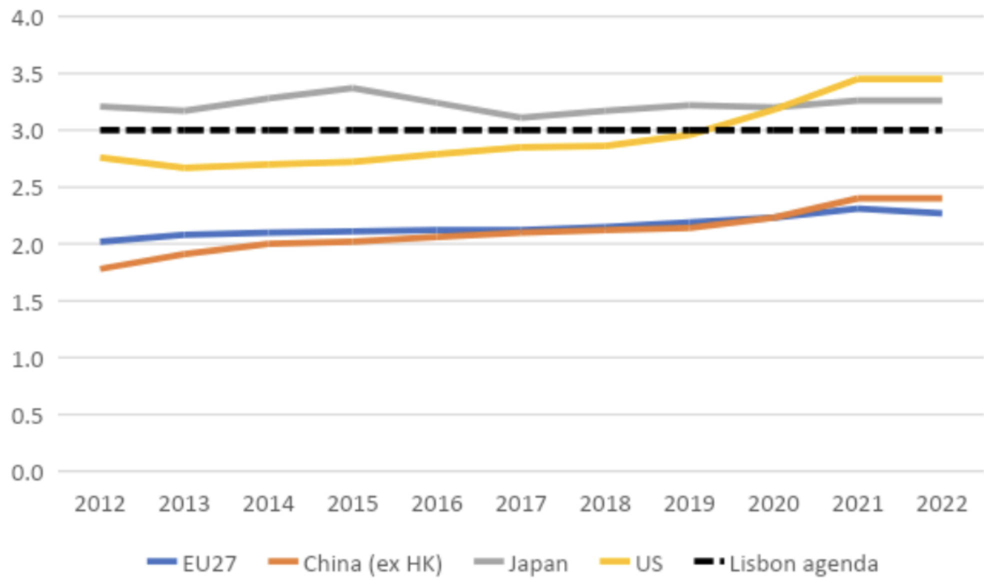

Figure 4.R&D funding (public and private) as percentage of GDP in major regions (constructed using data from ESABCC, 2024).

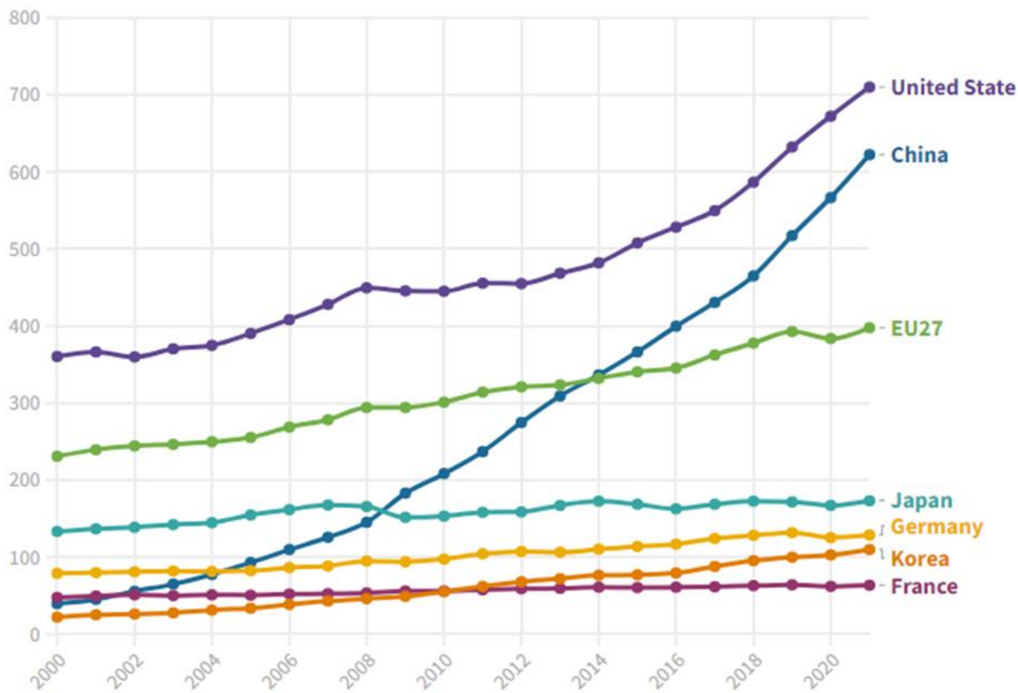

Figure 5. Gross domestic expenditure on R&D (in billion USD in constant PPP prices) for selected economies, 2000-2021 (OECD, 2023: 48).

Lagging EU R&D inputs are also a problem for energy and mobility domains (Figure 6). On the positive side, European public R&D funding (from Member States and European Framework Programs combined) in priority areas from the 2014 Energy Union strategy[2] is at similar levels as in China and the United States, at around 0.04% of GDP (Figure 11). The problem is that private R&D funding in Europe is significantly smaller than in China, Japan and Korea (but larger than in the United States). This is partly because incumbent European firms (like electric utilities and automakers) have long resisted low-carbon transitions and delayed reorientation efforts (Kungl and Geels, 2018; Richter and Stegen, 2022). This allowed Asian new entrants to gain a head start in emerging low-carbon innovations.[3] The involvement of firms in both R&D and the production of low-carbon technologies has also enabled Asian countries, including China, to develop effective innovation eco-systems, where firms also closely interact with research institutes, universities and policymakers.

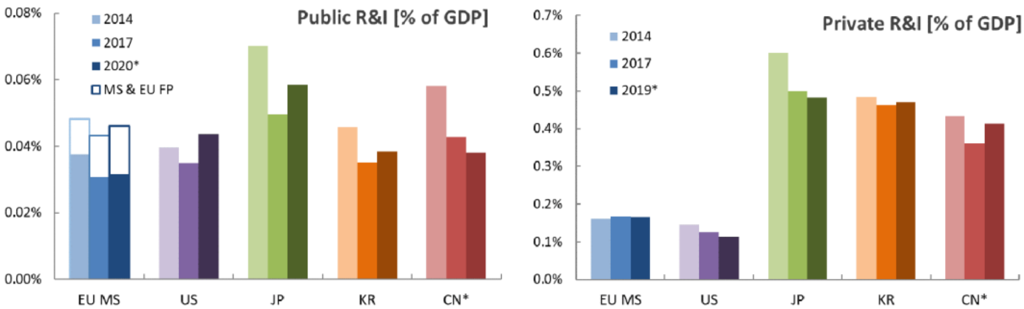

Figure 6. Public and private R&I investments (as a share of GDP) in Energy Union R&I priority areas (CETO, 2022: 15).

China's rise in research and innovation is not an accident but the result of years of dedicated policies and strategic adjustments, aimed at 'upgrading' the country from a cheap mass producer to an innovation-oriented high-tech producer. We briefly discuss this transformation in Box 1 because it is essential for strategic thinking about Europe's competitiveness to better understand major competitors.

Box 1. China's long-lasting effort to stimulate manufacturing capacity and technological development (see Chapter 2 in OECD (2023) for more detail)

In 2006, China's Guidelines on National Medium- and Long-term Programme for Science and Technology Development (2006-2020) launched the 'indigenous innovation' campaign which aimed for China to catch up in existing technologies with Western countries using a range of policies R&D investment, tax incentives, and financial support.

[2] The Energy Union R&I priorities were: 1) renewable energy technologies, 2) carbon capture (usage) and storage, 3) nuclear energy, 4) efficient building energy, 5) energy efficient transport system, 6) smart technologies.

[3] It is a common pattern in technology transitions that incumbent firms with vested interests in the old technology are slower to engage with radically new technologies than new entrants (Utterback, 1994; Geels, 2005). This often leads new entrants to outcompete incumbents, which may lead to the latter's decline or downfall (Christensen, 1997).

Box 1. China's long-lasting effort to stimulate manufacturing capacity and technological development (see Chapter 2 in OECD (2023) for more detail)

In 2010, China focused parts of its post-financial crisis stimulus funding on 'strategic emerging industries', including renewable energy, electric vehicles, and information technology.

In 2015, China launched the Made in China 2025 industrial policy (CSET, 2022), which lifted the ambition to leapfrogging Western countries at the innovation frontier and making China into an STI "superpower" by 2049. This industrial policy was complemented by an explicit and focused R&I policy (including incentives for patenting) that aimed to develop a world-class innovation ecosystem and achieve leadership in ten key industries and technology areas, including electric vehicles, railway equipment, power equipment (including renewables and grids), new materials, information technology, artificial intelligence (AI), and robotics.

In 2021, China launched its 14th Five-Year Plan (2021-2025), which placed technology and innovation at the heart of China's economic development strategy. Aiming to become a global leader in strategic industries, frontier technologies and basic science, it also stated intentions to increase R&D expenditures by 7% per year and doubling innovation patents by 2025 (OECD, 2023). In a speech on 28 May 2021, Xi Jinping explained the Plan's rationale, stating that: '*Scientific and technological innovation has become the main battlefield of the international strategic game. The competition around the commanding heights of science and technology is unprecedentedly fierce*' (Boullenois et al., 2023).

These developments have made China into a significant competitor in research and innovation as well as manufacturing.

In terms of R&I outputs, China in 2020 accounted for the largest (32%) percentage of scientific publications on Clean Energy Technologies, followed by India (9%), the United States (8%), South Korea (4%), and Germany (3%). The EU-27 produced 16% of CET-related publications in 2020 (European Commission, 2022: 12). China also leads in terms of top 10% mostly highly cited publications with regard to eight clean energy technologies (hydrogen and ammonia for power, supercapacitors, electric batteries, photovoltaics, nuclear waste management and recycling, biofuels, nuclear energy, and directed energy technologies) (ASPI (2023).

In terms of patents, which is an indicator of inventive outputs (and intent to commercialise), China is also leading both Europe and the United States in clean energy technologies (Figure 7). The great majority of Chinese patents are from the electricity and transport domains (respectively 99,423 and 48,127 patents), which aligns with the country's recent focus on renewables and electric vehicles. A recent analysis (European Commission, 2022) acknowledges that China leads in clean energy patenting, but suggests that only a minority of Chinese patents are 'high quality' and that Europe and the United States, in fact, have more 'high quality' clean energy patents (Figure 8). Another report (Clemens et al., 2024) also suggests that Chinese patent numbers are likely inflated because government subsidies for new patents exceed the cost of registering a trademark, making patenting economically attractive, even if the patentee has no intention to commercialise the invention.

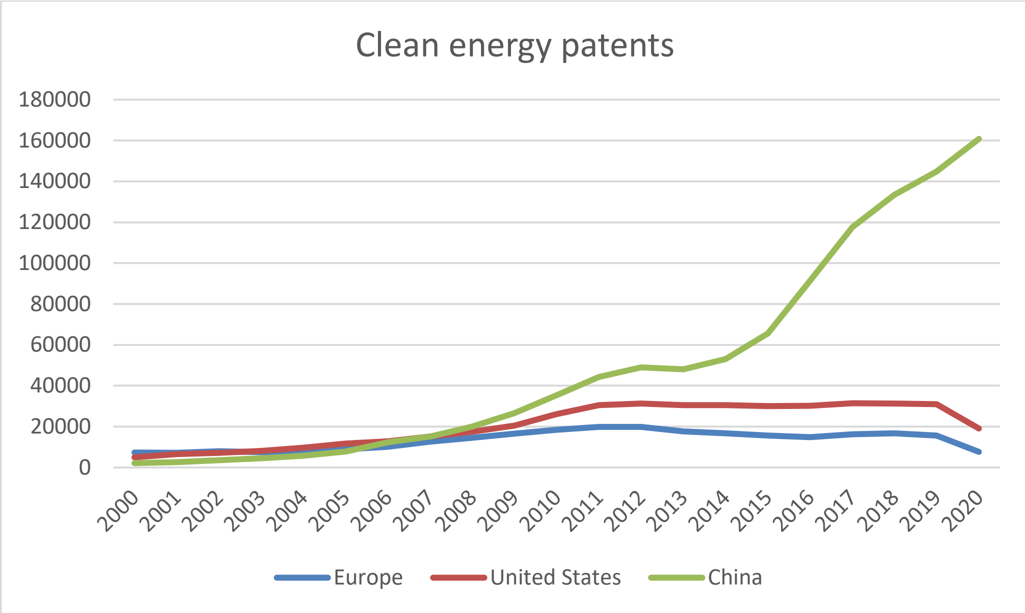

Figure 7. Clean energy patents across multiple sectors (electricity, transport, buildings, industry, waste) and technologies (solar-PV, wind, batteries, solar thermal, biofuels, storage, heat pumps, CCUS, fuel cells), 2000-2022 (constructed using the IRENA INSPIRE database[4], technology patent reports).

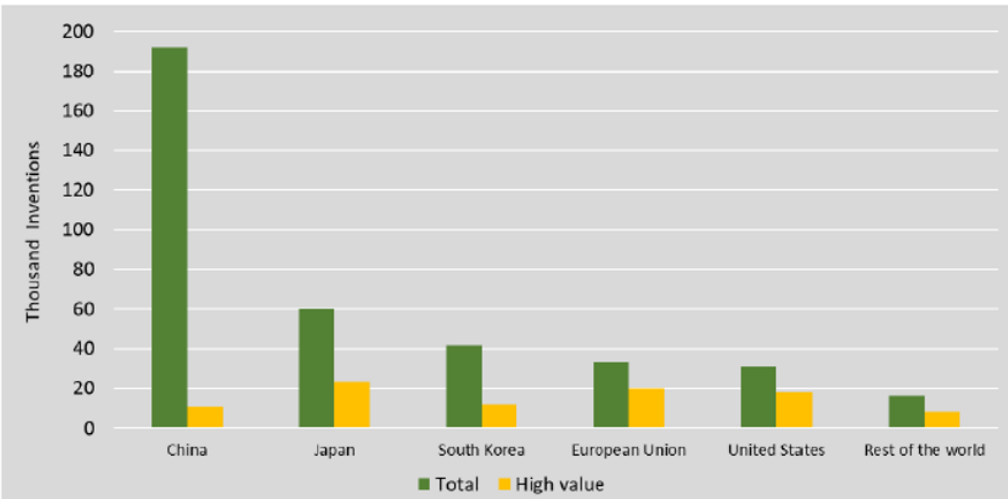

Figure 8. Number of clean energy patents for major economies (European Commission, 2022: 17), with 'high value' patents often defined as applying to multiple world regions).

Nevertheless, the overall implication from this analysis is that Europe is falling behind competitors (especially China) in the deployment, manufacturing, research and innovation of low-carbon technologies in energy and mobility. We thus agree with the sense of urgency

[4] INSPIRE stands for the International Standards and Patents in Renewable Energy. The International Renewable Energy Agency (IRENA) made this database using information from the Patent Statistics (PATSTAT) dataset of the European Patent Office.

expressed by Letta and Draghi, and the imminent need for Europe to adjust its R&I (and industrial) policies. Our discussion of research and innovation performance also suggests that future European R&I policy should make strategic assessments of areas where European firms could potentially compete and where this is unlikely because of the dominance of competitors. Chapter 4 will discuss this further.

2.3. The security challenge

The rapidly changing, global geopolitical[5], geoeconomic[6] and security setting has cross-sectoral influences, which means also that future R&I policy on energy and mobility needs to account for these changes. Increasing global insecurity and rise in military conflicts, which we have seen in the past few years, hence challenge global politics and international relations in which energy and mobility related technologies, services and resources play an important role (Kivimaa et al., 2022; Scholten et al., 2020). For instance, in the past, and still today, the fossil fuel trade has played an important role in international relations. Globally, coal trade is still increasing, after a dip caused by the COVID-19 pandemic, while natural gas and oil trade are also gradually increasing (UNCTAD, 2021). Nevertheless, in the longer term, it is estimated the expansion of renewable energy, electrification and hydrogen will reduce fossil fuel trade (JRC, 2023) and change international relations (Blondeel et al. 2021). Examples of such effects are well visible in the energy and mobility domains, where development in renewable energy technologies and electric mobility has meant that countries previously heavily dependent on natural gas and coal imports, are today somewhat less affected by actions of fossil fuel producing countries than before (although there are still major dependencies on fossil energy), but increasingly exposed to risks related with other primary commodities, in particular critical raw materials. This trend has been particularly evident in the EU, where many member states that had experienced expanding renewable energy or nuclear power developments fared better as a result of the 2022 energy crisis. Instead, those relying largely on natural gas for heating were worse off. Therefore, rapid developments in energy systems reliant on renewable energy, energy efficiency, heat pumps, electrification and green hydrogen will provide overall security benefits (Kivimaa and Sivonen, 2023). However, change in mobility systems has been slower than in energy production, and oil dependency of mobility continues to be substantial.[7]

Security is a much broader issue for Europe than merely geopolitical changes. It also deals, for example, with risk of disruptions in global trade and supply chains, defence, climate change -induced security crises with cascading impacts across borders, and societal tensions with risks of violent conflicts (Busby, 2022; Carter et al., 2021; Kivimaa and Sivonen, 2023; Żuk and Szulecki, 2020). For example, the North Atlantic Treaty Organization (NATO) and militaries are considering climate change as an essential security issue (Farham et al., 2023). Security of supply has been a long-term objective for European energy security, but in many member states, its advancement has relied on 'markets will deliver security' approaches and ignoring risks caused by geopolitical changes (Kivimaa, 2024; Kuzemko et al., 2022).

[5] Geopolitics refers to how geographical factors influence international relations, and how geographical assumptions impact global politics.

[6] The term 'geoeconomics' has recently been used more specifically in relation to innovation and technological change. It has been argued to address changes in geography of demand and supply affected by technological innovation (Blondeel et al., 2024).

[7] As a result, research on energy transitions has also seen an increase in studies on the geopolitics of renewable energy and hydrogen, exploring questions such as which countries are winning or losing, the peace and conflict potential of renewable energy, and the consequences of the energy transition (renewable energy and fossil fuel phase-out on international relations (Blondeel et al., 2021; Van de Graaf et al., 2020). These studies have, however, largely focused on international relations and broader security-oriented research on energy and mobility innovation has been lacking. Some recent research has emerged that more specifically has tried to link security to socio-technical energy and mobility transitions, although this area is emerging and requires more empirical studies in the changing context (Kester, 2022; Kivimaa et al., 2022).

Related to mobility, transport security has been little discussed, mainly in relation to technologies used in transport systems and supply chains (De Liso and Zamparini, 2022). So far, dual use technologies with defence applications have been excluded from Horizon Europe specific programmes and defence R&D has been funded via the EDF (European Commission, 2024). When energy and mobility transitions accelerate in society, it has implications on the defence sector, raising questions of whether defence-specific solutions for fuels and other energy use will be decoupled from the rest of the society or are they ways to align them.

The increasing vulnerability of trade and supply chains is affected by multiple risks, including wars and conflicts between states, escalating impacts of climate change, and use of sanctions or other policy tools affecting international trade (Cui et al., 2023; Imbs and Pauwels, 2024; Kivimaa et al., 2024). Besides security of supply, climate change has also been noted to cause multiple direct and indirect security risks. These are evident in increasing weather-induced short and long-onset events (e.g. draught, forest fires, flooding, hurricanes) as well as rising risk of conflicts, health crises, migration, etc. as cascading effects (Busby, 2022; Carter et al., 2021). For energy and mobility innovation, such increasing vulnerabilities and risks, create a need for (1) improving energy and resource efficiency further (this reduces the impact of supply security related crises related to energy, material and component flows); (2) taking into account escalating impacts of climate change by improving the resilience of new energy and mobility innovation and systems and by investing also in early warning systems; and (3) seeking innovation and systemic changes which can tackle multiple objectives simultaneously (i.e. sustainability, competitiveness and security). The impact of heightening global insecurity on energy and mobility transitions is not straightforward, with simultaneous supportive and hindering effects (Kivimaa, 2024). For instance, the importance of Norway's oil and gas production for European energy security has been emphasised by European Commission President von der Leyen (von der Leyen, 2023).

Europe's experiences with supply chain problems with personal protective equipment and medicines during the 2020 and 2021 COVID-19 pandemic and with Russian gas supplies in the winter of 2022 and 2023 (which Russia curtailed in retaliation to Europe's responses to Russia's full-scale invasion of Ukraine) increased the awareness of European policymakers of vulnerabilities stemming from strong dependence on international supply chains and single suppliers. This awareness also led to increasing concerns about the dominant role of China in the manufacturing and supply of low-carbon technologies (Figure 6). The mining and processing of essential minerals for low-carbon technologies (like cobalt and lithium) is also highly concentrated, with China having dominant positions in processing capacity (Table 2). The availability and supply of critical minerals and metals have emerged as a key supply security issue in Europe during the 2020s, addressed, for example by the Critical Raw Materials Act, approved in March 2024.

	Extraction and mining	Processing
Copper	8%	40%
Nickel		35%

	Extraction and mining	Processing
Cobalt		65%
Graphite	64%	90%
Lithium	13%	58%
Rare earth elements	60%	87%

Table 2. Chinese share (in %) of global mining and processing of selected minerals in 2019 (constructed using data from IEA, 2022a).

Concerns that China could use Western dependencies as geopolitical leverage are not purely hypothetical. In July 2023, for example, China restricted the export of two rare metals (gallium and germanium), which are used in the production of electric vehicles and form critical inputs for microchips and some military weapons systems. And in October 2023, China imposed export controls on graphite, which is an essential material in the anode side of lithium-ion batteries. Many experts view that China has become a major power in critical materials supply chains by taking strategic actions which have concentrated its ownership of certain materials, e.g. lithium and cobalt, by way of purchasing mines in different continents (especially Africa) and lowering its own technology dependence on western countries (Kivimaa and Sivonen, 2023).

China has also required some users of the critical material it produces to locate their production in China and involve Chinese companies (Criekemans, 2018). In response to security and supply chain concerns, the European Commission has introduced the somewhat ambiguous concept of 'open strategic autonomy', which, on the one hand, indicates that Europe wants to protect its domestic industries and reduce supply chain vulnerabilities by increasing domestic manufacturing capacity in core technologies (to 40% by 2030), but, on the other hand, acknowledges that Europe will continue to depend on imports for the foreseeable future, but should diversify its supply chains and needs to remain open for international collaboration (Damen, 2022; Trippl et al., 2024). Some claim that the concept is left broad and open on purpose to increase its political buy-in (Miró, 2023; Schmitz and Seidl, 2023).

The precise balance between domestic manufacturing and imports will likely vary between technologies and sectors, depending on international concentration and Europe's manufacturing capacity. Nevertheless, the developments in open strategic autonomy and sovereignty are seen not only as efforts to improve European security but are also about rediscovering innovation and industrial policy in the EU (Trippl et al., 2024). An important dilemma and trade-off is that European manufacturing of low-carbon technologies (like batteries or wind turbines) will likely result in products that are more expensive than imports from China. This, in turn, would make the low-carbon transition more expensive (for policymakers and consumers), slower, and increase social acceptance problems.

We suggest that policymakers should address the challenge of geopolitics and security strategically and be explicit about trade-offs. We also suggest that R&I policy can play significant roles in alleviating security, for example by developing new materials for low-carbon technologies (e.g. alternative battery chemistries) and solutions improving the efficiency of materials use and their recovery, developing new recycling techniques for existing batteries, solar panels and wind turbines (so that rare materials can be reused), and by developing improved manufacturing processes (that improve material efficiency). In addition, new innovations and their systemic integration into changing energy and mobility systems should consider increased resilience of systems to disruptions from different security risks. Developing such roles, however, means tightening coordination and collaboration across sectors – between R&I policy for energy and mobility and policymakers and sectoral actors in the areas of defence, security and foreign policy. Chapter 4 will discuss this further.

2.4. The societal acceptance and justice challenge

The fourth challenge includes the questions of social justice, acceptance and resolving potential tensions and conflicts related to energy and mobility transitions (e.g. Jenkins et al., 2016; Sovacool et al., 2019; Williams and Doyon, 2019). Finding solutions to these questions requires institutional changes and efforts towards social innovations (see Innovation Pathway 8 [4.8.]). The European Commission has increasingly paid attention to social justice pertaining to low-carbon energy and mobility transitions, creating the Just Transition Mechanism and the European Social Fund to improve justice pertaining to phasing out carbon-intensive industries and helping citizens with access to new technologies. However, these first efforts leave open questions of how to address the possible global injustices caused by European transition efforts and how to recognise injustices that more vulnerable groups (e.g. children, the elderly, or indigenous groups) are facing both from the effects of climate change and mitigation activities (Kivimaa et al. 2023).

Advancing just energy and mobility transitions is complex, because they involve multiple different questions of justice - where one action may improve justice on one dimension (e.g. minimising local environmental and social injustices of mining critical materials in the Global South) and simultaneously worsen injustice elsewhere (e.g. increasing mining of critical materials in Lapland creating negative environmental and livelihood effects for indigenous people). Or vice versa, emphasising local or national economies in the European energy transition can create global injustices via extraction of resources in the Global South by means of artisanal mining, child labour and poor working conditions (Sovacool, 2019). Calls for increased energy and mobility justice highlight the need for public policy to create means to recognise and evaluate different dimensions (distributive, recognitive, and procedural) and scales of justice (local to global) to make informed value choices and decisions.[8]

The societal acceptance of innovations or policies has recently risen on political agendas because of instances of vocal opposition from consumers, firms, and societal groups. Examples include the French 'yellow vest' protests in 2018 against increased fuel taxes, Dutch farmers protests in 2019 against stricter nitrogen regulations protests and Europe-wide farmer protests in 2023/24 over multiple grievances (including green policies), protests from Londoners in 2023 against proposed expansions of the ultra-low emission zone (because this would raise costs for those who could not afford to buy electric vehicles), protests in Germany in 2023 against proposed gas boiler bans (which would push people towards buying more expensive heat pumps).

[8] In the last few years, research on energy and mobility justice has heavily expanded, yet there is still rather little knowledge on how to resolve the complex questions related to just transitions, e.g. what weight to give to local versus global effects, short-term versus long-term effects, and how can indigenous people and future generations be best represented in decisions.

These protests led national and European policymakers to weaken proposed policies or create exemptions, which decelerate transitions in certain countries and sectors. It also highlighted the importance for policymakers to ‘bring society along’ in transitions. In 2021, the European Commission created a EUR 17.5 billion Just Transition Fund for the 2021-2027 period to deal with social acceptance problems, but this was mainly focused on compensation of regions and workers that would be adversely affected by low-carbon transitions (such as coal mining regions). However, research suggests that compensatory schemes have had limited acceptance in targeted fossil fuel or peat production communities (Lempinen, 2019; MacNeil and Beauman, 2022). Low-carbon transitions also require a degree of buy-in and enthusiasm about future pathways, more support for lower-income groups (who will likely struggle to adopt electric vehicles, heat pumps, or whole-house retrofits), and more consultation and engagement with relevant stakeholders about the (un)desirability of low-carbon innovations.

Societal resistance to energy and mobility transitions also links to increased populist politics in different European countries (Ćetković and Hagemann, 2020; Vihma et al., 2021; Yazar and Haarstad, 2023; Żuk and Szulecki, 2020). Populist movements have used different tactics to politicise decarbonisation, reframing cultural values to form alliances with anti-decarbonisation movements and dismantling key decarbonisation institutions (Yazar and Haarstad, 2023). Populism undermines political institutions, questions the integrity of bureaucracy, the courts and journalism with an intention to object to scientific evidence (Vihma et al., 2021). Therefore, the challenge of societal justice and tensions requires also addressing the issue of populism besides improving acceptance.

To address, anticipate, and mitigate societal acceptance challenges, policymakers (including R&I policymakers through technology assessment or responsible research and innovation policy (Novitzky et al., 2020) could do better in terms of evaluating transition pathways and innovations on a wider range of criteria, including affordability, fairness (by spreading costs and benefits across social groups), and accessibility. They could also develop and articulate narratives that focus not only on negatives (such as costs or limiting climate impacts), but also on positives such as job creation, health benefits (e.g. from cleaner air), and potentially cheaper electricity, transport and heating (if electricity costs from renewables continue to decrease and people switch to electric vehicles and heat pumps).

Given the challenges to rapidly advance energy and mobility transitions oriented to phasing out fossil fuels and accelerating zero-carbon innovations, more radical propositions have been advanced that suggest that societies should reverse the current consumption and economic growth oriented outlooks, with these propositions justified by their proponents with the magnitude of the overconsumption challenge that threatens planetary boundaries (O’Neill et al. 2018; van den Bergh and Kallis, 2012). These propositions include calls for ‘degrowth’, ‘sufficiency’, and ‘well-being’. For instance, degrowth refers to a political and social transformation leading to substantially reduced flows of energy and resources in the society (Kallis et al. 2018; Kębłowski, W., 2023). For mobility, degrowth has been associated with abolishing public transport fares that also contradicts the principles of growth-driven capitalism and austerity (Kębłowski, 2023). Energy sufficiency is used more specifically in the energy context to argue for reduced use of energy services to minimise the environmental impacts; it differs from energy efficiency that may not result in overall demand reduction but has also been argued to suffer from rebound effects (Sorrell et al. 2020). In the mobility context, focusing on sufficiency would mean demand reduction, modal shift and improved car-sharing (Sandberg, 2021) while such changes in mobility practices and cultures have been hard to achieve despite long-lived calls for that effect. These calls have largely remained in the margins of political debate and policy efforts, as they misalign with the perceived need for growth to pay for social welfare, low-carbon transitions, defence upgrades, which all need large sums of money.

Despite rather slow progress and shortcomings in the effects of implementing measures to improve the social acceptability and social justice of transitions - or even a larger lack in advancing new social paradigms oriented to reversing energy and mobility demand – it is important to keep pursuing solutions to this challenge.

3. Vision and overarching policy objectives

In light of these recent contextual changes (Chapter 1) and new challenges (Chapter 2), future European energy and mobility systems should, by 2040-2050, ideally have the four characteristics, as presented below. The characteristics also take into account the policy objectives to progress on sustainability (aligning the reversal of GHG and pollutant emissions, biodiversity loss, and socio-economic development), security (including the diversification, reliability and resilience of access to resources, energy and mobility) and affordability (requiring low-cost energy and mobility services to people and businesses, and therefore also fostering competitiveness). In the EU, important related objectives include the European Green Deal's overall aim for Europe to become climate-neutral by 2050 (net-zero), the goal of open strategic autonomy, the EU Biodiversity Strategy's objectives to halt the loss of biodiversity and reverse the negative trend in biodiversity by 2030, the REPowerEU goals to save energy, diversify supplies and produce clean energy, and the Just Transition aim to 'leave no one behind'. Therefore:

1. In terms of functionality and performance, future European energy and mobility systems should be low-emission, cost-competitive, energy- and resource efficient, integrated, and flexible. With regard to climate mitigation, Europe has ambitious goals, including a 55% reduction of GHG emissions by 2030, 90% by 2040, and 100% by 2050. Crucial enablers for developments towards these systems are digital technologies for better system integration, in energy and mobility, taking a multi-modal approach, the electrification of energy end-uses, a shift to low-cost, low-carbon electricity, changes in products and services towards an optimised use of available resources, avoiding waste and embracing economic circularity, and – for energy end-uses that are hard to electrify directly and to manage impacts of residual emissions – the combination of fuel switching and carbon-negative technologies (including carbon capture).

2. Future energy and mobility systems should also involve significant degrees of European manufacturing to enable profitability, support employment and maintain economic vitality. Ideally, European energy and mobility-related firms would also be able to export internationally and compete in global innovation races. This will be challenging, however, and may not be possible in all low-carbon technologies, which means that Europe may need to specialise and focus especially on those innovation areas where firms have a concrete competitive advantage compared to China, the United States, and other international competitors.

3. To reduce security risks, Europe has the policy objective of 'open strategic autonomy', which means that energy and mobility systems will need to be reliant on diversified supply chains and increased domestic manufacturing of low-carbon technologies to cover significant fractions of European demand combined with active efforts on demand reduction. Importantly, increased EU-level manufacturing is necessary to address security-related concerns and over-dependency, even in areas where Europe may struggle to compete in international markets. It means also that Europe may need to use instruments that favour technology transfers (such as conditionalities for the access to its markets) in cases where it is does not (or no longer) have a technological edge, while also leveraging its peculiarities (e.g. its low-emission economy, the social protection integrated in its economic system, the use of responsible business practices and

cybersecurity-related conditions) to favour the diversification of product and services - as already foreseen in the Net Zero Industry Act (European Council, 2024), as this can support demand for domestically produced ones.

While this increased domestic manufacturing will reduce supply chain risks, there is a risk that this will increase the cost of low-carbon technologies (compared to cheaper imports), which may negatively affect the speed and social acceptance of low-carbon transitions. To manage this risk, it will be crucial that Europe remains open to international trade and research and innovation collaboration, that it leverages the strength of its single market with policies that encourage larger volumes of production (and hence lower unit costs) for technologies with high prospects for domestic and global growth, and that it leverages other key European strengths (such as the availability of technical knowledge, lower cost of capital in comparison with emerging economies). This process will need to face the reality of new technological cost developments, and therefore include an increased focus on technologies for which there is a clear indication of stronger demand (due to better cost competitiveness) – such as heat pumps for space heating or electric powertrains for road transport vehicles – despite structural changes in manufacturing assets and supply chains. For this reason, it will require additional policy support to enable the European industry in accessing the necessary raw materials. This is already foreseen in the Critical Raw Materials Act (European Union, 2024). It will additionally require complementary action in trade policy and will benefit from complementary measures to make our targets more tangible, as noted by Draghi (Groupe d'Etudes Politiques, 2024; Draghi, 2024).

4. Future European energy and mobility systems will have several societal benefits compared to current ones, including cleaner air (and fewer premature deaths) and improved affordability and hence also economic competitiveness (because learning curves will continue to deliver unit cost reductions, net of inflationary pressures). Key examples include:

   - Solar, wind, leading to lower levelised cost for electricity production, even when accommodating grid and flexibility-oriented adjustments;

   - Batteries, enabling lower costs of stationary electricity storage thanks to unit cost reduction with increases in production scale, progress in chemistries and energy density and, through electric vehicles, also for electric mobility; and

   - Heat pumps, enabling cheaper heating, thanks to lower operational costs and declining capital costs with technology learning and economies of scale.

   In addition, the energy and mobility transitions offer potential for improved social justice, if it is steered in a way that increases citizens' and local communities' role and power as energy consumers and prosumers. The social side of energy and mobility systems development should also take into account how policy actions and supply chains influence developments outside Europe, seeking to reduce direct and indirect negative effects on the Global South.

Building on the IEA's Net-Zero roadmap (IEA, 2021; IEA, 2023e), IRENA's Energy Transitions Outlook (IRENA, 2023), the IPCC analysis on emission mitigation (IPCC, 2022), the list of technologies included in the EU Net-Zero Industry Act (European Council, 2024), the impact assessment of the 2040 EU climate target (European Union, 2024) and other analyses having relevance for specific energy[9] and mobility[10] sectors, we suggest that the innovation pathways which will be discussed in Chapter 4 will be central for a net-zero transition.

4. Research and innovation priorities for energy and mobility systems

This chapter discusses in more detail how the four challenges play out in the low-carbon innovation pathways for system transitions in energy and mobility. Based on an assessment of the four challenges, we also make specific recommendations for R&I actions for each selected innovation pathway. These recommendations discuss:

- Basic research, directed toward greater knowledge or understanding of the fundamental aspects of knowledge, to seed opportunities for disruptive changes. This has both cross-cutting and specific relevance for clean technologies.

- Applied R&I to solve practical challenges and reduce costs of innovations that are close to deployment. This creates conditions for accelerated deployment and strengthens opportunities for competitiveness. Applied R&I has a more technology- or pathway-specific nature than basic R&I.

- Deployment actions, which seek to produce more meaningful, applicable change, and needs to be focused on resilient and systemic innovations, already close to price/performance parity and/or having a clear pathway towards it, with scale increase and technology learning.

To emphasise the systemic dimension of transitions, Innovation Pathway 1 (4.1.) starts with a discussion of system integration, focusing mostly on the enabling role of digital technologies that can act as the ‘glue’ in aligning multiple innovations and as a facilitator of progress in terms of optimisation, both for energy and mobility. Innovation Pathway 1 (4.1.) also pays specific attention to mobility system transitions, especially regarding connectivity, automation and sharing. Innovation Pathway 2 (4.2.) discusses infrastructural innovations in mobility and energy systems. Innovation Pathway 3 (4.3.) discusses solar PV and wind, which are expected to bring major contributions to the decarbonisation of electricity generation, in the EU and beyond, and are critical for industrial development. Innovation Pathways 4 and 5 (4.4. and 4.5.) focus on the electrification of energy end-uses, which are key enablers of energy efficiency and diversification advantages. Innovation Pathway 4 discusses heat pumps (which can be major enablers of energy efficiency enhancements and suppliers of low- and medium-temperature heat for building and industry) while Innovation Pathway 5 discusses electric vehicles (which are particularly relevant for road transport and the automotive sector) and batteries (a key enabler of electric vehicles, and for which electric vehicles are key growth driver). Innovation Pathways 6 and 7 (4.6. and 4.7.) discuss alternative fuels and feedstocks. These are relevant for sectors that are hard to fully electrify (including aviation, shipping and heavy industry) and have climate mitigation and security benefits, but may struggle to scale up and achieve cost parity. Innovation Pathway 6 discusses biofuels in transport, while

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[9] These include IEA, 2020b for iron and steel, Madeddu et al, 2020 and IRENA, 2024a for industry, Ueckerdt et al. (2021) for the specific role of e-fuels, Creutzig et al. (2014) on limitations of bioenergy availability and relevance of its prioritisation for sectors that are difficult to electrify, Rosenow (2024) for buildings, Schmidt et al. (2019) on electricity storage.

[10] These include analyses specifically related with the decarbonisation of aviation (ITF, 2021c, MPP, 2022, ICAO, 2022 and IRENA, 2024a), shipping (ITF, 2020a, World Bank, 2021, IRENA, 2021, IRENA, 2024a), trucks (IEA, 2017 and ITF, 2022), urban mobility (OECD, 2021) and road vehicles (IEA, 2024c), as well as the impact assessment of the EU Sustainable and Smart Mobility Strategy (European Union, 2020).

Innovation Pathway 7 discusses hydrogen and its derivatives with regard to the overall energy system, including transport applications. Innovation Pathway 8 (4.8.) discusses social innovations, which can be relevant in both energy and mobility systems (see Table 1) to improve their sustainability and resilience. Innovation Pathway 9 (4.9.) discusses Mobility as a Service (MaaS) as a particular kind of (technologically-mediated) social innovation that is particularly relevant for mobility systems.

We acknowledge the importance of energy- and resource-efficiency improvement (in appliances, lighting, building shell), but do not discuss them further. The reason is that these improvements are mostly incremental innovations, which misaligns with our focus on radical innovations and system transitions. We also acknowledge the relevance of CCS, but do not discuss them, because this innovation pathway has limited scalability and deployment potential across Europe, although it will have (some) importance for countries with offshore CO_2 storage options (e.g. around the North Sea), for some industrial applications (chemical plants, cement production, steelmaking, in competition with low-carbon hydrogen as a reducing agent and possibly as a complement of carbon of biogenic origin) and for negative emissions, alongside other carbon dioxide removal technologies. CCS is also less about energy and more about capturing back-end emissions of industrial facilities, and also and of limited relevance for mobility. Similarly, nuclear electricity is not discussed because it is beyond the paper's remit (although there are already European policies clearly opening to the option of nuclear-based fuels, e.g. in the case of aviation, through the ReFuelEU aviation regulation).

4.1. Systems integration enabled by digital technologies

Where the traditional energy landscape was demand-driven, a combination of distributed storage and market incentives for time-of-use flexibility can help align demand with increased supply variability, as energy transitions unfold towards greater shares of variable renewables, with enhanced demand-responsiveness. AI-driven tools and solutions, ranging from preference learning to the machine-to-machine economy, can help manage the complexity of decision making by creating an automated, integrated and sustainable energy and mobility landscape. Highly integrated IT systems can also support billions of market interactions and energy management decisions in real time and throughout grid and market networks of distributed energy, storage, and flexibility assets.

4.1.1. Relevance for accelerating low-carbon transitions

Due to their pervasive nature, their implications for society and economic productivity, there are clear expectations that digital technologies – including those underpinning system integration – will remain a key pillar of the future economic system.

Whether or not they will be capable of accelerating low-carbon transitions depends on the way their potential contribution will be exploited (ITF, 2021a). In particular, the contribution of digital technologies – including AI – to accelerate low-carbon transitions depends on their area of application and the balance between the increased electricity demand that they require, the energy savings derived from their system optimisation potential and whether and how this potential will be used for energy and emission savings (rather than for other objectives).

Current evidence points towards increases in electricity demand from digital technologies (IEA, 2024c), with data centres expected to represented over 3% of total power demand by 2030 (Draghi, 2024), but also opportunities for systemic advantages. While further increases are expected in upcoming years from the new wave of technology developments related with

AI (IEA, 2024c), when applied to energy, and in particular electricity, digitally-enabled system integration[11] has offered enhanced efficiency, reliability, and flexibility by optimising the interaction of renewable energy sources, storage, and demand-side management.

Distributed energy resource management systems (DERMS), in particular, have shown that they can contribute significantly to deliver systemic advantages by managing and optimising the performance of distributed energy resources (DERs) such as solar panels, wind turbines, battery storage, and electric vehicles. In doing so, they have contributed to facilitate the transition to a low-carbon energy system with minimal emissions and maximal resource utilisation, net of risks related with rebound effects.[12] DERMS enhance this integration by enabling real-time monitoring and control of DERs, ensuring that these resources are used efficiently and effectively within the broader energy system.

Transport and mobility have also witnessed a substantial increase in the application of digital technologies. This includes the cases of connectivity and automation, which come with a highly disruptive potential to significantly reshape passenger and freight mobility (ITF, 2021a).

4.1.2. Competitiveness, supply chain and deindustrialisation

The EU accounts for a relevant share (in terms of value) of IT and information services, an industry that has a strong global leadership and a strong development in the United States (ITIF, 2023). Leading EU countries by size include Germany, France and Italy (Figure 9). European countries experienced rapid increases in global market share growth, relatively highly skilled IT workforces and modest wage levels. Sweden and the Netherlands rank highest in the EU in terms of shares of global outputs with respect to the global average (ITIF, 2023). China's overall weight is comparable with the EU, in the field of software, systems integration and business services, but there is also evidence that the EU has tended to specialise on mid-tech industries, being exposed to a risk of lower growth opportunities, and that China's development is clearly on a growing trend (Fuest et al. 2024).[13]

[11] Energy system integration involves comprehensive planning and operation across various energy carriers (e.g. electricity, hydrogen, heat), infrastructures, and end-user sectors (industry, buildings, mobility). This approach has the capacity to strengthen connections between these components to achieve decarbonization without compromising affordability and reliability.

[12] The rebound effect arises in cases where technology progress leads to cost savings, in addition to a reduction in energy use (and related environmental impacts), inducing a growth in product and/or service demand and therefore resulting in lower energy use reductions and environmental benefits than those that would in a case where product and/or service demand remains unchanged.

[13] On the other hand, China has a major advantage and important strengths in hardware, engineering and manufacturing of computers, electronics and optical products, where it is the global leader, accounting for more than a quarter of the overall global output (ITIF, 2023). This is a field where the EU (mainly countries that were already in the Union before 2004) lost very significantly market share. No EU country has shares of global outputs exceeding the global average in the area of computers and electronics (ITIF, 2023). Globally, countries with the highest rates for this indicator are Taiwan, Singapore, Korea, Malaysia, Thailand and the Philippines.

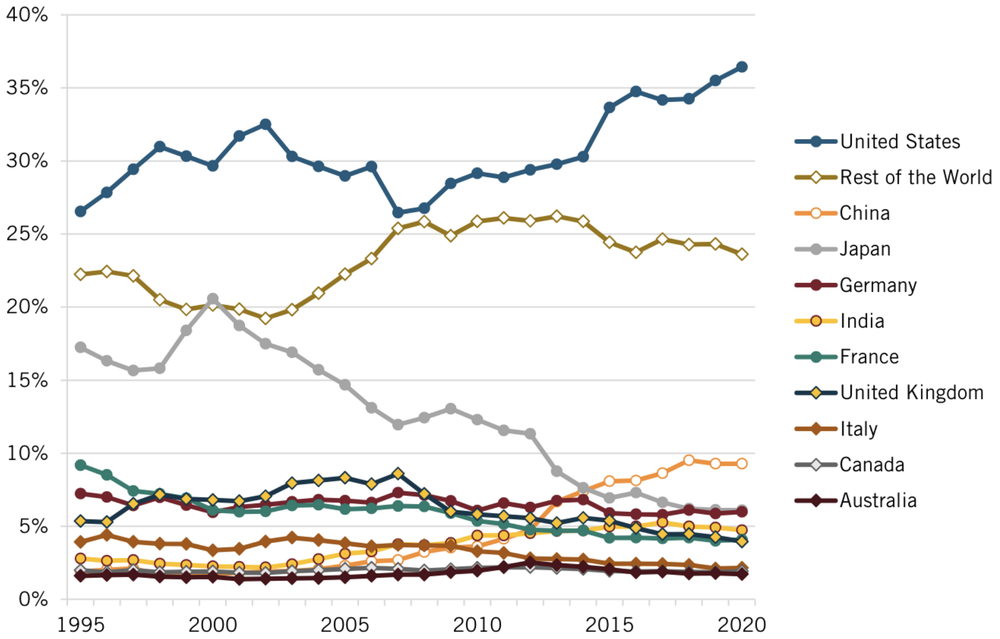

Figure 9. Historical shares of global output for top 10 producers in IT and information services (source: ITIF, 2023).

The physical layer of the decarbonising energy landscape also varies widely in different geographic and geopolitical regions. Many of the innovations are proprietary in nature and designed to meet specific contexts, thereby presenting a scalability challenge. The ability of businesses utilising digital platforms to manage energy-related activities is dependent upon market size, readiness of communication infrastructure, and regulatory readiness (Duch-Brown, N. and Fiammetta, R. 2020). The EU has been steadily closing the gap in R&D investment in digitalisation in comparison to the US (European Investment Bank, 2023). A significant challenge in competitiveness, however, lies in the integration of locally and contextually fragmented layers of digital infrastructure with sufficiently innovative markets that offer incentive to decarbonize via participation in automation-enabled flexibility markets.

4.1.3. Security

Global concentrations in the supply of semiconductors and electronic components can lead to significant challenges for the availability of sensors and chips. These challenges, in turn, can result in delays and increased elevated costs for IT and information services, including systems integration projects.

As the digital layers of the energy and mobility landscape are increasingly integrated into systems, they provide more entry points for attack. The complexity of systems means that a weakness in one component of the system can result in compromise of another component.[14]

[14] For example, a vulnerability in the software of smart metering devices in a smart grid system could be exploited by cyber attackers, manipulated data could be sent to a central control system, causing incorrect energy distribution. Consequently, some parts of the grid overload while others are underpowered, resulting in widespread power outages and damage to infrastructure.

Grid stability and reliability could be attacked via the many distributed methods of congestion management, e.g. by manipulation of charging schedules. The lack of interoperability and standardisation across different components and manufacturers leads to vulnerability - e.g. due to delays in communication and corrections, but it could also limit damage, as it would also delay the pace of diffusion of cyberattacks (with the same mechanisms). Lack of integration of outdated legacy systems leads to compatibility problems and productivity drawbacks. Greater standardisation can enhance productivity while also helping address cybersecurity vulnerabilities, as long as it does so in a way that integrates cybersecurity safeguards.

Regulations and compliance protocols must be designed to protect cyber security. Establishing redundancies is necessary to maintain operations during attack and disaster. Monoculture issues in ICT could lead to widespread failures under edge conditions.

Security challenges can also arise from a surge in demand for energy and resources (including critical raw materials, for the case of vehicle electrification) needed to serve the requirements of digital technologies, in particular those that enable high degrees of automation without a contextual transition toward forms of system integration that emphasise the relevance of right-sizing and sharing of assets (such as individually owned autonomous cars or single-passenger services performed by autonomous cars, even if shared).

4.1.4. Societal acceptance and justice

Uneven development of the technological and infrastructure layers of systems integration could lead to inequalities that exacerbate differences in urban and rural access to the benefit of demand flexibility and dynamic pricing. Markets and ICT investments may predominantly focus on high- and middle-income areas. Simplistic AI approaches may not gain user trust, resulting in lack of effective demand response.

Lag in policy development may fail to anticipate potential drawbacks of vehicle automation, leading to misalignments with sharing and powertrain technology transitions, inducing increases in total automobile travel, related energy consumption and GHG emissions (associated with clear societal drawbacks, paired with acceptance barriers) or may not succeed in protecting people who lack mobility flexibility or who are critical workers.

Rural areas may end up generating utility-scale electricity but not benefitting from the generation or from demand flexibility. Cross-subsidies due to poor tariff design can disadvantage those who cannot afford to invest in DER or beneficial electrification.

4.1.5. Research and innovation actions

Achieving system integration requires overcoming critical challenges, including ensuring interoperability among different physical components. Key issues involve integrating data from various sensors into a coherent system, protecting data from unauthorised access, and maintaining continuous, accurate data collection from IoT devices.

Cost management is a significant challenge, requiring scalable technology deployment. Even when cost barriers are overcome, rebound effects can increase transport activity and energy demand. Physical infrastructure must meet rising demand without disrupting services, and assets must be protected from extreme weather and cyber-attacks.

As communication layers integrate into energy and mobility systems, comprehensive network coverage, bandwidth management, latency control, and standardised communication protocols are essential. Interoperability between devices using the same networks is crucial for integrating vehicles, charging infrastructure, and mobility services dynamically.

Data integrity and privacy are also critical. Efficient data processing and storage, along with integrating diverse data sources into a unified system, are necessary to prevent bottlenecks. Creating and adopting standards ensures compatibility between new and existing systems, with updates accommodating new technologies.

Ensuring AI algorithm accuracy and reliability requires high-quality data, ethical considerations, and addressing the potential surge in energy consumption from AI growth. User interface applications must be intuitive, engaging, customisable, and secure, providing widespread technology access and managing energy demand.

Effective integration of these layers can enable a seamless transition to a decarbonized energy and mobility landscape, ensuring optimal performance, sustainability, and user engagement. Addressing challenges related to energy demand increases through enhanced technologies and ensuring the pace of adoption and energy savings surpass the effects of increased deployment is crucial for success.

4.1.1.1. Basic research

Systems integration of mobility and energy requires extensive interconnectivity. This is supported by decades of research in digital and communication technologies. The EU should fund primary research in these areas.

The EU should explore and implement regulations for "high-risk" and "forbidden-risk" AI categories related to energy and mobility systems integration, as outlined in the EU AI Act. This regulatory framework is crucial for managing AI risks in critical infrastructure, ensuring safety, security, and ethical compliance.

Specific research work streams should explore top-down directives to ensure cybersecurity and data privacy across interconnected systems, regardless of public or commercial data access.

Research on the machine-to-machine economy, where autonomous devices transact and exchange data without human intervention, should be promoted and advanced to applied research.

Research into interconnected energy and mobility systems is relevant for both civil and military applications but must consider unintended consequences. The EU should prioritise research aligning connectivity and automation technologies with sustainability, economic, energy, and resource efficiency to enhance competitiveness. Basic R&I can make AI systems less energy- and data-hungry, e.g. learning from fewer examples.

Understanding the behavioural component of moving away from individually owned cars and devices, known as psychological ownership, is critical. Research should explore strategies to foster collective ownership and promote shared mobility benefits, addressing resistance to behavioural change.

True cost pricing of energy grids and transportation infrastructure is vital. Accurate pricing of environmental, social, and economic costs can incentivize sustainable practices, reduce overconsumption, and ensure fair cost distribution. R&I in this area should develop pricing models that internalise external costs, addressing economic challenges in the energy transition.

4.1.1.2. Applied research and innovation

Applied research should improve understanding of life-cycle environmental impacts of autonomous and connected mobility services, aligning them with sustainability and decarbonisation.

Designing future cities to accommodate sustainable connected, autonomous, shared, and electric (CASE) vehicle technologies is essential. Urban planning models should integrate CASE technologies and "net-zero by design" concepts, promoting compact city development and reducing emissions.

Managing increased mobility demands in single-occupancy vehicles, prioritising shared vehicles, and enhancing public transport in suburban and rural areas are important considerations. Research should develop measures to control congestion and energy use, including dynamic pricing, shared mobility, and efficient public transit integration.

Freight transport, especially over long distances, can benefit from enhanced vehicle connectivity and automation. Applied research can foster progress in logistics, improving systemic efficiency and powertrain shifts.

Investigating smart grid technologies and demand-side management strategies to optimise EV charging and grid impact is crucial. Vehicle-to-grid (V2G) systems, stationary storage, battery swapping, and electric road systems are relevant research areas.

Siting and sizing EV charging hubs to meet demand without straining the grid is essential. Research should identify optimal locations and scales for charging infrastructure.

Developing digital platforms to act as network orchestrators is vital for scaling sustainability-aligned digital technologies. These platforms should coordinate energy and mobility services, optimising resource allocation and data flow.

Promoting applied research in road and grid pricing approaches can strengthen capacity in weaker regions. Collaboration with regulatory authorities in each Member State is key.

Developing system integration solutions adaptable to diverse geographic and geopolitical circumstances is essential. Research should design adaptable frameworks ensuring high-level policy coordination while fostering ground-level innovation.

Investigating strategies to leverage decentralised energy and mobility systems for enhanced energy and cyber security is necessary. Research should explore robust DERMS and decentralised cybersecurity protocols.

Research comparing single versus multiple technology standards for smart grids should inform the development of flexible, interoperable standards, ensuring smooth integration and cybersecurity safeguards.

Developing comprehensive frameworks to address security and privacy issues in evolving energy technologies is imperative. Research should focus on advanced encryption, secure communication protocols, and privacy-preserving data analytics.

Exploring methods to enhance consumer trust and privacy in smart grids is essential. Developing transparent data usage policies and consumer control over personal data addresses privacy and trust challenges in interconnected, data-rich smart grids.

4.1.1.3. Deployment

Developing a DERMS and Demand Response Aggregation (DRAs) is crucial for optimising the integration of distributed energy resources into the grid. Advanced strategies for charging, heating, and cooling systems, and efficient resource allocation markets, are essential.

Formulating policies to design integrated and interoperable commercial solutions from the outset prevents future fragmentation and inefficiency. This includes integrating software protocols enabling efficient communication and operation across different systems.

Promoting market innovation for flexibility across regions with diverse geographic and demographic needs is vital. Tailored strategies should address unique regional characteristics, ensuring effective implementation and utilisation of flexibility solutions.

Spreading systemic integration innovation through diverse regions requires adaptable integration frameworks tailored to specific regional needs, ensuring widespread and inclusive benefits.

4.2. Infrastructural innovations

Transport and energy networks like roads, railways, pipelines and electricity grids are major elements of the European economy. These infrastructures form the backbone of the mobility and energy transport and distribution systems, which were built over many decades. They are crucial to enable passenger and freight mobility and deliver energy to households, businesses and services.

Infrastructures for mobility and energy have a demonstrated role as a facilitator of economic development, with greater increases in economic outputs in areas with a stronger infrastructure availability (ITF, 2017).

Because of these fundamental considerations many post-COVID-19 policy packages included significant infrastructure spending programmes (IMF, 2020). Opportunities to deliver productivity increases while also addressing climate challenges also explain the orientation of significant shares of these spending packages towards climate-aligned investments.

4.2.1. Relevance for accelerating low-carbon transitions

Post-COVID-19 infrastructure investments in climate-aligned infrastructure altered, to a good extent, a trend where infrastructure provision, planning and design was not strategically prioritised but rather focused on supporting existing modes of transport and forms of energy.

The change in the way infrastructure investments were steered came from the COVID-19 shock, which altered the needs of transport networks, and from a growing acknowledgement of unfolding technological shifts, especially the increasing deployment of renewable energy, electric vehicles, and batteries. Key instruments for stronger strategic infrastructure steering included, in the EU, the taxonomy of sustainable activities and deliberate choices by EU governments to earmark a significant part of their infrastructure-related expenditures (including related to the NextGenerationEU funding) for options fully aligned with emission mitigation.

The renewed strategic focus on infrastructure innovation in energy and mobility systems not only relates to accelerating low-carbon transitions and the need to adapt industrial capacity to technological shifts, but also to the need to rethink urban environments, with major road space reallocations following the COVID-19 shock. Both developments imply parallel transformations of productive activities and behaviours, which are acting as engines for innovation.

Evidence of changes induced by technology developments and shifts in infrastructure investments is tangible in cases that see electricity expanding into areas that were previously supplied by petroleum products. Key examples include heat pumps, electric vehicles, renewable energy supplies, all coming with increased needs for electricity demand, grid enhancements (from more power lines to digital technologies for better system integration and different forms of electricity storage[15], enabling more flexibility to better accommodate supply variability and demand response). Hydrogen is also another potential example, because infrastructure to transport and store hydrogen is an important enabler for hydrogen use and trade, even if international trade in hydrogen is today at a very nascent stage. Transporting and storing hydrogen – which needs to be low-carbon to make sense as a replacement of fossil fuels as energy carriers (JRC, 2024) – is technically more challenging than the handling of fossil fuels today[16] (IEA, 2023g).

Prospects for future developments confirm this change, as the world's electricity use needs in the next decade are expected to grow 20% faster than they did in the previous decade to achieve countries' national energy and climate goals (IEA, 2023f) and as street redesign and reallocation towards more sustainable transport modes are necessary to achieve CO_2 emissions reductions in a way that also addresses equity issues (OECD, 2021 and ITF, 2021b).

4.2.2. Competitiveness, supply chain and deindustrialisation

The importance of infrastructure for economic growth is well recognized (ITF, 2017). The quality of infrastructure networks is an important consideration when determining how competitive a country is relative to its peers. Recent developments in technology costs indicate that the supply of adequate infrastructure to accommodate a transition towards increased reliance on electricity as an energy vector is crucial. Paired with end-use efficiency, electrification is key for affordable energy supplies as well as for climate mitigation. Power system interconnection – including high voltage direct current (HVDC) lines[17] – is being used to strengthen grids to accelerate renewables integration, with advantages from improved grid stability, increased energy security, enhanced flexibility in managing power demand and supply fluctuations, while also reducing costs of the operation of the grid system and the curtailment of renewables (which comes with the need for a greater reliance on thermal electricity generation plants) (IEA, 2023g).[18] Additional advantages also arise from the capacity of interconnectors to widen the availability of low-cost, low-carbon renewable

[15] These range from flywheels to pumped hydro and include compressed air, liquid air and electrothermal energy storage technologies (Schmidt et al., 2019 and Guan et al., 2024).

[16] This includes the need to liquefy or compress hydrogen or to convert hydrogen into carriers such as ammonia or liquid organic hydrogen carrier (LOHC), the need to develop dedicated storage facilities, with important cost implications, while dealing – at the same time with challenges to bring down the cost of low-carbon hydrogen supplies.

[17] High-voltage direct current (HVDC) involves fewer power losses thank alternate current and is especially well suited for long distance connections, needed to balance grids with higher supply variability and bridge challenges occurring over multi-day periods, thanks to differences of meteorological conditions across geographies.

[18] Although the operational costs are only a fraction of the cost of building a new transmission line, cumulative operational costs from structural congestion can be high enough to justify investment in infrastructure additions or upgrades. A good example is the interconnector between Germany and Norway, known as the North Sea Link, which supports the integration of renewable generation by enabling the efficient exchange of clean electricity between the two countries (IEA, 2023g).

electricity, with net advantages for the decarbonisation of the industrial system, in a context requiring policy action – including to reduce GHG emissions – to address climate change, as the lack of access to affordable low-carbon energy exposes the economy to asset stranding risks.

This is especially relevant in global regions – like the EU – that are comparatively poor in terms of availability of fossil energy resources, and thus structurally need a strong energy efficiency and economic productivity focus (also in light of the growth of China as a competitor in terms of industrial capacity and as an economy reliant on transformation and, increasingly, exports, to generate value), and anyway likely to benefit from greater energy diversification, for reasons of resilience.

Hydrogen infrastructures are also relevant for competitiveness, mainly for energy intensive industries (and despite competition from areas with high renewable energy endowment), as long as hydrogen is not outcompeted by other technologies (such as CCS, for steel, pumped hydro for long duration electricity storage, and direct electrification for low-and medium temperature heat). Developing trade in merchant hydrogen would also entail complexities requiring careful consideration of the cost (as this has direct implications for competitiveness), benefits (including opportunities for mitigating asset stranding risks, but only for cases where hydrogen is cost competitive versus alternatives) and potential trade-offs in exporting and importing countries (as this influences the capacity of the European industry to withstand international competition).

For mobility, street redesign and reallocation towards more sustainable transport modes – in particular public transport – also have relevance for competitiveness, as public transport is essential to provide affordable mobility for low-income households and to those without access to a car, serving both equity and economic development needs (e.g. enabling access to education and employment opportunities). Urban densification, transit-oriented and transit-integrated development are also important in this context, as compact urban development patterns and higher density combined with public transport planning have been highlighted as a way to avoid inefficient and costly patterns of development based on car travel (ITF, 2021c). This is an aspect that is especially relevant in the EU, as transport systems remain a central pillar of oil demand, and the EU is a major net oil importer.

In terms of supply chains, infrastructures are not exempt from barriers and bottlenecks that have arisen in recent years. Key materials needed in transport and energy infrastructures do not only include cement and steel (needed for roads, bridges and pipelines), but also copper, aluminium (needed for the electricity grid), semiconductors (needed in power electronics and for electricity grids, including HDVCs) and battery materials (as battery storage is increasingly being adopted for frequency regulation and other grid services).

Regarding industrial competitiveness, Europe has an established construction industry (European Commission, n.d.), and also a significant presence in electricity infrastructure industries, with major competitors in the United States, China, Japan and – to a lower extent – India (IEA, 2023g). Cement and steel are sectors requiring major progress in terms of technology developments, given the high GHG emissions from conventional production processes, with impacts on competitiveness, supply chains and deindustrialisation risks that depend on the capacity of the sector and the EU more broadly to stimulate and accelerate innovation.

4.2.3. Security

The COVID-19 pandemic provided important lessons on the role of road space reallocation and the use of active modes of transport to enable greater resilience of transport systems. Infrastructural choices such as the reallocation of road space were crucial to allowing travel in the absence of, or with reduced, public transport services (OECD, 2021). Denser cities, also structured in a way that enabled proximity between people and places, had greater opportunities for better resilience than cities that did not, as they were less reliant on long-distance trips.

In the absence of the specific circumstances related with COVID-19, the reallocation of road space can enable a greater modal diversity for the provision of urban mobility needs, including options that combine walking, cycling, micro-mobility and public transport for passenger mobility, while also fostering service improvements for public transport, and therefore ultimately enhancing the attraction capacity for public transport.[19]

Indirect benefits from densification, transit-oriented and transit-integrated development and providing quality alternatives to car use through infrastructural choices can also help better manage energy security challenges, thanks to structurally lower energy demand for shared vehicles in public transit. As shared forms of mobility are also supplied by highly utilised vehicles, and highly utilised vehicles are paired with economic benefits if they shift to energy efficient technologies, the same infrastructural choices have the capacity to foster a technological transition towards electrification. This, in turn, enables energy security advantages. Thanks to better resource efficiency for transport systems with higher shares of public transport and shared modes, this also comes with additional advantages from a security of supply perspective (net of effects related with economic circularity[20]), thanks to lower overall needs for critical materials.

Regarding electricity grids, modern and digital technologies are vital to safeguard electricity security during clean energy transitions (IEA, 2023g). This is not only the case due to increased flexibility needs with growing shares of low-carbon, low-cost renewable electricity, but also because additional transmission lines – including long-distance interconnections – can bolster resilience. Importantly, enhanced and modernised grid infrastructures, as enablers of renewable energy production increases, are also indirect enhancers of overall energy security, thanks to the far greater diversification and energy efficiency of technologies enabling low-carbon electricity production with respect to other energy carriers. Increased electrification and grid infrastructure investments are also particularly important at a time of fragile natural gas markets and concerns about gas supply security, as failing to build out grids increases countries' reliance on gas (IEA, 2023g).

Regarding hydrogen, if economically viable, increased trade could be an opportunity to improve energy security by reducing fossil energy imports and diversifying the supply countries for hydrogen imports. Hydrogen also offers possible security-related and resilience advantages long duration energy storage, alongside mechanical (pumped hydro in particular), thermal (e.g. rocks, bricks, molten salt storage), other chemical (e.g. sulphur and iron powder) and electrochemical (batteries) technologies (FCA, n.d., Schmidt et al., 2019, Guan, 2024 and Crownhart, 2024).

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[19] Quality and convenience of public transport are considered the strongest attraction for public transport use (ITF, 2021d).

[20] Greater demand and use of critical materials in earlier phases of the transition can enable greater material availability in the economy, with advantages from an economic circularity perspective, as these same materials can turn into resources once recycled and processed (through approaches that are also – in general – more energy efficient with respect to primary extraction and processing of materials).

Security risks, relevant for mobility and energy infrastructures, also arise from the necessity to ensure resilience in case of conflicts and climate-related considerations. For instance, the increased extension of electricity transmission and distribution grids could increase exposure to climate hazards such as wildfires and changes in the frequency of extreme weather events (such as floods). Improving the resilience of substations involves factors such as the use of equipment with higher specifications, enhanced cooling mechanisms and improved flood protection measures.

Cybersecurity is also of relevance, as instances of malware being planted in the manufacturing process or in update programmes, known as software supply chain attack (e.g. in the form of malicious code or a backdoor embedded in critical hardware or software) can also cause massive vulnerabilities in systems with increased reliance on digital technologies (IEA, 2023g).

4.2.4. Societal acceptance and justice

The development of energy and mobility infrastructure projects tends to have long lead times (years, if not a decade) for projects like pipelines, port terminals, and underground gas storage facilities.

Grid connection for renewable power projects is also facing bottlenecks, as large transmission system projects can take a decade or more to complete, meaning that many renewable power projects are waiting in grid connection queues, which is causing delays in the clean energy transition. At the macro-scale, this is revealed by a growing disconnect between renewable electricity production and grid investments (IEA, 2023g).

Documented, acceptance-related reasons resulting in barriers for the accelerated deployment of clean energy projects also include delays in the identification of priority areas. An iconic example of recent developments exists in Italy, with a pause for several months required for new installations in Sardinia (ANSA, 2024).

Infrastructure-related changes in mobility can also include large, transformative interventions involving significant road space reallocation – with the case of Barcelona's superblocks being one of the most iconic (OECD, 2021). Like energy infrastructure projects, these can entail delays due the need for socio-political support. Both for energy and mobility, more efforts need to be made towards early and frequent stakeholder involvement in project planning. This starts by establishing effective communication channels to ensure stakeholders are heard, making sure to engage the local population and authorities though public consultation and information meetings, where the benefits brought by the project can be made clear (IEA, 2023g). Increasing policy acceptability can also benefit significantly from communication efforts and deliberate efforts to link actions to positive societal outcomes (OECD, 2021).

On the technical side, best practices (e.g. underground cables instead of overhead lines for grid connections) can be adopted to limit the impact visual and environmental impact, but care need to be taken as cost increases can result in other acceptability challenges (due to affordability problems, as price differences can translate in higher prices) and loss of competitiveness.

4.2.5. Research and innovation actions

4.2.5.1. Basic research

Basic R&I can focus on fundamental opportunities and challenges related with infrastructure deployment, including the assessment of economic costs and benefits, enhancing the quantitative understanding of costs and benefits and also considering the dynamic mechanisms that characterise systemic responses to infrastructure investments.

Basic R&I can also take further steps to better understand responses to specific infrastructure choices, analysing the complex global dynamics that can characterise them (e.g. related with the use of hydrogen as a tradable energy carrier in the context of a systemic transition towards a net zero economy, including implications for competitiveness, in light of costs and competition from other technologies and global supplies). These include complex feedback loops, with different examples available in the case of energy and mobility, having increased complexity if additional layers of innovation (e.g. related with digital connectivity and technological developments enabled by infrastructure deployment) are factored in.[21]

Scenario-based work and strengthened foresight exercises are particularly important in this field, alongside the development of analytical tools that can support this work. Due to the complexity of the task and its novelty (demonstrated by challenges in the way these complex dynamics can be anticipated), this is a case where redundancy in R&I initiatives could be well justified.

These considerations also have particular relevance for the EU policy making process, specific dynamics taking place across Member States, especially in cases where infrastructure (or delays) choices can lead to geographically heterogeneous results.

Further complexity, deserving adequate attention in R&I activities, also relates to health and environmental implications (including second and third order effects) of infrastructure investment choices.

4.2.5.2. Applied research and innovation

Applied R&I can be instrumental to ease the deployment at scale of infrastructures capable of supporting the EU in the achievement of its ambition and the management of major challenges like climate change, energy security, resource efficiency, equity and social acceptance, at once.

Key examples of applied R&I activities in this field include the development of risk assessments regarding specific investment and strategies allowing to better streamline administrative processes, and to foster societal support for their construction. Other examples

[21] For example, only very limited infrastructure for hydrogen deliveries is currently in place, most often not at scale, and therefore assumptions on technologies and emissions are subject to a high degree of uncertainty (JRC, 2024). Grid expansion and modernisation needs to happen at speed and scale, and building new grids needs to go hand in hand with improved use of existing infrastructure and new technologies (IEA, 2023). For mobility, the increased use of cars and related traffic volumes is not a fatality to which transport and climate policies need to adapt to, but the result of unsustainable system dynamics: induced demand, urban sprawl, and the erosion of shared and active modes of transport (OECD, 2021). At the same time, the car industry – like the aviation industry – plays a key role as a mobilizer of innovation and serves dual use (civil and military) purposes, meaning that dynamics that may result unsustainable from an urban mobility perspective may need to be balanced with other considerations (e.g. with respect to strategic considerations).

include activities that can help shape regulations and incentives for better use of existing capacity, meeting sustainability objectives while respecting safety and resilience constraints.

Applied R&I can also focus on planning (e.g. defining project pipelines, standardising procurement and technical installations) and supply chains (especially in cases that potentially face over-dependency risks and related bottlenecks).

Planning exercises – like the scenario work mentioned for basic R&I – can also have specific relevance for the intersection between energy and mobility, especially in cases – like high power charging needs for long-distance heavy duty electric trucks – where specific needs are likely to alter historical patterns of energy (and potentially also mobility) demand. Applied R&I can help make sure that plans integrate long-term energy transition considerations alongside near-term needs, supporting better anticipation and taking an integrated approach for the transformation of energy and mobility systems.

Specific R&I activities can also ease progress on targeted topics with particular relevance for infrastructure developments. Flexibility is a key example in the case of energy (and in particular electricity), as it is needed at different times to smooth out supply and demand curves that change throughout the day and during different seasons and it can also involve a specific role for hydrogen (especially for long duration energy storage, although still in competition with other technologies – which may themselves form part of applied E&I on this topic).

Applied R&I can also improve the understanding of remuneration structures for different types of infrastructure services. An example in energy refers to the possibility to cost-effectively maintain sufficient capacity that can be piloted and contribute to resilience, while still enabling a cost effective and affordable transition. For mobility, applied R&I can help determine pricing frameworks for both public transport and private vehicles allowing infrastructure to best serve demand needs (while also accounting for equity-related challenges). This example also intersects the need to secure stability in governmental revenues to pay for infrastructure investments, bridging the risk of revenue gaps from fuel taxes in a context where fossil fuel demand needs to decline.

Other areas of specific relevance for applied R&I on infrastructure (also discussed in Innovation Pathway 1 on system integration [4.1.]) include digitalisation and cybersecurity and AI algorithms. The latter can support the planning, optimisation and predictive maintenance of energy grids, assets and usage (Draghi, 2024).

4.2.5.3. Deployment

R&I specifically focused on deployment can improve the efficacy of stakeholder engagement, ultimately contributing to the enhancement of the acceptability of infrastructure-related investments and the subsequent implementation, while not losing sight of competitiveness constraints.

R&I efforts oriented towards technology deployment can also help improve coordination across stakeholders, including different administrations, technical bodies in charge of different subsystems (e.g. distribution and transmission, in grids), especially in cases where infrastructure investments move out of conventional, historical functions, into novel, updated ones (e.g. not only enabling energy flows from generation to demand, but also enhancing flexibility, in the grid example).

R&I activities can also include project-specific tasks, with the aim to streamline implementation and installation, possibly accelerating the pace of delivery.

4.3. Decarbonising electricity production with solar PV and wind

A large part of the energy transition is focused on electrification of different sectors, such as industry, heating and transport. The applications and scale of solar PV and wind power have expanded very rapidly, especially in the last five years, driven by major cost reductions, making them clear priorities for low-carbon electricity generation. Future increases are also not only expected, but encouraged, as both technologies are widely regarded as a key pillar of low-cost and low-carbon energy systems.

As they are paired with increasing variability in energy supply patterns, solar PV and wind are also strengthening the need for increased flexibility in electricity systems.

4.3.1. Relevance for accelerating low-carbon transitions

Low-carbon electricity production from solar PV and wind have clear, demonstrated and well-documented capacity to deliver major GHG emission cuts in electricity production, also considering a life-cycle perspective (NREL, 2021).

Technology developments, including enhancements in the conversion efficiency of solar panels, the industrialisation of their production (especially in China) and increased scale of wind turbines were crucial to enable major reductions in cost, resulting in very dynamic increases in deployment in recent years, based on economic competitiveness, especially in markets that give variable renewables dispatching priority over thermal electricity production (EMBER Climate, 2024).

For solar, geopolitical challenges added to technology improvements and scale increases to make production attractive also in Northern regions of Europe, and not only in the South, where the potential is more relevant. Wind is a significant source of electricity in some EU member states with greater potential, especially in the North Sea. Solar and wind deployment has been very dynamic not only in the EU. China added more than half of the world's new wind and solar generation in 2023, following other years of unprecedented additions, and growth of capacity installation was strong also in other global regions (EMBER Climate, 2024, IEA, 2024d).

The vital role of both solar and wind technologies to accelerate low-carbon transitions is also very clear in all decarbonisation scenarios by the IPCC and other major global institutions (IPCC, 2022, IEA, 2023e, IRENA, 2023). This is grounded on a clear alignment with sustainability, demonstrated capacity to contribute to diversify and decarbonise the electricity mix (even becoming instrumental) and clear prospects of continued reduction in cost and in large-scale manufacturing.

4.3.2. Competitiveness, supply chain and deindustrialisation

Low-carbon electricity production from solar PV and wind do not only have clear, demonstrated and well-documented capacity to generate low-carbon electricity with low-emissions, but also at low-cost. This is also the case in terms of levelized costs that integrate the need to pair solar-PV and wind with electricity storage technologies, despite energy losses and the need for additional investments (IEA, 2020b), as shown in Figure 10.

Significant opportunities to deliver greater cost reductions are also paired with digital technologies, thanks to the capacity of the latter to enable better system integration (IEA, 2019a).

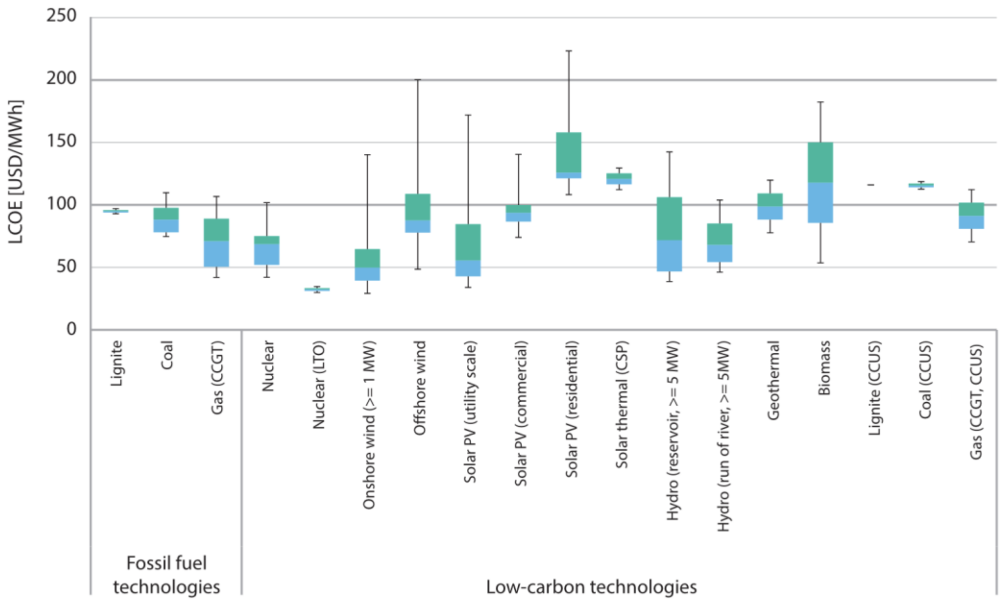

Figure 10. Levelised cost of electricity by technology (source: IEA, 2020b).

Remaining opportunities for cost reductions stem from margins for continued technological progress in cell energy conversion efficiency, from multiple options (NREL, 2024), technology learning, including from production scale up. The modularity of solar PV deployment is especially important in this context, as a key enabler of mass production in a context of sustained demand.

Low-carbon electricity production from solar-PV and wind are growing globally. Manufacturing growth is currently characterised by a strong competitive advantage acquired by China, especially for the commercialisation of low-cost solar PV (IEA, 2022b). Wind turbine manufacturing is an area where the EU industry has a strong track record, thanks to strong demand in the past, largely met by EU based producers. Nevertheless, wind turbine manufacturing has also seen Chinese manufacturers experience significant gains in market share and orders, as the country leads in both onshore and offshore installations (Enerdata, 2024). Part of the reasons explaining the strength of China in these sectors lie in scale economies and learning-by-doing improvements in manufacturing, a dynamic growth environment, a deliberate desire to reduce dependency on oil and gas, and the associated industrial policies developed in China over the past two decades. Other reasons lie in cost-competitive access to raw materials at scale, lower exposure to challenges related with rising costs, with respect to the EU competitors, and a policy environment that encourages investments in scaling up manufacturing capacity (Enerdata, 2024).

Taken together, these dynamics come with potential advantages, but not exempt from risks. Advantages relate to the possibility to deploy low-carbon energy production capacity at lower cost.

Risks relate to deindustrialisation (in case of loss of competitiveness, for wind) or missing industrial development opportunities (where the competitiveness gap is already wide, as in the case of solar PV) for the EU.

Over-dependency on Chinese supplies also exposes risks of weaker resilience (e.g. in cases of supply chain disruptions, which can increase significantly in case of conflicts). Diversification is also relevant for geopolitical reasons, as structural growth of low-cost, low-carbon technology providers also comes with strengthened global influence. These dynamics call for efforts for increased supply diversification to be scaled-up, but such a development also needs to pay attention to the necessity to take place in a way that guarantees competitiveness, securing demand and enabling the diversification to be self-sustaining, from an economic perspective.

Due to the current relevance of these technologies for the acceleration of the EU energy transition, managing these risks also requires a careful balance between market openness and R&I and industrial development strategies that can enable the EU to catch up on manufacturing gaps.

Major opportunities and challenges linked with solar PV and wind also come from strong differences in energy production costs between areas with high endowment and low endowment in solar and wind resources, as these differences have direct implications for industrial and economic competitiveness. High endowment offers major opportunities for low-cost, low-carbon energy supplies (capable of attracting investments thanks to greater competitiveness). As global areas with high potential for solar and wind energy are not necessarily co-located in places with existing industrial assets (including cases of major EU industrial clusters), the competitive advantage that they could have risks to expose these same assets to early stranding risks and significant social costs (with competitiveness for the overall socio-economic system), while favouring investments in competing locations.

This points towards a significant role for increased production capacity, at scale, and strengthened grid capacity (including via interconnectors), as the enhancement of competitiveness across different geographies that they enable also reduces asset stranding risks.

4.3.3. Security

Low-carbon electricity production from solar PV and wind come with a key energy security advantage, offered by the quasi-universal availability of solar resources and by a widespread potential available for wind energy.

Significant solar energy potential exists in Southern Europe, while the wind energy potential is highest in Northern Europe (Solar Atlas, n.d. and Wind atlas, n.d.). This comes with risks, due to the variability of solar and wind energy. Relevant opportunities for cross-EU synergies exist, especially in the presence of investments in strengthened grid capacity (namely via interconnectors) as these support reduced risks from variability of production and, at the same time, enable much wider access to low-cost, low-carbon electricity, increasing competitiveness. However, the intermittency of solar and wind energy still remains a systemic challenge creating an acute need for the further development of electricity storage solutions, such as batteries or other long-duration electricity storage technologies, and in demand-response solutions, having significant relevance and already a growing track record (e.g. from smart metering and hourly pricing) as an area of application of digitally-enabled system integration solutions (IEA, 2018a).

Rising deployment of modular, variable renewables, in particular solar PV and wind, requires grid strengthening and is set to raise demand for critical minerals (IEA, 2024e). Increases from solar PV and wind and related grid and electricity storage technology developments are significant for copper. Wind also uses significant amounts of rare earth elements, for permanent magnets (IEA, 2024e). Managing risks from a surge in critical raw material demand requires a mobilisation of investment into the mining sector, especially in a context of strong international competition. The dynamic growth of manufacturing capacity in China was paired with significant developments to secure raw material supplies (IEA, 2024e). Without diminishing the relevance of primary supply, as deployment increases, materials accumulate in the economy and recycling can play an increasing role to manage the growth of primary mineral requirements.

One unresolved security-related technical challenge is the blurring or shading effect of wind turbines on air surveillance imaging. For the defence sector, in the Eastern border of the EU, accurate defence air surveillance is vital and, hence, wind power construction has been banned near border areas and requires specific assessments in other areas (Kivimaa, 2024). For instance, Finland has created a compensation area for offshore wind in the Western coast, where wind power producers participate in the costs of new radars (Finnish Wind Power Association, 2024). In Estonia too, new radar technology has solved part of the challenge (ECDI, 2023). Recent technical assessments, however, have concluded that even the latest air surveillance technology cannot handle high wind turbines close to important areas for national defence (Räty, 2023).

Other security challenges related to solar PV and wind include: risks of intended and unintended disruptions to the electricity supply (shared with other electricity-related, grid-reliant technologies), although it has been claimed that these have potentially smaller effects in distributed electricity systems, where the affected parts can be disconnected; The availability of minerals, metals and technical components required - although not affecting day to day operation similarly as fuel availability.

4.3.4. Societal acceptance and justice

Solar PV and wind energy tend to enjoy a favourable perception due to alignment with climate change mitigation and energy diversification goals. They are also subject to a positive perception in countries (e.g. EU Nordics, for wind energy) where the technologies have offered opportunities for job creation and socio-economic development. They face greater challenges where climate and energy diversification advantages are not paired with industrial development.

Other social acceptance challenges are related with the "not in my back yard" phenomenon, reflecting an unwillingness of individuals to accept the construction of projects in the proximity of their property, which may or may not be solidly rooted in equity and/or environmental considerations (such as visual nuisance or nature loss, in nature-rich areas).[22]

Additional social acceptance risks may arise in cases not resulting in an equitable distribution of benefits (including with respect to job creation), compared with options that have structurally different impacts on the destruction of existing industrial assets (e.g. due to continued reliance on technologies – such as steam turbines – that were also needed for thermal electricity generation).

[22] A prominent example is reflected by opposition for offshore wind projects off the Atlantic coast of France (White, 2022).

More social acceptance challenges relate with the implications of competitiveness dynamics and supply chain concentration, especially in cases where technology transition towards solar PV and wind is accompanied by risks for industrial capacity and job creation, but also when their need for upfront capital outlays is at odds with an equitable distribution of access to low-cost electricity across society.[23]

Opposition to wind power is also visible in cases where economic benefits of wind power are seen to occur elsewhere (the latter is the argument for the Norwegian anti-wind power movement). Regional inequalities have been observed between those regions gaining tax revenue and new industrialisation via expanding wind power and those regions not able to construct wind power (e.g. YLE, 2022).

4.3.5. Research and innovation actions

4.3.5.1. Basic research

Due to the structural disadvantage of the EU in terms of competitiveness versus, China, which far exceeds competitors in every stage of global PV manufacturing and is also gaining ground on wind technologies, basic R&I action should focus on areas offering opportunities to reverse the gap, seeking a competitive advantage with a focus on advanced technologies, where Europe – and in particular Germany – have demonstrated competitiveness (NREL, 2024). As large-scale manufacturing is essential to build an ecosystem that enables enhanced competitiveness, these efforts also need to be paired with applied R&I, focused on scaling up manufacturing while doing so in cases where competitiveness is still at reach – i.e. where technological opportunities with the potential to yield better results over the long run (ITIF, 2020).

For solar PV, basic R&I priorities include the acceleration of the readiness of solar cell technologies with high conversion efficiency, new/alternative materials such as perovskites silicon-based tandems and solar cell architectures (including but not limited to cases that enable better repairability), bifacial cells and modules, the reduction of raw material use and costs, the minimisation of amount of material per panel, innovation in advanced fabrication/manufacturing processes, and, as more panels get installed, recycling technologies and extraction of secondary raw materials from end-of-life PV panels (IRENA, 2019a, IEA, 2022b, Baiju and Yearma, 2022).

Basic R&I for wind has been focused on bigger and better performing turbines, including offshore applications (IEA, 2019b). Other areas of innovation include innovations in rotor blade design, optimised power electronics, digital turbine monitoring and controls, manufacturing techniques reducing requirements, reusing and recycling materials used in wind turbines (IRENA, 2019b).

Basic R&I actions, e.g. regarding changes in weather patterns, could also address the resilience of solar electricity and wind generation capacity (including offshore) against climate-related weather disruptions.

[23] Policies like the establishment of the Social Climate Fund, in pairing with targeted carbon pricing for transport and buildings, have the deliberate aim to help address these issues.

4.3.5.2. Applied research and innovation

Applied research can support the deployment of solar PV and wind production capacity, as well as the need to catch up towards a reduction of over-dependency risks regarding manufacturing capacities, especially for solar PV.

Regarding PV manufacturing, innovations are crucial to move down the experience/technology learning. This means that applied R&I investments need to be developed alongside basic R&I to ensure technological progress and diversity in solar PV technologies (ITIF, 2024a). Combining public and private funding is also important for the creation of new, specialised ecosystems, as these clusters can enable synergies and benefit from positive dynamics, e.g. enabled by resource sharing and collaboration (ITIF, 2024a; Draghi, 2024). The relevance to support not only basic R&I but also large-scale deployment is clear in cases where manufacturability and process innovation require technology learning effects to support the competitive commercialisation of advanced PV technologies, e.g. due to far higher energy conversion efficiency v options already manufactured at scale today (ITIF, 2020). The same framework needs to ensure that there is demand for advanced PV products, as this is a key condition to enable large-scale alternative production pathways with respect to the incumbent industry.

As offshore wind technologies share elements of their supply chains with oil and gas offshore energy operations, applied R&I programmes can support the EU industry to leverage its expertise and innovation capacity beyond turbines, for the construction and maintenance of offshore capacity (IEA, 2019b). Applied R&I support for wind energy has also the opportunity to leverage EU-based innovation ecosystems that are by now a consolidated industrial reality.

The components and materials for solar PV and wind technologies are dependent on global value chains, emphasising a need for new research knowledge on the complex questions around justice and security, pertaining to these value chains (from the local to the global scale) and how this complexity should be governed - when value choices need to be made between different political objectives and the location of injustice effects - by the EU and its member states.

Applied R&I efforts are also important to address remaining challenges due to supply variability of solar and wind energy, especially for periods of low wind or sun, requiring energy storage, interconnections and readily available power generation capacity (and related primary energy) to ensure system resilience. These R&I activities relate closely with priorities already discussed for digital technologies and system integration, as they have great potential to lower levelized costs of variable renewable energy generation. Key examples, also relevant for mobility, include smart and even bi-directional/vehicle-to-grid charging, as enablers of the participation of vehicles to electricity demand response mechanisms, as already foreseen by legislation regarding the functioning of the electricity market.

Other examples of applied R&I facilitating the integration of variable renewables (beyond cases applicable to mobility) in the energy system also include a wide range of electricity storage technologies (from batteries to pumped hydro and possible alternatives to it, such as solutions based on thermal energy, compressed air or hydrogen).

Applied R&I activities for enhanced system integration for variable renewables can also leverage the current advantage of EU countries with respect to China, and - as long as better tools for trans-Atlantic cooperation in R&I are deployed – also opportunities from the global leadership of the United States in IT and information services.

Research developments should also consider the end-of-life management of solar PV and wind electricity generation devices, including the technical feasibility and economic relevance, repurposing of components and/or recycling of materials. Research activities may also support specific applications of solar PV and wind for mobility applications. Examples include vehicle-integrated and/or vehicle-added solar PV (hampered by small contributions to overall mileage), or wind assistance (with specific relevance for shipping).

From a security standpoint, applied R&I can also help overcome the technical challenges related to alignment of solar and wind power construction, on the one hand, and national defence and other air surveillance systems on the other.

4.3.5.3. Deployment

Technologies that achieved major progress in terms of cost competitiveness thanks to major scale-up of manufacturing (currently mainly in China) offer opportunities to deploy cost-effective solar PV capacity.

A strong track record of EU-based wind energy production, including both onshore and offshore wind, also matches key policy choices to scale up renewables in the EU energy mix.

In this context, R&I on governance and enhanced social acceptance is a priority to enable both solar PV and wind electricity to accelerate their commercialisation and increased deployment, contributing to the achievement of European policy goals. One area of particular interest for wind energy is the repowering of existing wind farms when they reach the end of their operational life, as this could offer opportunities - thanks to technology progress - to scale up significantly electricity generation without increases in land-use, while maintaining benefits of their wind farm such as local taxes and community projects (Wind Europe, 2023). R&I with a social acceptance focus can also help manage deployment challenges arising from increasingly large-scale wind installations.

Enabling an increase in domestic production for solar PV and wind production capacity requires the combination of certainty of demand and investments in large-scale supplies for highly performing technologies. Opportunities to enable this are emerging from recent policy developments (in particular in the finalisation of the Net Zero Industry Act), including the introduction of non-discriminatory, non-price criteria for solar PV deployment.

4.4. Low- and medium-temperature heat in buildings and industry

Close to 80% of household energy use is dedicated to heating and cooling. According to Eurostat's 2022 data, the total final energy consumption for space heating in residential dwellings across the EU amounted to 1,784 TWh (Toleikyte et al., 2023). Natural gas accounted for 38% of this energy consumption. Oil contributed an additional 14%. Meanwhile, Europe's increasing temperatures mean demand for energy for cooling is anticipated to increase, accounting for as much as 10% of energy demand from large cities by 2025 (EEA, 2023). Hence future developments in the heating sector are important.

4.4.1. Relevance for accelerating low-carbon transitions

The electrification of residential and commercial heating (and cooling) and low- to medium temperature industrial heat processes represents a significant decarbonisation opportunity. 50% of EU final energy consumption derives from space heating in buildings. Approximately 75% of heat demand is covered from fossil fuels and around 60% of overall heat demand is consumed in buildings (European Commission, 2023). Electrification of industrial processes that require heat up to approximately 1,000 degrees Celsius (low- to medium-heat) does not require a fundamental change in the industrial process setup but rather replacement of equipment, such as heat pumps, conventional boilers, infrared, microwave, and radiofrequency heaters (for heat up to 400 ºC) or induction, resistance, and arc furnaces (for heat above 400 ºC and up to 1000 ºC), with a piece of electric equipment (Madeddu et al. 2020; McKinsey 2024).

Yet obstacles to the electrification of residential, commercial, and low- to medium-heat industrial processes hold back the EU from making best use of the decarbonisation potential of existing technology, including lack of regulatory frameworks, inadequate building efficiency - despite significant regulatory developments in the recent past, especially with the finalisation of the Energy Performance of Buildings Directive (European Union, 2024), lack of information and promotion, supply chain and manufacturing issues, and a shortage of trained labour (Eurelectric, 2024).

In conventional circumstances, heat pumps can transfer 300% or more energy from the external environment than the electricity required to power them. As long as the electricity powering heat pumps at local homes and buildings or district heating and cooling (DHC) systems is sustainable, the transition to the electrification of heating can provide one of the fastest routes to rapid decarbonisation, net of manufacturing and installation constraints.

Distributed heat pumps are already at a high state of technological readiness. One of the largest obstacles to progress remains the lack of insulation and air sealing in the buildings they serve, which reduces efficiency and effectiveness. In this sense, the technology readiness of the buildings they serve becomes more important than the efficiency of the heat pump itself.

Analysis by the Joint Research Centre of the European Commission shows that replacing 30 million fossil fuel individual boilers in residential dwellings with heat pumps would reduce the EU's gas and oil consumption by 36% in these dwellings (JRC, 2023). In the large majority of cases, switching from a fossil fuelled boiler to a heat pump will result in lower bills for heating. While the additional heat pumps will deliver more stress to power grids, the impact is relatively modest and can be reduced, or even alleviated, by activating demand-side flexibility measures.

Obstacles to decarbonisation via District Heating or DHC are more considerable. The share of district heating in the final energy use for space heating and water heating is evaluated at 12% at the EU level. Over 17,000 district heating networks in Europe supply heat to 70 million citizens (Euroheat & Power, 2023). Obstacles to increasing decarbonisation with DHCs are technical, economic, regulatory, and social. Although the individual components of DHCs are at a relatively high TRL (e.g. heat pumps or waste heat), the next challenge in DHCs is the integration of different elements in a manner that is more efficient, intelligent and cheaper. Intelligent systems that use smart metering and control solutions for optimisation must be developed, along with consumer empowerment measures to exploit multiple energy resources, including waste heat recovery, heat pumps, thermal storage, co-generation and renewable energy integration, and to roll-out solutions for the integration of intelligent thermal network with smart electricity grids (Cordis).

With regard to low- and medium-heat industrial processes, up to a heat demand of approximately 400 degrees Celsius, electric alternatives to conventional equipment are already commercially available. Electric heat pumps for low- and medium-temperature heat demand and electric-powered mechanical vapour recompression (MVR) equipment for evaporation are already used on some industrial sites.

Electric boilers that can generate industrial heat up to approximately 350 degrees Celsius are widely available (Eurelectric, 2024).

For this heat category, solar thermal technologies also have an untapped potential, especially in southern European countries. Electro-thermal energy storage technologies (which use electricity to produce heat and then store it in a heat storage medium such as bricks) also have the unique ability to use electricity generation by intermittent renewables (solar, wind) to fulfil the large-scale and continuous heat demand necessary for industrial sites, complementing and also competing with (if they are not developed in a way that integrates them) heat pumps, for low- and medium-heat processes.[24]

4.4.2. Competitiveness, supply chain and deindustrialisation

As they come with very significant energy savings, heat pumps have the capacity to bring major reductions in operational costs for industrial and residential/commercial heating needs. Whether this translates in an overall systemic advantage, enabled by greater economic competitiveness, depends on the relative balance of investment costs and energy/cost savings. Conditions for better competitiveness are best with low capital costs and low operational (hence electricity and maintenance) costs. The best opportunities for net improvements for industrial competitiveness arise for sectors that mostly use low and medium temperature processes, as these constitute the best entry points for electrification, while also allowing allow for a gradual transformation, since existing machines can be retrofitted, eventually also via hybrid systems (Madeddu et al. 2020).

The EU is the global market leader in air-to-water heat pump manufacture, supporting a competitive advantage in terms of international competitiveness (Eunomia, 2024). The EU's leadership risks being affected by recent declines in sales - even if moderate, as shown in Figure 11 (IEA, 2024a), and reversible (IEA, 2024a).

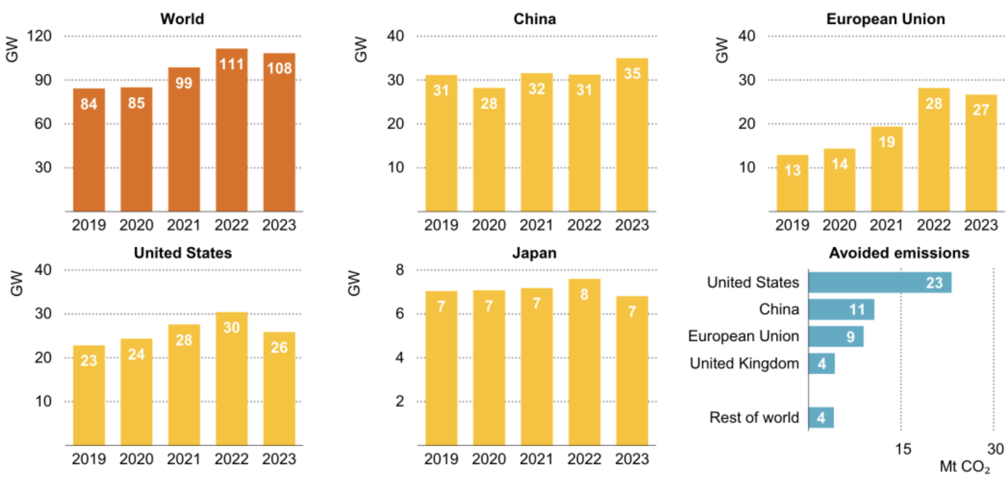

Figure 11. Heat pump sales and avoided emissions (source: IEA, 2024a).

[24] Heat pumps are more energy efficient converting electricity to heat than electro-thermal energy and technologies and are thereby typically more cost-competitive. However, heat pumps can require extensive on-site changes and electro thermal energy storage systems can provide heat at higher temperatures than heat pumps alone (Guan et al. 2024).

China's increased competitiveness and US expansion of production capabilities since implementation of Inflation Reduction Act policies also pose significant challenges. These threats should be seen in relation to an analysis of European competitiveness in climate neutral industries: though competitive in all but early-stage technology innovation, the EU struggles with a negative and deteriorating heat pump trade imbalance (European Commission, 2023).

A rapid scale-up of heat pumps will require more and higher skilled workers throughout the manufacture-to-installation value chain. The EU's heat pump supply chain is vulnerable in a few areas, including a large dependence on imported compressors and semiconductors.

Europe has been a leader in developing and deploying advanced DHC technologies (which can rely on centralised heat pumps, while maintaining the reliance on existing distribution networks), particularly in countries like Denmark, Sweden, and Germany. This has given Europe a competitive edge in expertise and innovation in this field. Yet Asia (led by China) and North America (with initiatives like the US Inflation Reduction Act) are rapidly advancing their own DHC technologies and systems. The competition is intensifying as these regions scale up production and deployment, potentially eroding Europe's leadership position. The EU should consider the role of public R&D and early-stage technology development to maintain a competitive advantage.

4.4.3. Security

Similar to the case of electric vehicles, discussed below, heat pumps offer major energy security advantages, as they are uniquely positioned to diversify energy demand, in buildings and industry, away from the dependence on fossil fuel imports, and related price fluctuations (Agora Energiewende, 2023).

Additional advantages can also be derived from synergies between low-cost, low-carbon electricity production and the contextual availability of energy storage capacity (in the form of heat), meaning that heat pumps can be part of a range of solutions - enabled by digital technologies and system integration - that provide valuable grid services, becoming an asset rather than a liability for the electricity system.

A security of supply risk may exist in cases where component and material supply for heat pump production rely on manufacturing in a concentrated set of countries outside the EU. Yet, the changing climate provides a more alarming threat to security which must be considered. Not all heat pumps are designed to provide cooling as well as heating (although this is becoming a standard) nor do all homes and buildings have the capability to utilise a heat pump designed for cooling if there is a lack of locations for the outer unit. Nevertheless, the increased adoption of cooling air source and ground source heat pumps also improves people's living conditions in hotter conditions, as most devices offer cooling besides heating (unlike traditional gas boilers or district heating systems).

Heat pumps do not require critical raw materials for their production, and they are therefore subject to low security risks, in that respect. As they are reliant on digitally-enabled control systems, they are affected by over-dependency of semiconductors (European Union, 2022).

Reversible heat pumps can be used for cooling purposes, supporting the capacity of the EU to handle health risks arising from likely increases in the frequency of heat waves during the summer, as these cause the largest share of fatalities related to climate extremes in Europe.[25] Making sure that this contribution is also aligned with sustainability requires that their energy use is paired with increased capacity to generate electricity from low-carbon sources.

The management of district heating systems based on heat pumps, including data security, could be integrated into digital security management policies focusing on public infrastructure. However, perhaps the more critical security threat for these same district heating systems is their vulnerability to extreme weather events. Heat waves, prolonged sub-zero temperatures, and flooding (among other extreme events) can disrupt service and damage equipment.

4.4.4. Societal acceptance and justice

One of the primary obstacles to adoption is the principal agent problem, resulting in a conflict in priorities between the owner of an asset and the person using it. Similar to other low-carbon technologies (including but not limited to electric vehicles), heat pumps are economically most attractive because of their low operational costs, enabled by their high energy efficiency, but they are also subject to significant investment cost requirements. Renters may not have an incentive to invest in the heat pump, as they only see cost savings from efficiency improvements when they do not have access to a long-term return on the investment. Owners also have limited interest in investments, if they hand over their asset through rentals, unless there are mechanisms enabling them to recover capital investments through the valorisation of the asset with better energy efficiency.

There is a clear risk of financially vulnerable groups being excluded from this transition without targeted financial support. There is a suggestion that existing regional inequalities will increase, and that political choices will need to allocate resources between investments to support the most effective use of heat pumps, and delayed investments to counter social inequality (Savage, et al., 2022). Indeed, European policy developments already integrate a combination of tighter requirements to enhance energy efficiency for existing and new assets, financial allocations to promote technology innovation and mechanisms – including the Social Climate Fund, replenished through a dedicated Emission Trading Scheme for buildings and transport, to manage these challenges (European Union, 2023).

4.4.5. Research and innovation actions

4.4.5.1. Basic research

Industrial electrification is an area of high potential for innovation, especially in the context of a net-zero transition, and heat pumps are poised to play a major role in that context. However, as heat pumps are a well-established technology, with high technology readiness, there is relatively limited scope for basic R&I to accelerate their deployment.

Despite overall technological maturity, current materials and components may limit heat pump efficiency and environmental impact. New refrigerants, including the use of natural refrigerants and new materials could jointly enhance performance and reduce the global warming potential of refrigerants (EHPA, 2021, ITIF, 2021). Existing thermodynamic cycles may also not maximise heat pump efficiency. Novel, innovative alternative cycle technologies

[25] Summer temperature records are broken regularly and heatwaves are currently, and will continue to be, more intense and frequent than before (EEA, 2022). From 1980 to 2020, for example, heatwaves were responsible for 86%-91% of fatalities caused by weather- and climate-related extreme events in the EEA member countries. This corresponds to 77,000-129,000 deaths over this period (EEA, 2022).

could significantly improve efficiency and performance (EHPA, 2021, ITIF, 2021). Research should also investigate advanced heat transfer fluids to enhance heat pump efficiency (EHPA, 2021).

Redesigning and reengineering low-temperature industrial processes, including through better system integration and for enhanced heat recovery, is a field where basic R&I can help take advantage of the characteristics of heat pumps (ITIF, 2021).

4.4.5.2. Applied research and innovation

Integrating heat pumps into various energy systems can be complex and the electrification of industry implies significant changes in production processes, meaning that industry investments in electrification, not only monetary but also for the acquisition of technical expertise, are constrained until a clear scenario is presented where electricity is going to be cost-competitive (Madeddu et al. 2020).

Applied R&I can help unlock stronger prospects for growth for heat pumps. Designing low-temperature industrial heat pump systems that are flexible and diverse in their end use applications is critical to wider adoption and decarbonisation (ITIF, 2021). Better integration techniques and modular designs could enhance scalability and system compatibility for existing heat demand and industrial assets. Research should focus on system integration techniques to improve modularity and scalability and explore advanced control strategies for integrated energy systems.

The retrofitting of existing DHCs to become more efficient and resilient requires the integration of data from end users, the integration of different forms of power (electric and waste heat), and the management of complexity. Retrofitting should be encouraged with applied research projects that incorporate existing technology with emerging system integrations technology.

The need for urban cooling centres to ensure access of all citizens to cooling during heat waves should be considered as a critical component of urban planning and building permitting. Research should focus on identifying best public policy approaches to give the largest number of citizens access to cooling regardless of economic circumstance and on removing administrative barriers. Research should also address heating and cooling as an energy poverty question to explore ways to improve access to buildings that are not too cold or hot.

Designing optimised heat pumps and producing components efficiently with modelling, simulation, and innovative manufacturing can lead to more efficient and cost-effective designs. Applied research should optimise heat pump design and explore innovations in manufacturing techniques, including 3D printing, for heat pump components.

Heat pumps need to interact seamlessly with other energy systems. Research on sector coupling can improve energy system flexibility and integration with renewables. Efforts should focus on understanding the interaction of heat pumps with other renewable energy sources, electric vehicles, and smart grids, and studying the role of heat pumps in demand response and grid flexibility.

Current heat pumps may not be efficient enough for all applications. Enhancing design and optimising components can lead to higher efficiency, especially for industrial uses. Research should aim to improve heat pump efficiency through better design and component optimisation and develop high-temperature heat pumps for industrial applications.

4.4.5.3. Deployment

It is important that deployment-oriented R&I investigates what explains the large differences in heat pump deployment and diffusion in different EU member states and helps find ways to promote diffusion in areas where it has been slow. Reasons to be considered include differences in cost of capital, and solutions include financial instruments to overcome these. Deployment-oriented R&I can also support governments to improve understanding and awareness of the possibility of using reversible air conditioners as heat pumps, in cold months, as this could support the EU in reducing its fossil fuel import dependency (although it may come also with challenges related with the cost of take-or-pay contracts for natural gas, in specific geographies, with implications that could lead to increases in the cost of gas in industrial applications, with negative impacts for competitiveness).

Innovative business models and collaborative platforms can accelerate market uptake, overcoming barriers to widespread adoption (Hyysalo et al. 2013; Hyysalo et al. 2018). Efforts should develop new integrated business models for heat pump deployment alongside other measures addressing energy demand of buildings and industry (Lazarevic et al. 2019), across residential, commercial, and industrial sectors, and create one-stop shops for financial advice, showcasing heat pumps alongside other energy solutions, and facilitating stakeholder collaboration (Brown 2018). Hence, heating and cooling should be addressed in the context of broader renovation and retrofit of buildings aiming to reduce energy demand.

Supportive policies and emphasis on promoting health and environmental benefits can encourage adoption. Initiatives should focus on formulating policies that encourage the adoption of heat pumps and renewable heating and cooling technologies (as well as passive heating and cooling to fit the changing climate), and advocate for stronger emphasis on health and environmental benefits in EU legislation.

Targeted training and certification programs can ensure labour capacity for high-quality installations and system reliability. Efforts should upgrade the skills of manufacturing and installation personnel through targeted training programs, and promote certification and standardisation to ensure high-quality installation and maintenance of heat pump systems.

4.5. Electric vehicles and electric vehicle batteries

4.5.1. Relevance for accelerating low-carbon transitions

Battery electric vehicles have been shown to have a clear advantage over other technologies in terms of GHG and pollutant emission abatement, and, especially if paired with renewable energy, also in terms of energy efficiency (IPCC, 2022, Bieker, 2021, Hill et al., 2022, EEA, 2024). Advantages are clear not only for cars and light vehicles, but also for trucks and buses.

Better cost effectiveness, not just for cars but also in other road transport and less limiting factors (in particular thanks to energy- and resource-efficiency advantages, despite changes in the structure of the resources needed) in comparison with competing technologies indicate that the electrification of road transport is a vital enabler of a low-carbon transition.

Market developments show consistent increases of EV deployment over the past decade, with impressive rates of growth, even if sales of electric cars remain significantly concentrated in just a few major markets: China, Europe and the United States. In 2023, electric car sales reached 14 million, up from 10.5 in 2022, 2-3 million in 2018-20, and less than 1 million before 2017 (EV volumes, 2024, IEA, 2024c).

Plug-in hybrid and battery electric vehicles accounted for almost one in five cars sold in 2023 (IEA, 2024c). Battery electric vehicles for one in eight. Due to these developments, electric car stocks have been consistently growing over the years (Figure 12).

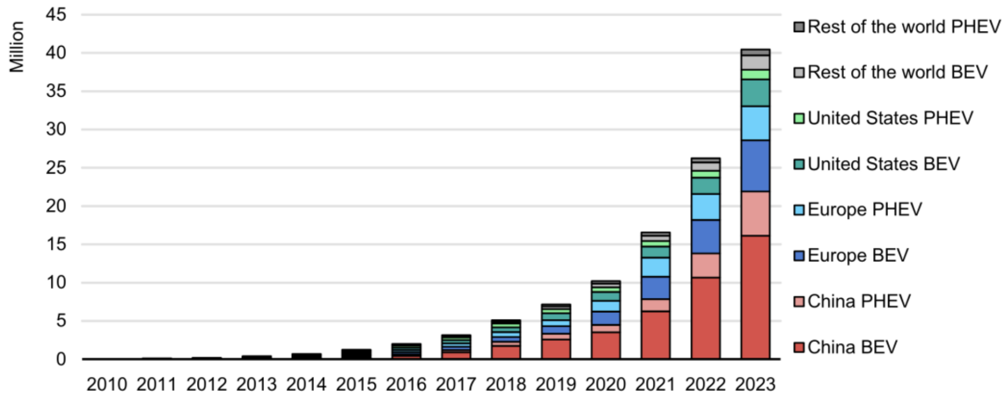

Figure 12. Global electric car stock by regions (source: IEA, 2024c).

Although much of the focus received by EVs in the public debate is on cars, this is not the market segment where EVs reached the largest sales numbers and market shares. Globally, two wheelers and buses saw a higher EV penetration than electric cars and light commercial vehicles (FIA Foundation, 2023). Rapid developments, with accelerating dynamics, are also picking up in the truck sector (BNEF, 2024), with a clear case for increased electrification in urban environments and increasing evidence of growing opportunities also for long haul (IEA, 2018b; Ainalis et al. 2020; BMDV, 2020; Gründler and Kammel, 2021; ITF, 2021a; IPCC, 2022; Plötz, 2022; ITF, 2022b). Clear development opportunities also exist for short-distance ships – including several ferries deployed in the Nordic region (ITF, 2020a; DNV, 2024) – and for novel applications in the aviation sector, for urban air mobility (although these are likely additional to existing uses, and hence not paired with net emission cuts).

EVs are also generally aligned with improved health impacts of road transport, thanks to the abatement of emissions of local air pollutants, especially in urban areas (World Bank, 2022), despite the need to address non-exhaust emissions of particulate matter and although magnitudes of the association of EVs and health impacts vary (Pennington et al. 2024).

4.5.2. Competitiveness, supply chain and deindustrialisation

Battery electric vehicles are capable of delivering net savings in terms of total cost of ownership, especially in highly-utilised vehicles, due to better energy efficiency, especially if they can access low-cost electricity supplies, in a way that support the flexibility of the electricity system, and increasingly also in average conditions (Morrison and Wapperlhorst, 2023 for cars in Germany, ITF, 2021d for trucks in the EU, IEA, 2024c for a recent, general assessment, in multiple geographies).

With important exceptions in China, battery electric vehicles are also subject to higher upfront costs versus combustion engine vehicles (IEA, 2024c), posing specific challenges for households and businesses in emerging economies, as they tend to face higher borrowing costs.

China was particularly successful in developing advanced and highly competitive electric vehicle and battery industries, including the related supply chains, pairing them with major production facilities, meaning that it has acquired a competitive advantage (Carey and Klayman, 2024; Fitch, 2023). This includes clear opportunities and to increase its exports, supported by investments in increased export capacity (Yang, 2024; Weilan, 2024).

As in the case of solar PV and wind, reasons explaining the strength of China include economies of scale and learning-by-doing improvements in manufacturing, a dynamic growth environment, a deliberate desire to reduce dependency on oil and gas, and the associated industrial policies developed in China over the past two decades and major efforts to develop a cost-competitive access to raw materials at scale.

Contrary to solar PV, which is not a stronghold of European industry, the risk exposure of the EU automotive industry (and the EU economy more broadly) to these factors is very significant, as car and truck production have a central role in the EU industrial fabric.

EU efforts for increased supply diversification need to be scaled-up, especially for batteries, while also paying attention to the need to maintain its prominent position as a global technology provider, as a major automotive exporter. Challenges are particularly strong given the significant early mover advantage acquired by China, resulting in a global over-dependence on Chinese supplies (IEA, 2023a). Structural differences in the determinants of production costs (cost of energy and raw materials, manufacturing facilities and labour), especially with respect to China, are especially hard to manage and point towards concrete risks of deindustrialisation.

Managing these risks requires a careful balance between market openness and the selectivity enabled by non-discriminatory non-price criteria allowing increased product diversification, in line with the concept of open strategic autonomy. The former is important in light of a disadvantage of European players in terms of access to raw materials and intermediate products in the battery supply chain, such as anode and cathode materials, and also required to enable Europe to attract investments from leading battery companies, most often not headquartered in Europe. The latter is important to extract greater value from social and environmental sustainability, as well as responsible governance/business conduct.

Making sure that the transition is an industrial development opportunity, not just in China, but also in other geographies, is crucial for social stability and also important for strategic reasons, due to the relevance of the automotive, battery and semiconductor industries for both civil and military applications.

4.5.3. Security

Electric vehicles come with a significant energy security advantage, as they are uniquely positioned to diversify energy supplies away from petroleum products, in a sector (road transport) that has been traditionally almost entirely dependent on oil supply.

As shown by the early moves developed in the European Nordic region, and in Norway in particular, the development of charging infrastructure is more likely to be effective in the presence of strong electricity grids (IEA/Nordic Energy Research, 2018). Modern, smart and expanded grids are essential for a successful energy transition, and expanded grids are critical to enable such levels of growth as the world deploys more electric vehicles, instals more electric heating and cooling systems, and scales up hydrogen production using electrolysis (IEA, 2023g). If left unmanaged, EV charging can lead to a need to adjust grid capacity and require substantial infrastructure investment (Valogianni et al., 2019), increasing electricity costs. On the other hand, managed charging has been shown to offer major opportunities to help managing electricity loads, both for local grids and nationwide systems, ultimately resulting in lower electricity costs, thanks to better use of grid capacity (Muratori, 2024). EVs can be enablers of advantages from synergies between low-cost, low-carbon electricity production from variable renewables, as contributors to increased power system flexibility, thanks to the availability of energy storage capacity represented by their batteries. EVs tend to use - on average - only a fraction of their storage capacity and - especially for home charging - they can be effectively paired with digital technologies in the context of smart grids. Grid integration and energy security advantages are less evident for trucks and buses (despite remaining energy efficiency, energy diversification and emission mitigation advantages), due to much higher power requirements and high utilisation rates.

Despite these advantages, major increases in the reliance of EVs on critical raw materials security of supply risk (especially lithium, nickel and cobalt) to come with a different set of security-related challenges (Bongartz et al. 2021), calling for coordinated policy and industry action to diversify value chains and avoid over dependence.

Like other vehicles, EVs also need digitally-enabled control systems (including for connectivity), and their resilience is therefore negatively affected by over-dependency of semiconductors (European Union, 2022).

As EV deployment grows, opportunities available to reuse and recycle the materials used in their batteries strengthens - as long as material recycling capacity also increases - their capacity to offer a significant contribution to economic circularity, ultimately supporting a structural transition to lower risk exposure to supply availability constraints for the European economy.

4.5.4. Societal acceptance and justice

Electric vehicles tend to enjoy a favourable perception due to alignment with climate change mitigation and energy diversification goals, but they are also increasingly becoming increasingly divisive. Reasons include higher upfront costs, fears of deindustrialisation (either from missing opportunities to seize market shares or from the net declines already visible for internal combustion engine vehicles) and related social disruptions, especially in countries with automative industry subject to competitiveness pressure, and even more so if they struggled to attract investments in new manufacturing capacity.

As in the case of heat pumps, discussed above, European policy developments has already integrated a combination of tighter requirements to enhance EV market penetration, financial allocations to promote technology innovation and social protection tools to manage these challenges, best represented by the Social Climate Fund, meant to support most exposed businesses and households to manage transitional challenges (European Union, 2023).

Other challenges that risk to further exacerbate acceptability issues are also related with an inequitable distribution of benefits (e.g. due to larger cost savings for people that own a garage or a parking spot and can have access to low-cost, low-carbon electricity from solar PV, and all this following lower cost access to capital), especially in the presence of policies that support increased demand to sustain the industrial technology transition.[26]

[26] Also in this case, as for solar PV, policies like the establishment of the Social Climate Fund, in pairing with targeted carbon pricing for transport and buildings, have the deliberate aim to help address these issues.

Specific actions have already been undertaken, not just at the Union level but also in specific Member States, to address these challenges. Key examples include conditional access to EV purchase incentives based on income, caps in the availability of incentives based on vehicle value, targeted actions prioritising EV deployment in company cars (often more frequently used in early years and sold at a lower cost in the second hand vehicle market, and therefore potentially enabling broader access to EVs at a lower cost), with funding from differentiated vehicle taxation or carbon pricing, or both.

Business models for EV charger deployment have heterogeneous performances, with stronger business cases for home and workplace chargers, thanks to their capacity to deliver electricity at lower costs, and for bus chargers and commercial vehicle chargers in logistic depots, thanks to the possibility to ensure high usage rates. Destination chargers also have a stronger pathway for increased deployment, as they can be supported by commercial interests that have the capacity to generate more value than the cost incurred through electricity supply. Greater challenges exist for publicly accessible chargers, due to higher investment costs, unless there are conditions enabling their frequent use.

Overcoming infrastructure availability challenges will likely require public interventions to guarantee minimum access (also referred to as a “right to plug”) and adequate maintenance of publicly accessible chargers, irrespective of their power capacity – and in any case including fast chargers (French Ministry of Ecological Transition, 2019). Bridging remaining cost gaps will be especially important in communities that face challenges to access private charging, such as those not having access to private parking (French Ministry of Ecological Transition, 2019). Key initiatives have already been developed, e.g. in the EU, at the trans-national level, with the Alternative Fuels Infrastructure Regulation (European Union, 2023), but more policies are needed to bridge infrastructure access and availability gaps at the national and regional level, with tools that are likely to require public financing.

4.5.5. Research and innovation actions

4.5.5.1. Basic research

Due to the structural disadvantage in terms of competitiveness, basic R&I action should focus on the acceleration of the readiness of advanced and material-efficient battery technologies, such as bipolar batteries (Toyota, 2023), lithium-ion batteries with advanced and low-cobalt anodes, advanced cathodes (US DOE, 2022), solid state, lithium sulphur and alternative chemistries involving sodium, potassium, magnesium and calcium (US DOE, 2022, Vedhanarayanan and Lakshmi, 2024), as well as technologies and processes capable of delivering productivity increases in battery manufacturing and upstream steps of the battery value chain – i.e. refining, processing, and assembling the raw materials into battery cells (Batt4EU, 2024). Examples include additive manufacturing, flexible manufacturing, autonomous final assembly, as well as AI and digital technologies more broadly. Basic research shall not stop at battery technologies, but it can also facilitate the formation of supply chains and new markets and support their growth.

End-of-life vehicle, battery and material recycling is a crucial area of technology development for EVs, as they are a major driver of material demand increases, as recycling has the potential to reduce the demand for raw materials going forward. Basic R&I can strengthen opportunities to ensure that increased EV deployment will be accompanied by the emergence of an industrial capacity enabling the cost effective and environmentally sustainable recovery of valuable minerals. Battery recycling is also especially important as the European economy decarbonises.

Reasons include the lower energy requirements paired with secondary material extraction in comparison with primary materials and the increase in the domestic availability of materials that accompanies the growth of EV and battery deployment.

Basic R&I initiatives also need to focus on the improved understanding of the barriers faced by EVs, batteries and their supply chains in society. These R&I activities also need to consider structural drivers regarding skills requirements and enabling infrastructures. Their relevance stems from the deep rooting for incumbent technologies, based on unabated fossil energy, in the existing industrial fabric. Given the impact of EVs, batteries and their value chains on global manufacturing and trade patterns basic R&I can also be instrumental to enable progress in the development of an updated trade agenda, especially if it supports activities that foster and support a global dialogue, not limited to the EU but also deliberately open to historical EU partners, in the Global North and developed, emerging and developing economies in the Global South.

4.5.5.2. Applied research and innovation

Applied R&I activities can keep supporting the definition of clear pre-requisites for the transition, including in particular technical standards regarding safety, durability and environmental requirements for EVs, batteries, as well as safety, durability and interoperability of charging infrastructure (FIA Foundation, 2023; ITF, 2021a) and similar technical standards regarding the continuous development and update of the EV charging infrastructure. Doing so in multilateral fora - such as the United Nations World Forum for the Harmonization of Vehicle Regulations (WP.29), the International Organization for Standardization (ISO) and the International Electrotechnical Commission – is especially important to enable technology development based on a levelled playing field across the World.

Applied R&I can facilitate the development of novel applications and product innovation (e.g. in new mobility and software-defined vehicles) and can also foster progress in new vehicle and battery pack architectures, as well as the development of novel applications.

Applied R&I can include solutions, also fostered by AI, that enable the industry to go beyond earlier automation approaches adopted in the automotive industry and deliver a deep transformation of the way in which electric vehicles are designed, manufactured, operated and serviced (Draghi, 2024).

Research activities focused on batteries can support advanced manufacturing processes, including those fostered through the use of AI, enabling material savings and cost reductions. R&I can strengthen safety and help address liability concerns. R&I can also support recycling and reuse through programmes that enhance traceability, leveraging data sharing, and strengthen access to information regarding the battery state of health. As EVs are deployed, applied R&I activities can also focus on the extraction of secondary raw materials from end-of-life batteries, supplementing reuse and enabling recycling. Taken together, these R&I actions can favour economic-, energy- and resource-efficiency, thanks to primary material savings and cost reductions. This can have positive spillovers for repairability for local industrial development and job creation.

4.5.5.3. Deployment

Deployment-oriented R&I programmes can also support progress in the development of novel approaches for modes of transport that are already past low technology readiness and close to large-scale commercialisation. Trucks and related charging technologies are key targets for these activities. For trucks, the development of cost-effective energy and resource efficient approaches enabling access to electricity is one of the areas still open to uncertainties, especially for long-distance movements, with solutions ranging from electric road systems to very high power (MW) chargers to battery swapping. Partnerships with research activities carried out in other global regions can be especially relevant for this. The same topic requires strong attention for intra-EU coordination to leverage the potential of the single market.

Similar to the case of solar PV, deployment-oriented R&I for EVs – including activities enabled by AI – also needs to support a scale up in production capacity, as well as the need to catch up towards a reduction of over-dependency risks. This is not only relevant for battery manufacturing, but also for primary material extraction and processing.

Deployment-oriented R&I is also needed to anticipate and govern the challenges for the stability of governmental revenues of the EV transition. R&I activities can help explore a range of different solutions, not limited to differentiated taxation for vehicle registration and the use of fuel taxes that are coherent with differences in carbon intensity, but also including the consideration of road user charges. A key reason for an R&I focus on this lies in the complexity that accompanies the shift to road user charges, as it requires anticipation and finding a balance between stimulating innovation while addressing revenue shortfalls and social equity impacts. Equity considerations are also relevant for the energy price reforms enabling the removal of fossil fuel subsidies, with large economic welfare gains (IMF, 2023).

These reforms are crucial to provide much needed price signals, beneficial to level the playing field for long-lived, low emission technologies. However, they also need to be accompanied by robust assistance for communities (including low-income households and small businesses) that are disproportionately affected by the technology transition. In this respect, R&I activities can support the development of well-tailored programs toward the poorest segments of society, helping alleviate potential concerns with limited impacts on fiscal balances.

Social science research should also increase its focus on other equity-related challenges and opportunities for EV diffusion, in particular to lower income groups, and the need for solutions capable of easing, at once, a transition that is economically sound and socially just. For example, R&I on programs like social leasing for electric cars or trucks, financed by carbon pricing or other forms of differentiated taxation, can help improve access to EVs for lower-income groups and small businesses can be enhanced and incentivize manufacturers to offer affordable EV models, driven by projected growing demand for high volume, complementing low profit margin. Deployment-oriented R&I is also important to enable a broader and more affordable access to publicly accessible charging and address the need to ensure a "right to plug", especially for communities that face structural barriers to install home chargers and also do not have the option of workplace solutions. Key examples of tools that can respond to this need can build on existing regulations and incentives for the mobilisation of private investments for EV charging. They include measures facilitating the installation of charging points at a limited cost in buildings and parking facilities, programs to deploy on-demand charging points, incentives for the investment of private operators in charging hub, the creation of regulatory and support framework for highway-based fast charging stations (French Ministry of Ecological Transition, 2019) and the use of public service contracts (eventually including the bundling of different locations) for minimum deployment.

Other key priorities for applied R&I activities include the management of transitional risks in society, as the EV transition is likely to be characterised by a combination of greenfield and brownfield investment, not necessarily co-located.

Box 2. Need for policy coordination, beyond R&I, to address overdependency risks for batteries (and solar PV hardware)

Similar to the case of solar PV hardware, enabling a surge in domestic production for batteries is unlikely to be solely enabled by R&I efforts, and very likely to require increased reliance on instruments capable of mobilising private investments alongside public resources. In the United States, where the federal government has been the major player in providing funding for research, major increases in support for research and development to strengthen EV battery supply chains include more than USD 8.5 billion for critical minerals activities (Carey et al., 2023).

Policies accompanying the mobilisation of public R&I investments and supporting an increase in private investments may need to include a mix of trade tariffs or price undertakings and conditional access to policies supporting EV demand and supply, reversing the tools deployed over the past decades in China to acquire its current competitive advantage (Oh, 2021).

Instruments that can complement increases in public R&I support and regulatory requirements (already in place) include in particular non-discriminatory, non-price criteria for EV and battery deployment (such as those emerging from the finalisation of the Net Zero Industry Act) and recycled content requirements (such as those already included in the Battery Regulation and the Critical Raw Materials Act). For batteries, key examples include carbon intensity thresholds for access to incentives/purchase subsides, and/or regulatory requirements related with forced labour in EV and battery value chains, as these could help favour the relocation of productive capacities in a way that increases the diversification of the value chain (Hermine, 2024; Sebastian et al. 2023). Some of these are already in place in France, where access to EV purchase incentives is conditional to the carbon intensity of EV battery production and other environmental requirements (Légifrance, 2023). Industrial choices to be developed in this context will also need to include a positive investment dynamic for EV manufacturing countries (including developed and emerging economies), enabling increases in capacity utilisation and other positive impacts for increased competitiveness (Hermine, 2024).

Securing a resilient and cost-effective market shift can also benefit from the development of joint ventures or technology-transfer agreements with partners for investments in the EU with companies with extensive capacity in battery manufacturing industry (and the related supply chain), not headquartered in the EU (but rather in China, Japan or Korea), as this can be instrumental to enable learning across different sectors of the battery production process. In this respect, conditionalities for access to the European market may be necessary to ensure attractiveness for investments and moving towards more diverse global battery value chains. Financial support offered to stimulate supply diversification and manage overdependency and deindustrialisation risks could be bound by local recruitment and apprenticeship clauses, similar to the practice under the Inflation Reduction Act (Draghi, 2024).

Similar considerations are also applicable to solar PV. In both cases, specific attention shall also be paid to the creation of synergies with R&I activities allowing to seize

Box 2. Need for policy coordination, beyond R&I, to address overdependency risks for batteries (and solar PV hardware)

opportunities to offer large scale manufacturing opportunities to technologies that are not yet at high technology readiness levels.

Increased diversity in EV and battery value chain also requires the declination of the concept of open strategic autonomy in trade policy, since some of the capital needed to mobilise investments will move across borders, and so will raw and processed material/products (including semi-finished products). R&I support can be instrumental to assess pros and cons of different choices in this area from economic and social perspectives, as decisions in this field come with heavy geopolitical implications.

Policies promoting responsible material sourcing practices could be instrumental to steer investments in material sourcing and processing – including those made by major international extractive companies – towards greater diversification, as long as they also offer opportunities to generate value from product diversification. R&I activities are important in this field to support the definition of standards and frameworks enabling the development of policy decisions and favouring stakeholder dialogue, within and beyond the EU borders (e.g. with historical trade partners of the EU in the Global North, as well as developed, emerging and developing economies in the Global South). Joint international supply auctions – such as those already foreseen in the EU Critical Raw Materials Act – can also integrate minimum requirements in terms of transparency for sustainable sourcing, while also remaining open to competition.

4.6. Biofuels

4.6.1. Relevance for accelerating low-carbon transitions

Biofuels are already part of the road transport fuel mix and are likely to play a growing role in long-distance transport (e.g. aviation, shipping, trucking), where the use of batteries and electrification faces greater structural challenges, linked with size (paired with cost) and weight constraints (IPCC, 2022; IEA, 2023e3; IRENA, 2023; ITF, 2020a; ITF, 2021c; ITF, 2023a; ICAO, 2022).

Figure 13 shows that current biofuel production is largely reliant on food and feed feedstocks (OECD/FAO, 2024). The capacity of biofuels to abate emissions depends strongly on specific pathways and feedstocks (Cai et al. 2022; Prussi et al., 2021).

Significant abatement of life-cycle GHG emissions are achievable with feedstock derived from sustainable agriculture, forest management and land restoration practices (Tilman et al. 2009). Pathways reliant on low-carbon process energy can also enhance GHG savings. Biogas/biomethane also come with significant life-cycle GHG emission reduction advantages, if assessed against an alternative resulting in atmospheric release of methane.

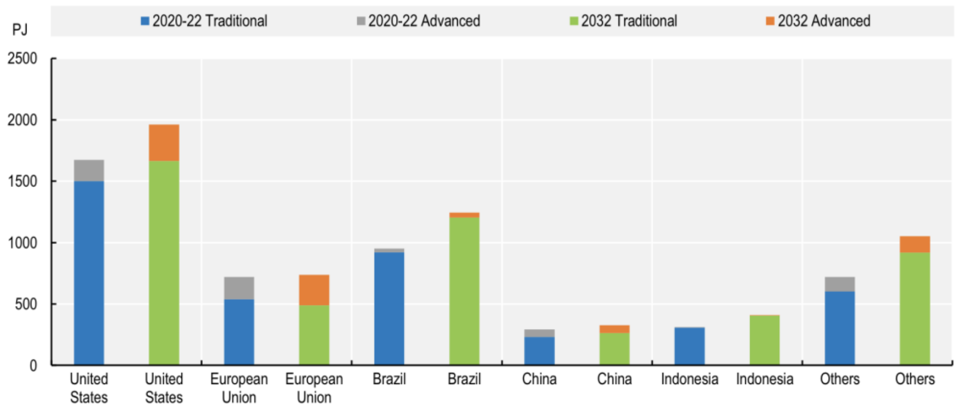

Figure 13. Current (2020-2022) and projected (2032) world biofuel production from traditional[27] and advanced feedstocks (Source: OECD/FAO, 2024).

An effective life-cycle GHG emission abatement is subject to risks in cases not reliant on low-carbon process energy and sustainable feedstock sourcing practices. Ensuring that sustainable and advanced biofuels play an effective role in climate mitigation requires a combination of factors contributing to a progressive rather than a sudden process (Trinomics, 2022). These factors include an increased shift toward cellulosic (non-food-based) feedstocks (ICL 2021), the cultivation of crops in zones with sustainable agronomic practices in farming land and in land with natural constraints (unused, abandoned, and degraded land) (Panoutsou et al., 2022), the exclusion of options whose use would release large quantities of carbon (irreplaceable within a reasonable time scale), in favour of options (e.g. managed forests and limited extraction of wood and energy) that can increase forest growth (IRENA, 2019c), clarity and in regulations to account for feedstock, agricultural and forestry practices that lead to land use change risks,[28] also in light of weaknesses in the link between increased demand for biomass resources and improved agricultural or forest management responses, (see Giuntoli et al., 2019 for the forest case), selective identification of options (e.g. harvesting practices) that do not result in removal of soil carbon stocks and technological progress in the conversion processes (IEA Bioenergy, 2019d; US DOE, 2022).

Additional opportunities may also come from improved agricultural and smart farming practices (such as the use of robots, drones, and digital technologies to optimise fertiliser and pesticide use, as well as human labour), which increase the potential for food and feed–based crops to be part of a future biofuel production mix in a way that aligns with sustainability requirements (US DOE, 2022).

Further complexity and important challenges, especially for specific feedstocks, arise from indirect emissions, in particular from land-use change (Sumfleth et al. 2023).

[27] Traditional feedstocks are here defined as food and feed crop-based biofuels.
[28] These include, for example, avoiding diverting to bioenergy the use of wood chips, saw dust, and black liquor already needed by competing activities, such as sawmills, leading to a net increase in demand for biomass. In agriculture, this includes the diversion of residues towards the bioenergy sector, inducing substitution for uses already in place (e.g. bedding, heat and power production) when it is not compensated by practices (such as increased reliance on renewable electricity production) freeing up sustainable biomass resources for biofuel production.

4.6.2. Competitiveness, supply chain and deindustrialisation

Current biofuel production is largely reliant on food and feed feedstocks (OECD/FAO, 2024). Brazil and the United States account for most ethanol production, being far ahead of any other country (OECD/FAO, 2024).

To date, the production of ethanol, biodiesel, and renewable diesel has been primarily driven by policy action, consisting mainly of mandates and rebates. Policies developed before 2007 were mainly focused on increasing biofuel supply and demand. Subsequent measures, especially in Europe and the United States, paid growing attention to the impacts of biofuels on food and feed prices and the environment, including direct and indirect land use changes and biodiversity loss. The results of these actions led to a significant slowdown in the growth rate of biofuel production from 2010 (Cazzola, 2022).

The EU and Indonesia are the main global producers of bio- or renewable-diesel, followed by Brazil and the United States (OECD/FAO, 2024). The EU is mainly reliant on rapeseed, Indonesia on palm, Brazil and the US on soybeans. Waste oils and fats are also relevant for renewable diesel destined to the EU market, and likely subject to increasing demand, going forward, for the production of sustainable aviation fuels (SAFs) for the aviation market. Historical market dynamics also show that domestic production in the EU is subject to greater land availability limitations, in comparison with Brazil and North America, which are also the global areas with lower production costs.

Despite significant policy efforts to scale up advanced biofuels, not based on food or feed, crops and/or reliant on sustainable agriculture practices. Policies also support the integration of low-carbon hydrogen as a feedstock (in some form of renewable fuels of non-biological origin [RFNBOs]). However, existing data point towards very limited uptake (IEA, 2023c) and structural limitations in sustainable biomass supply (ECA, 2023). Some forms of renewable diesel (consisting of hydrotreated vegetable oils [HVO]) and jet fuel (from hydroprocessed esters and fatty acids [HEFA]), reliant on waste oils and fats, could be the exception regarding hydrogen, as they already need it in their production process. However, they currently rely on hydrogen of fossil origin, produced with carbon capture.

Production costs are currently higher than the fossil benchmark, but lower than other alternative fuels. Costs risk to be structurally higher for biofuel options (including food and feed and lignocellulosic feedstocks) reliant on more sustainable feedstock sourcing practices, especially in the absence of practices providing an economic reward for these practices. Cost savings may arise from valorisation of waste (namely for biogas/biomethane), from low-cost, low-carbon process energy, and from technologies helping minimise use of fertilisers while maintaining or increasing yields.

Lignocellulosic feedstocks require further technological progress, as they struggled to gain access to the market with past attempts to promote their use, both in the EU and in the United States. Structural challenges derive for all biofuels from the sparse nature of biomass resources. Co-valorisation in other sectors (e.g. paper and pulp, wood industry) can enable possibilities for some cost reductions.

Biofuels on food and feed crops require profound changes in agricultural practices to be produced sustainably (World Bank, 2020). They are capped in the framework of the EU policy, but still allowed in other global areas (in particular the United States, where most ethanol is derived from corn, and in Brazil, where ethanol is produced from sugar cane and biodiesel from soybeans).

Biofuel production is also subject to challenges related with price dynamics, as fluctuations in fossil fuel prices directly impact the competitiveness of biofuels and as countries prioritise surplus commodities for biofuel production to safeguard food availability and security, increasing uncertainty surrounds feedstock supply (OECD/FAO, 2024). Further risks relate to possible impacts on food prices, since increases are especially problematic for emerging economies (OECD/FAO, 2023).

While Europe today finds itself currently facing difficulties linked to the import of 'fraudulent' biofuels, especially from China (EBB, 2024), leading to a near-term glut and the application of trade tariffs (USDA, 2024), non-food and non-feed crops for oleochemical biofuels (waste oils) are available in limited amounts – with volumes produced that are structurally lower in comparison to fuel demand and that were recently reported to approach supply limits (IEA, 2022c). Additionally, this is not without challenges for sustainability (indirect impacts on virgin oil demand and, through that, on land use).

The availability of sustainably produced biofuel supplies with low life-cycle emissions also risks to be structurally limited due to higher costs versus conventional sourcing practices (shared with food and feed production from agriculture), especially in the absence of a policy-steering (ECA, 2023). As agricultural and biofuel feedstocks (namely vegetable oils) are traded internationally, further challenges arise from the necessity for international coordination.

From a perspective looking at existing industries, biofuels offer the opportunities to avoid asset stranding due to the possibility for specific pathways to enable lower life-cycle emissions, but - in a net-zero pathway - only as long as their large-scale deployment is feasible at scale. This is why there is merit, for resilience, in the prioritisation of biofuel use in sectors (e.g. long-distance aviation, shipping) whose decarbonisation and energy diversification face structural challenges with direct electrification.

Prospects are also challenging for a large increase of supplies of RFNBOs reliant on a combination of biogenic carbon sources and hydrogen, as these are subject to limitations in the joint availability of biogenic carbon and low-cost, low-carbon hydrogen production to have hopes to have chances to be cost-competitive. This adds to challenges related with the complexity of conversion technologies and lower cost opportunities requiring large scale investments in chemical plants, with high-risk profiles.

4.6.3. Security

Advantages from energy diversification from the energy of biogenic origin of biofuels are mitigated by low energy return on energy invested in comparison with fossil benchmark and other options (Trinomics, 2023; ANL, 2023), adding to fossil-based inputs (fertilisers, thermal energy used in biomass conversion plants, diesel fuel for biomass collection, in the absence of a technology switch towards electrification for agriculture/forestry machines) for production.

While biofuels are available in many countries in different formats (e.g. agricultural crops, organic waste, forests or forest industry waste), thereby, providing an additional element in security of supply. Especially, when biomaterials can be used alongside other energy sources, e.g. in boilers, or stockpiled, they can be attractive for energy security. Nevertheless, biofuels - especially those currently produced at scale - come with significant land use requirements, competing for land with other activities, starting from agriculture. This competition comes with significant energy and food security risks, especially in case of conflicts or other external factors constraining land productivity (such as shortages of fertiliser supplies), as these could lead to price spikes. Such a risk is concrete, as demonstrated recently by Russia's full-scale invasion of Ukraine, as it led some EU governments to restrict biofuel production (Esonye et al., 2023).

Despite possibilities for genuine contributions to GHG emission reductions from specific pathways (in particular if based on waste and capable of displacing methane emissions), the potential of biofuels to reduce GHG emissions or provide environmentally sustainable energy at scale (and hence in blends with high shared low-carbon pathways) is increasingly questioned, indicating that the scale up in production of unsustainable forms of biofuels can result in environmental and climate security risks. Similar challenges exist for the abatement of air pollution, as biofuels are still reliant on combustion and requiring after-treatment technologies, even if there are opportunities available from pathways that enable high fuel quality (similar to synthetic fuels, derived from hydrogen).

4.6.4. Societal acceptance and justice

Biofuels may be generally subject to a positive perception, favoured by the renewable origin of part of their energy and their alignment with reduced asset stranding risks. Societal acceptance tends to evolve with increasing awareness of challenges related with competition for land use with agriculture and/or dynamics leading to land clearance, including internationally,

Social acceptance of biofuels is also subject to challenges due to the complexity of the assessment of their contributions to different developments, ranging from sustainability and climate-related impacts to the protection of existing industrial assets.

Regarding sustainability and climate-related impacts, complexity in the sustainability assessment of biofuels from a life-cycle perspective is exacerbated by multiple production pathways, not easy to group in the context of divulgation narratives. Further difficulties arise from the even greater complexity characterising the determination of land-use change effects, as this involves responses to price signals taking place also in agriculture and forestry, and as system responses are also related with agricultural and forestry market developments. Additional uncertainties also exist regarding the cost-effective and sustainably-available potential, as this is heavily dependent on a variety of assumptions regarding yields, despite a general consensus pointing towards the importance of a cautionary approach (Creutzig et al., 2015; IRENA/IEA, 2017).

Regarding the social acceptance of biofuels, there are cases pointing towards a positive influence from lower risks of destruction of existing industrial assets, despite opportunities for the development of new, alternative, assets for competing technologies and the relevance of timely action to seize industrial development opportunities from these alternatives (and avoid being the victim of net losses from not doing so). A key example is the position taken by stakeholders that risk being negatively affected by e-mobility regarding battery electric vehicles for road transport.[29] These cases are balanced by a negative perception arising from higher risks of locking-in continued use of fossil fuels, as biofuels can be used in blends with fossil fuels for transport.

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[29] The case of Italy is a concrete example, as part of its automotive industry struggled to mobilise investments and seize opportunities, already before the global transition towards electric vehicles (Hermine, 2024). Alongside stakeholders in its chemical industry, Italy is currently supporting a case for increased reliance on biofuels, domestically and internationally (Biofuture Platform, 2024) and also raising questions on the feasibility of electrification (Brunetti, 2024).

Social justice effects incur, when old and virgin forests are used for the extraction of biofuels for energy and transport, influencing the local environment and, in Lapland, the culture and livelihoods of Indigenous Sami People.

4.6.5. Research and innovation actions

4.6.5.1. Basic research

Basic R&I priorities related to biofuels shall consider technologies supporting a broad transition towards resource- and energy-efficient practices regarding the provision of biomass resources. The importance of this for basic R&I activities lies in a wide relevance of these R&I activities, not limited to biofuels but also touching the domains of agriculture and forestry, as well as a broader perspective on the provision of ecosystem services.

Basic R&I covering all sectors involved in land should support sustainable practices enabling the sustainable provision of biomass resources, not limited to biomass yield increases but also integrating the delivery of net benefits for ecosystem services. Basic R&I shall also enhance understanding of impacts of economic activities having sizable and use footprint – including biofuels, bioenergy, agriculture, pulp and paper and forest industries, amongst others – regarding other ecosystem services, and the contextual necessity to ensure that these activities do not lead, directly or indirectly, to increases in GHG emissions or loss of biodiversity. In this way, it can support public policy developments having to manage the competition for land use between energy, food and feed and other biomass-based products (e.g. wood for the paper, timber and construction industries).

Improved capacity to recognize the environmental value of non-farmed land, related carbon storage and contributions to the reversal of biodiversity loss are also important priorities for basic R&I activities regarding biofuels, bioenergy, agriculture, forestry and other industries reliant on bio-based resources. R&I can be a key enabler of more sustainable ways to source biogenic carbon for these industries, ultimately contributing to the better alignment with sustainability of the chemical industry and transportation modes that will have less opportunities to electrify, directly or indirectly, including in particular aviation and shipping. Research is also needed on how to improve the long-term governance around biofuels, ecosystem services and nature protection.

4.6.5.2. Applied research and innovation

Applied R&I activities help reduce uncertainties on the sustainability of specific biofuel feedstocks. These include cover crops, different types of waste materials, and are not limited to dedicated energy crops and crops used for food and feed production. The same type of R&I is important to keep improving the understanding of life-cycle impacts of biofuel production.

Applied R&I activities can also support basic R&I to align bioenergy uses with sustainability requirements by looking further down the value chain, into conversion processes. Key examples include the optimisation of bioenergy conversion pathways, e.g. by integrating low-cost, low-carbon renewable resources, energy efficiency enhancements through energy recovery, electrification and heat pumps and/or the integration of biomass conversion processes in other industrial clusters. Other examples focus specifically on the improvement of biochemical, oleochemical and thermochemical conversions of bio-based resources into transport fuels.

Applied R&I can also foster the utilisation of concentrated streams of CO_2 of biogenic origin with renewable and other low-carbon forms of hydrogen for the production of carbon-bearing e-fuels/RFNBOs, while also maximising GHG emission reduction from biomass conversion into transport fuels. Due to challenges regarding the joint availability of both biogenic carbon and low-cost, low-carbon hydrogen, applied R&I activities can also enhance the capacity of policymakers to assess the actual availability of RFNBOs reliant on biogenic carbon streams.

Concrete examples of instruments enabling applied R&I activities to make a difference regarding biofuels and RFNBOs using biogenic carbon range from the development of prototypes to the validation of technology performance, scaling and integrating into relevant systems.

4.6.5.3. Deployment

R&I for early commercialisation is likely best targeted to sectors that are clearly paired with a high adoption potential for sustainably produced biofuels with low life-cycle emissions, but are also currently not priority markets. Aviation and shipping are clearly amongst the top priorities in this respect, across all transport modes. R&I activities focused on early commercialisation are also important for sustainably produced biofuels that cannot rely on existing transport, storage and distribution infrastructure (such as bio-methanol).

Examples of R&I activities with specific relevance in this phase include support to establish manufacturing capabilities, the support for first of a kind pilot stage demonstration (e.g. through grants and other de-risking instruments for this type of investment), the provision of technical assistance for customer discovery and business strategy development.

4.7. Hydrogen and hydrogen derivatives

4.7.1. Relevance for accelerating low-carbon transitions

Figure 14 shows that current hydrogen production is largely reliant on natural gas as a primary resource (IEA, 2024f). This is paired with high levels of CO_2 emissions per unit energy. Without a technology switch, hydrogen production is not a low-carbon option.

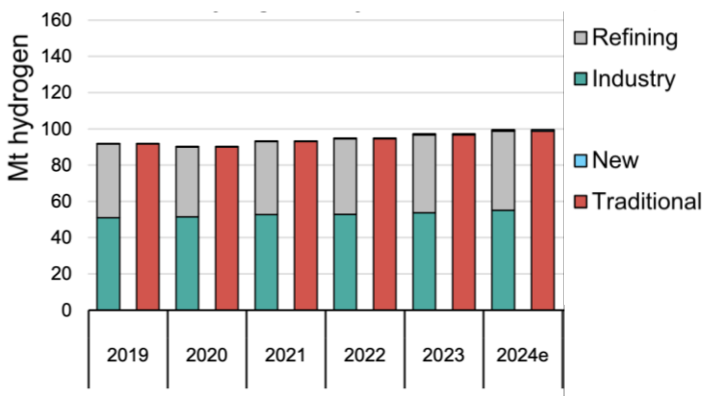

Figure 14. Hydrogen use by sector (Source: elaborated from IEA, 2024f).

Figure 14 also shows that the largest users of hydrogen today include the refining sector and other major industrial complexes, mainly for the production of ammonia (a key feedstock for fertilisers) and methanol (used to create numerous high-quality basic chemicals). Roughly one twentieth of all hydrogen demand ending up in refineries and industry is also used for the production of iron and steel (IEA, 2024).

Key alternative pathways to produce hydrogen with GHG emission reductions include electrolysis – which uses low-carbon electricity (either from nuclear or renewables) as the primary energy source – or the use of carbon capture and storage to manage emissions from fossil-based technologies (IEA, 2019c). Low-carbon hydrogen may also be derived from biomass, but this option faces constraints related with its sustainable production (as discussed in the Innovation Pathway on biofuels [4.6.]).

Hydrogen-derivatives (consisting of renewable fuels of non-biological origin, i.e. RFNBOs) include carbon-bearing fuels (methane, methanol and hydrocarbons) produced combining hydrogen with carbon of biogenic origin from concentrated sources, ammonia, and other synthetic, carbon-bearing fuels, obtained from low-carbon hydrogen and carbon derived from direct air capture of CO_2.[30] Their production comes with energy efficiency drawbacks. These come from the multiple conversion steps from primary energy to end-use product - many more than in fossil fuel production, and are paired with high low-carbon primary energy availability needs. They also come, for some hydrocarbons, with the advantage of being able to rely on existing fuel transport, storage and distribution infrastructure. Due to low technology readiness and high energy requirements, they are not currently economically viable, nor commercially available at scale.

Applications that can benefit the most for hydrogen or its derivatives for decarbonisation start from industrial applications that already require hydrogen inputs, such as the chemical industry (Madeddu et al. 2020), including the case of low-carbon fertilisers needed for GHG emission reductions in agriculture and biofuels. Low-carbon hydrogen is also relevant for iron and steel (needed for transport vehicles and transport infrastructure), where hydrogen will be in competition with carbon capture and biomass-based reducing agents (IEA, 2020a). It is also potentially important for long-duration electricity storage, despite competition with pumped hydro, compressed air storage (Schmidt et al., 2019), low-carbon fuels (with or without biogenic origin) used in thermal electricity plants and opportunities from HDVC interconnections to reduce the likelihood and length of events requiring long-duration electricity storage.

Due to greater efficiency of direct use of low-carbon electricity for the displacement of fossil energy demand, both hydrogen and hydrogen-based fuels also require specific conditions (regarding additionality, temporal and geographical correlation) in grids that do not have high shares of renewables to avoid indirect GHG emission increases (European Commission, 2024).

4.7.2. Competitiveness, supply chain and deindustrialisation

Low-carbon hydrogen production comes with a structural cost penalty versus fossil energy, if derived from fossil resources, due to the additional cost of carbon sequestration, meaning that it is only economically viable in the presence of regulatory requirements or carbon pricing

[30] A common feature of these fuels is that they need hydrogen (and, in turn, the primary form of energy from which hydrogen is produced) for their synthesis, alongside carbon (for methane or other hydrocarbons), oxygen (with carbon, for synthetic methanol) or nitrogen (for ammonia). They also need a technology switch for hydrogen production to offer GHG emission savings.

exceeding the abatement costs. Availability of fossil resources at low costs is also a key requirement for greater competitiveness of fossil-based low-carbon hydrogen (produced using CCS) and derived products. Similarly, biomass-based hydrogen has costs that are structurally higher than those of the primary resource from which it is produced.

Electrolytic hydrogen can be low-cost if produced from low-carbon electricity that is also available at very low-cost. This is possible in cases characterised by a high solar and/or wind potential – such as North Africa, the Middle East, Southern Asia, China and the western regions of South America, in addition to the North Sea and parts of the EU with higher renewable energy potential (IEA, 2019c; IEA, 2023g; IRENA, 2024b; OIES, 2024) – and it might also be possible in cases with high nuclear electricity production whose capital costs have already been amortised. Electricity costs are structurally lower, but hydrogen can offer opportunities to better exploit renewable electricity from variable renewables, helping to avoid curtailment (despite cost challenges).

To enable unit cost reductions for hydrogen as energy carrier, hydrogen also requires the development of technical standards regarding safety and emergency responses. This is especially relevant for end-use sectors, starting from those where hydrogen could have chances to complement or possibly substitute low-carbon electricity.

Hydrogen production from natural gas requires the development of CCS technologies. Hydrogen from low-carbon electricity requires a significant scale up in production and the parallel scale up in the production of electrolysers. Whether this can materialise depends on systemic responses, including energy and material efficiency solutions to deal with hydrogen-based products, if they are more expensive than alternatives based on fossil hydrogen, A key example, in this respect, is offered by fertilisers, as cost increases may spur greater reliance on precision agriculture, rather than an increase in hydrogen use. Prospects for hydrogen demand growth also depend on the capacity of hydrogen to compete cost effectively with other decarbonisation options, starting for direct electrification – as already shown by the case of battery electric and fuel cell cars, with a clear prevalence of the latter (a development also likely to happen also for trucks).

Due to efficiency losses, supply chain challenges (including overdependency) observed for low-carbon electricity production are exacerbated by electrolytic hydrogen production. For the same reason, supply chain challenges related with fossil energy are also exacerbated for low-carbon hydrogen production from fossil resources. Supply chain constraints (e.g. related with land availability and land use change) also exist for hydrogen derived from biomass, as discussed in the case of biofuels.

Due to its gaseous nature, hydrogen supply also requires the development of transport and storage infrastructure, facing significant challenges due to path dependency and the need for high volume demand to cut unit costs, in cases requiring long distance transport.

As in the case of other clean energy technologies (such as solar PV and batteries), electrolysers do not only require deployment at scale to experience cost reductions, but are also an area where Europe competes with China regarding manufacturing capacity. Current conditions see the EU having a greater share of a market that is still small, due to a struggle in mobilising demand with production costs that are still high. The market is also subject to tight competition on cost with China, with arguments in favour of opportunities for European manufacturers to withstand competition in terms of quality, energy efficiency and lower operational costs, despite higher capital costs, and diverging views on the use of incentives and other instruments supporting European manufacturers (Martin, 2023 and Martin, 2024).

Enabling increased hydrogen supplies is important to reduce deindustrialisation risks, especially for hard-to-abate sectors with few alternatives, including chemicals, primary steel and long-duration electricity storage. The case of chemicals is also particularly relevant for transport fuels, especially in cases where infrastructure costs were higher than those imputable incremental energy requirements in the production phase.

A key challenge for existing industrial assets – but also an opportunity for greenfield investments in areas with high low-carbon and low-cost energy availability – comes from the high cost of hydrogen transport and storage, as this clearly favours the movement of finished or semi-finished products rather than hydrogen itself, as energy carrier.

Hydrogen-based fuels (RFNBOs) require additional investments with respect to the production of hydrogen alone and they need technologies (such as air capture) that extract carbon, oxygen and nitrogen inputs and come with greater energy losses with respect to hydrogen as an energy carrier. This results in higher production costs, with negative implications for competitiveness. Despite less complex transport, storage and distribution infrastructure than hydrogen itself, resulting in significantly lower infrastructure costs, relevant applications are limited to decarbonising sectors that are not only challenging to electrify (e.g. long-distance shipping and aviation), but also subject to constraints for sustainable biofuel production scale-up and use of hydrogen alone as energy carrier.

4.7.3. Security

Reducing unit costs of low-carbon hydrogen production technologies can bring significant opportunities for the diversification of affordable energy supplies. These are especially important for the decarbonisation and the reduction of fossil energy demand in hard-to-abate energy end-use sectors, where hydrogen-based options are the sole option for decarbonisation – namely for chemicals (Madeddu et al. 2020), where hydrogen stands good chances to compete with alternative decarbonisation technologies – e.g. versus carbon capture, for steelmaking (IEA, 2020a), or where alternative, competitive decarbonisation solutions – e.g. pumped hydro for long-duration energy-storage (Schmidt et al., 2019), are limited in terms of availability (Royal Society, 2023).

In other end-uses, including buildings and land transport, several assessments point towards far lower energy efficiency than direct electrification, also likely paired with higher costs (Rosenow, 2022; Uerckerdt et al, 2021; Liebreich, 2022; IEA, 2023c; IRENA, 2023; ITF, 2022b). This confirms the caution introduced by delegated acts to the EU Renewable Energy Directive (and similar legislation being considered in the United States), requiring the prioritisation of low-carbon electricity for direct consumption and applying additionality requirements to hydrogen, unless there are already abundant low-carbon electricity supplies (European Commission, 2024), not to induce indirectly increases in fossil energy supply for electricity production. These choices are also suggesting that hydrogen from low-carbon electricity should be prioritised to improve energy security in cases where direct use of electricity is not a viable option, as direct use of electricity comes with greater energy efficiency from a life cycle perspective, in most cases. Hydrogen-based fuels face similar limitations and share many of the challenges with hydrogen, with the exception that they are likely to gain relevance for sectors that are hard to electrify directly (starting from long-distance shipping and aviation) and in cases where sustainable biofuel supplies face availability limitations or are subject to cost competitiveness challenges.

As electrolytic hydrogen is very much in the research and development stage, rather than full scale application, the broader energy security implications are unknown. There is evidence for clear opportunities for low-cost production of electrolytic hydrogen (IEA, 2019c; IRENA, 2022), and possibly also fossil-based hydrogen, as long as primary energy costs are also very low (IEA, 2019c), meaning that hydrogen could become a driving force of low-carbon industries globally, in a regulated environment. On the other hand, speculations that cross-border maritime trade in hydrogen has the potential to fundamentally redraw the geography of global energy clash with structural limitations paired with physical constraints (Liebreich, 2022; ITIF, 2024b), questioning (also based on cost considerations) arguments that suggest that hydrogen trade could create a new class of energy exporters, and reshape geopolitical relations and alliances between countries, and rather favouring other types of security risks, related with industrial migration and trade in low-carbon finished or semi-finished products.

While there are arguments supporting international governance and investments to scale up hydrogen value chains, as these could reduce the risk of market fragmentation, carbon lock-in, and intensified geo-economic rivalry (van de Graaf et al. 2020), the other arguments, likely more realistic, warn against moves in this direction, as it risks fostering developments towards technology options that risk to be structurally outcompeted by alternatives that are more energy efficient and less costly to transport, store and distribute (ITIF, 2024b). This is even more relevant in a context also characterised by increased adoption of system optimization, digitally enabled technologies, as these are likely enhancers of energy savings, further strengthening advantages available from energy and cost-efficient solutions (as opposed to options based on the idea of large-scale hydrogen availability).

4.7.4. Societal acceptance and justice

Societal acceptance of hydrogen and hydrogen-based fuels (in particular ammonia) as energy carriers risks to be hindered, especially for consumer-facing end-uses, by limited knowledge of the technologies using it as an energy carrier, by limited experience with this and by related safety and environmental risks. A key example is the case of ammonia spills, given the high toxicity profile of ammonia, especially relevant (given the interest of ammonia as a shipping fuel, due to lower production costs than other hydrogen-based fuels). Additional challenges also arise from the need for major supplies of low-carbon forms of primary energy – including variable renewables and nuclear – and, alternatively, for hydrogen of fossil origin, from the significant need for underground sequestration or alternative forms of carbon storage (e.g. as carbon black, in processes based on methane pyrolysis).

The high electricity requirements for dedicated projects aiming to produce hydrogen for industrial clusters come with social acceptance challenges related with visual impacts and nature loss (as already mentioned for solar PV and wind) or - in case of nuclear electricity - from other social acceptance concerns, especially in European countries that rejected it. In cases of installations of generation capacity and/or industrial clusters in peripheral areas, additional social acceptance challenges may arise from the need to adapt grid capacity.[31]

The costs of hydrogen production in Europe prompted criticism in the fossil energy and chemical industry for public policies aiming to encourage a scale up in production (Martin, 2024), despite encouraging signals regarding prospects for cost cuts from the recent hydrogen bank auction (European Commission, 2024).

[31] Further barriers to grid upgrades – partly addressed by recent developments related with strategic projects, in particular in the context of the Net Zero Industry Act, in particular the designation of strategic projects and related administrative simplifications – can be associated with the duration of permitting processes.

In cases paired with major reliance of hydrogen production in emerging economies, social acceptance risks pertain to regional and sustainable development and interregional justice, including critiques – already emerged in the case of the Desertec initiative – of divergent perceptions in the context of North-South global relations, including neo-colonialism, despite an original stated vision intending to overcome the North–South division in the Mediterranean area (Schmitt, 2018).

4.7.5. Research and innovation actions

4.7.5.1. Basic research

Technologies for the production of low-emission hydrogen are well developed: electrolysers are commercially available, but innovation can offer relevant contributions to decreasing equipment costs (IEA, 2023f). Basic R&I can support cost reduction in electrolytic hydrogen production through material substitutions in electrolysers and fuel cells, minimising reliance on precious metals (ITIF, 2024b). Material research can also address metal embrittlement challenges paired with hydrogen handling.

Basic R&I is also key to achieve cost reductions and crucial technological developments for technologies that are key enablers for carbon-bearing hydrogen-based fuels, including those needed for direct air capture of CO_2, electrochemical CO_2 reduction and highly integrated fuel synthesis processes, enabling high rates of heat recovery to optimise the overall efficiency of fuel production.

Other types of basic R&I relevant for an acceleration of hydrogen towards competitive performances and costs through enhanced assessments of system-wide opportunities where hydrogen can make a difference, taking a realistic approach that integrates honest assessments of transport, storage and distribution costs (not just production), challenges related with the achievement of economies of scale (unlikely to materialise for cases where hydrogen-based options are the second or third best, if not worse), and the existence of economic incentives from extended life of existing, carbon-intensive assets as instruments that can leverage initial demand growth.

4.7.5.2. Applied research

Research funding can help foster reductions in the cost of electrolytic hydrogen, alongside deployment scale up, while supporting competitiveness based on quality and energy efficiency and lower operational costs. Key areas deserving applied R&I actions include improving electrolyser efficiency for hydrogen production reliant on renewables and/or nuclear electricity as primary energy and fostering modularity in electrolyser and fuel cell stacks to enable cost reductions (ITIF, 2024b). Reducing critical material loads is also an area with relevance for applied R&I activities capable of fostering cost reductions for electrolytic hydrogen production (IEA, 2023f).

Applied R&I can also include activities on CO_2 capture and storage technologies, as well as methane pyrolysis and solutions for an effective use of carbon black in non-combustion application for pathways based on methane (ITIF, 2024b). However, these activities are far more relevant in global areas with abundant access to low-cost natural gas, likely excluding the EU. Applied R&I activities relevant for fossil-based hydrogen options could focus on the achievement of very high CO_2 capture rates for the production of low-emission hydrogen from natural gas. Key R&I activities are ongoing in this area, with autothermal reforming technologies being demonstrated at commercial scale (IEA, 2023f). In the EU, the cases (likely limited) where extended reliance on fossil resources can deliver greater benefits than a shift in primary energy supply are those with a more relevant case for public R&I support. Especially in a context of high gas supply costs for the EU (paired with high profit margins for fossil fuel companies), it will be important for R&I funds in this field to leverage private investments, rather than be largely based on public spending.

Other priorities for applied R&I activities relate with transportation, storage and distribution. While most technologies for hydrogen transport and storage are mature (IEA, 2023f), innovation and demonstration efforts can help prepare the sector for a possible scale-up. Specific examples include work on underground storage sites for long duration energy storage, technologies helping to understand and bridge challenges related with a transition from methane and for the development at scale of dedicated pipelines, as they remain the cheapest option currently available for this purpose, despite limitations and hardly any use today (ITIF, 2024b). System-wide research can also focus on integrations that deliver energy efficiency, cost saving and emission reductions for industrial clusters already using hydrogen and having the possibility to scale up towards the concept of "hydrogen valleys".

In the transport sector, applied R&I activities can also support the possibility to use hydrogen as an energy carrier in short-range aviation, where hydrogen competes with sustainable aviation fuels – for which it can also be a feedstock – and battery-based electrification technologies, even if prospective analyses do not foresee large-scale adoption for more than a decade (ITF, 2021c; ICF, 2021; ICAO, 2022) and hydrogen delivery infrastructure for airports would be extraordinarily expensive (ITIF, 2024).

R&I is also needed to foster the energy efficient use of hydrogen derivatives like synthetic hydrocarbons and ammonia in aviation and long-distance shipping, as this is a transport option that could face significant price increases (if not availability constraints) of alternative, sustainably produced low-carbon fuel supplies (Malins, 2023; ITF, 2021c; ITF, 2020a).

Challenges in scaling up for sustainably sourced biogenic resources suggest to prioritise available biogenic carbon for fuels, rather than releasing emissions of CO_2 of biogenic origin. Unless sustainable biomass availability challenges are effectively addressed, and, despite possibilities, on paper, to be paired with negative emissions, R&I activities related with biomass as a hydrogen feedstock are unlikely to be a priority (ITIF, 2024b).

Applied R&I activities are also relevant to support the development of technical standards regarding environmental performances, safety and emergency responses for hydrogen and its derivatives.[32] Safety and emergency responses are particularly important for the use of ammonia as a fuel, given its toxicity and spill behaviour challenges (ORNL, 2021).

4.7.7.3. Deployment

R&I activities related with hydrogen should support a phase-in of low-carbon hydrogen, starting from and focusing on energy end-uses that cannot be decarbonised cost-effectively through direct electrification, especially if biomass-based alternatives are constrained in terms of availability. Due to competitiveness risks, R&I shall also consider best policy approaches capable to manage deindustrialisation challenges.

Deployment-oriented R&I can also support further assessments on the role of hydrogen (and possibly also its carbon-bearing derivatives) in heavy-duty, long-distance road transport, as a possible complement for direct electrification, even if there is solid evidence that the latter

[32] These are especially relevant in cases where they can offer opportunities for more cost-effective options than electrification. Key examples include ammonia and methanol in shipping or synthetic jet fuel in aviation.

is likely to be the major focus of the technology transition in this sector, starting from urban/regional deliveries (BMDV, 2020; ITF 2022b) and including longer distances (ITF, 2022b). Due to remaining challenges regarding the best approach, R&I funding for targeted research could prove particularly beneficial for the emergence of effective strategies for high-power, heavy-duty vehicle charging and refuelling infrastructure.[33]

On the infrastructure side, a hydrogen transport and distribution network needs careful consideration, due to important risks (and therefore barriers) in the repurposing natural gas infrastructure (ACER, 2021), path dependency for hydrogen transport and distribution infrastructure developments, paired with legitimate reasons for uncertainties in expected demand and transport volumes.[34] The development of such a network – anyway expected to be significantly smaller than the existing natural gas network, even according to its key proponents (EHB, 2022; ACER, n.d.) – could benefit significantly from R&I activities for demonstration projects around industrial "hydrogen valleys" or clusters, as these would offer important learning opportunities to inform the following steps (including, eventually, decisions to not pursue further with the use of hydrogen as an energy carrier, in applications where this is technically too costly and not competitive with alternative decarbonisation pathways).

Social science-based analyses are additionally needed regarding the security and justice implications of scaled up and diffused hydrogen developments, including also the development of new governance tools to overcome related injustices.

4.8. Social innovations

Social innovations and their role in sustainable energy and mobility transitions have gained increasing interest in the last few years (Wittmayer et al. 2024). This interest has been based on an understanding that technological development on its own may not be enough to solve the challenge of decarbonisation, due, for example, to rigid institutional structures preventing the diffusion of technological innovations, increasing demand for resources and materials, as well as potential pushback from people against rapid technological change. The need for social innovations is also indicated in the literature on degrowth and sufficiency (see Chapter 2, 2.4. Social acceptance and justice challenge). Hence, social innovations offer potential to address institutional and user-based barriers for sustainable energy and mobility transitions. They also hold the promise of enabling deeper and more radical kinds of transformation, including different ways of living. Some concrete examples are the following:

- Community energy initiatives, which are decentralised small-scale forms of energy production (often solar-PV or wind turbines) with a high degree of community ownership and control (Hewitt et al., 2019; Delina, 2020);

[33] One promising possibility is the phased approach taken in the United States with the National Zero-Emission Freight Corridor Strategy for truck charging (DOE/DOT, 2024), as this is well suited to align public policy and investments in a way that is economically sustainable and therefore effective to foster synergies between public and private funding. An initial low regret solution could also be the strengthening of the high-voltage network in proximity of the main motorways, as many of the solutions being considered for heavy-duty energy needs (high power chargers, electric road systems, battery swapping and renewable hydrogen) would need it. Starting from a reinforcement of the network can help take final investment decision on the devices that would need to use it at a later stage, when technology developments allow for better visibility on the most appropriate option, while still ensuring that progress can be made for the deployment of key prerequisites.

[34] Due to competition with other decarbonisation technologies, based on direct electrifications, CCS and sustainably produced fuels of biogenic origin.

- Transition Towns, which are community projects that seek to reduce their dependence on fossil fuels by stimulating renewable energy production and lifestyle changes that reduce energy use (Connors and McDonald, 2011; Aiken, 2012);

- Energy cafes, which aim to provide information and advice to local citizens about energy bills, energy efficiency, renewable energy, and behaviour change. They tend to be run by volunteers (but often with grant money support) in a 'pop-up shop' format, which aims to lower the entry threshold (Martiskainen et al., 2018);

- Car-sharing, which started as a citizen initiative, with friends borrowing each other's cars. In the mid-1980s, organised car-sharing emerged in the form of cooperatives or clubs (which enabled sharing with relative strangers). Some cooperatives wanted to maintain the value-based sharing ethos, while others developed commercial for-profit business models that subsequently diffused widely in many countries (Truffer, 2003); and

- Mobility-as-a-service, which aims to reduce car dependency and individual car ownership while also improving the service offered by public transport by offering a more encompassing range of services than public transport systems alone (see also Innovation Pathway 9 [4.9.]).

Besides alternative ways of living, social innovations can be associated with policy and institutional innovations that aim to remove fundamental path-dependencies in institutional systems that act as barriers to energy and mobility transitions. Social innovations can essentially be characterised as novel social practices, social relations, and governing mechanisms that change the operation of energy and mobility systems, their governance and the thinking of actors (Sovacool et al. 2023).

4.8.1. Relevance for accelerating low-carbon transitions

In the energy and mobility contexts, social innovations have been used to refer to innovations contributing to emission reductions via non-technical forms of change, including conceptual innovations, process innovations, or organisational innovations, which ultimately aim to improve the welfare and wellbeing of individuals and communities (OECD, 2015) by tackling environmental and social sustainability problems (in particular high energy or mobility demand induced problems). Examples of social innovations include civic empowerment (e.g. citizens as active energy consumers and policy target groups), new forms of governance (e.g. more networked and inclusive forms of citizen participation), social configurations (e.g. energy communities) and the adoption of service-oriented business models (e.g. those aimed at energy demand reduction or mobility-as-a-service) (e.g. Dall-Orsoletta et al. 2022).

Social innovations are often linked to different visions and pathways for low-carbon transitions, which tend to be more radical than business-driven greening efforts, for example questioning conventional consumerism and advocating change in user practices and lifestyles (e.g. more cycling and public transport, reducing energy demand through frugality or sufficiency). They also tend to be more oriented towards local communities, social justice or alternative economic rationales, such as community ownership, shortening of supply chains, self-sufficiency and degrowth (Pel et al., 2020).

If social innovations would scale-up and diffuse widely, they could significantly reduce energy demand and greenhouse gas emissions. Social innovations can also enable the reduction of barriers for technological innovations (covered in Innovation Pathways 1-7) and thus accelerate low-carbon developments.

The problem is that there is not yet much empirical evidence that this is happening at scale. While there was a groundswell of activity in the late 2000s and early 2010s (mostly in European countries), social innovations like community energy appear to be struggling to diffuse more widely in countries like Germany, Austria, Denmark, and the United Kingdom (Wierling et al., 2018), Portugal, Spain, and Italy (Delicado et al., 2023) or Sweden (Warlenius and Nettelbladt, 2023).

The future role of social innovations in achieving rapid and large-scale emission reduction is therefore uncertain. Research is now focusing on other forms of expansion and diffusion such as replication of social innovations in other localities and the circulation of people and experiences between local projects (Moore et al., 2015). Research has also started to focus on the problems and barriers that prevent social innovations from diffusing more widely, including:

- The reliance on voluntary efforts and occasional grants, which makes them difficult to sustain over time and vulnerable to the departure of key people (Hossain, 2016);
- Mismatches with institutional and funding contexts, which are mostly geared towards firms and market-based innovations. Banks and other commercial investors also tend to be reluctant to lend money because grassroots and social innovation projects may be too small or lack viable business plans or commercial ambitions (Hossain, 2018). Activists may also lack the skills to write project proposals, report on progress, and provide financial accountability;
- The variability and context-specificity of social projects may also complicate the articulation of 'best practice' lessons that can be shared more widely;
- Social innovators may also not be interested in scaling-up and diffusion because they are committed to radical values such as 'small is beautiful' or degrowth (Seyfang et al., 2014); and
- The radical values and ideological commitments may not resonate with the wider population and cause social acceptance problems (Steward, 2018).

4.8.2. Competitiveness, supply chain and deindustrialisation

Some forms of social innovation can be commercialised, such as new types of business models (e.g. car-sharing and bike-sharing). But many forms of social innovation – community energy initiatives (or energy communities), energy poverty schemes (e.g. energy cafes for sharing information), social governance innovations – do not necessarily comply with a standard approach to competitiveness, supply chains and deindustrialization. Because many social innovations, e.g. service-oriented business models, are based on services rather than a large consumption of material resources or technologies, they are also less dependent on supply chain questions. Selected social innovations, such as those that connect to the pursuit of degrowth or sufficiency, try to escape from a focus on competitiveness and thus misalign with mainstream political debates.

Nevertheless, social innovations can play important roles in the diffusion and deployment of technical energy innovations. For instance, one-stop shop business models (Brown, 2018) or energy cafes (Martiskainen et al., 2018) provide information about a range of energy efficiency and renewable energy technologies that households and other customers can adopt. In particular, the wider uptake of energy service business models can enable the broader diffusion of technologies, alongside the emergence of new industries - while their uptake has been rather low on the residential sector but more used in industrial context (Lazarevic et al., 2019). Renewable energy communities can also contribute to increased renewable electricity supplies, with net benefits for an acceleration of overall electricity end-use price reductions (occurring more frequently with high renewable electricity generation shares).

4.8.3. Security

Social innovations potentially have many security advantages via improved energy efficiency or sufficiency, lowered energy and mobility demand and reduced energy and transport poverty. A key example in this context is offered by the concept of energy sobriety, which consist of organised and deliberate choices to avoid unnecessary energy demand, especially at peak times, to enable collective benefits, especially relevant in cases of urgent responses to crises, but also helpful to ease the transition away from fossil fuel dependence (Borne, 2022).

As they are often related to energy consumption rather than energy production, security advances enabled by social innovations are less dependent on international supply chains of critical materials - albeit building energy efficiency improvements often also have material requirements. Despite these potential benefits, political attention to energy demand reduction and associated social innovations has been relatively low in the EU even after the energy crisis of 2022.

Typically, the role of energy or mobility demand reduction has been ignored or given less value in discussions about energy or fuel security, although demand reductions can be vitally important in reducing demand peaks that cause the largest problems for security of supply.

4.8.4. Societal acceptance and justice

Many social innovations are initiated at the local level by citizens, activists or civil society actors, or otherwise address societal problems (e.g. energy poverty). The impacts of social innovations are also more local via improved local energy resilience or energy service provision, improving local-level energy justice. Social innovations may also improve justice by reducing the need for materials obtained from extractive industries - the impacts of which have created injustice effects, for example, in the Global South or among indigenous communities across the world. The embeddedness of social innovations in local communities may thus improve the societal acceptance of social innovations - albeit would not address more global questions of justice.

On the other hand, the radicality of (some) social innovations, especially those supportive of degrowth or sufficiency agendas, may not appeal to wider populations, causing social acceptance problems. This problem may be accentuated to the limited diversity in the membership of community initiatives. People involved in transition towns, for example, were found to be mostly white, middle-class, highly educated, and deeply concerned about environmental problems (Smith, 2012), which is only a small segment of the wider population.

In the case of degrowth, which is far less likely to have positive spillovers in terms of energy affordability and better access to mobility, social acceptance challenges also relate to macroeconomic and security-related implications, as a net reduction in the consumption of goods can reduce (especially if not compensated by a growth in services) the fiscal space that is necessary to enable different forms of social protection.

4.8.5. Research and innovation actions

4.8.5.1. Basic research

Because social innovation is still mostly in the emergence phase, more basic research is required to better understand the phenomenon (by distinguishing relevant dimensions and better defining it) and investigate a range of relevant issues such as: the dynamics of social innovation (in terms of phases, core processes, actor roles), the drivers and conditions of scaling and diffusion, differences and similarities with regard to technical innovation, and co-evolving interactions between technical and social innovations. The latter would require integrated funding calls where social and technological innovation are investigated on an equal footing, e.g. funding both service-oriented business model development and technological development or citizen engagement intertwined with the development of new technologies – supporting their integration in the future advancement of energy and mobility systems. The effects of digitalisation are also a basic research topic, because digital technologies and platforms can act both as enablers of social innovation but also as potential excluders of some actors. For instance, those elderly people that do not use digital interfaces and applications need different solutions for accessible energy and mobility services.

Basic research should also further investigate potential tensions and conflicts between accelerating low-carbon transitions (e.g. large-scale solar and wind parks), on the one hand, and social innovations and justice, on the other hand (Newell et al., 2021). Basic research could also investigate if or how social innovations can improve competitiveness in the EU, for instance by developing a social economy that uses (and imports) fewer resources but generates wealth through new product-service systems and new business models. More basic research is also needed to understand how social innovations can play a role in creating more societal resilience against crises (such climate impacts, pandemics, geopolitical conflicts, or energy crises) and developing alternative practices for disruptive situations.

4.8.5.2. Applied research

Applied research and innovation could focus on empirical issues such as assessing the effects and potential of social innovations in energy and mobility on large-scale emission reduction. Such research should also investigate how this potential can best be realised. Applied research on policy mixes could also provide more instrumental insights into what (combinations of) policy instruments work best in stimulating social innovation in different phases. Applied research could also stimulate more empirical research on specific social innovations such as community energy, car and bike sharing, and mobility-as-a-service to better understand their emergence and barriers to wider diffusion.

4.8.5.3. Deployment

Driving further deployment of social innovations should address the barriers to diffusion, which may require changes in policy support schemes and funding models (e.g. simpler and better tailored to the needs and capabilities of social innovators). Research should therefore also examine social innovation in relation to institutional innovation and issues of power and politics.

The wider social acceptance of radical social innovations is also an important topic, which may contribute to further polarisation since calls for demand reduction, de-growth, and sufficiency clash with dominant consumption practices and policy paradigms.

4.9. Mobility-as-a-service (MaaS)

Mobility-as-a-Service (MaaS) is a social innovation, technical innovation, and business model innovation, based on the concept of a single, digital customer interface to source and manage travel-related services. MaaS broadens applications that were first developed in the United States, leveraging global positioning systems to allow passengers to hail rides and drivers to charge fares and get paid. It does so by allowing the integration of public transport modes and of commercial transport services, such as ride sourcing, bike- and car-sharing and taxis, into a comprehensive, digitally-enabled, mobility offer.

4.9.1. Relevance for accelerating low-carbon transitions

MaaS is often discussed as part of the umbrella of sustainable mobility services as an enabler of lower greenhouse gas emissions thanks to the improved value proposition (which may be converted in greater adoption, reversing trends that saw public transport shares shrinking with the growth of motorisation) for integrated mobility options, including public transport and shared new mobility services (such as micromobility or ride sourcing).

Whether these emission reductions are effectively delivered depends on the effective capacity of MaaS to enable a lower use of privately-owned personal combustion engine vehicles or the individual use of ride hailing services (as these are paired with even higher emission per kilometre than private cars).

However, the impacts of traffic flows and GHG emission and energy savings from car-based ride sourcing (which is part of the MaaS offer) risk to be detrimental, rather than paired with improvements. MaaS needs to effectively foster sharing and more frequent use of vehicles with high utilisation rates to be aligned with sustainable development (ITF, 2020b). If the lower total cost of ownership of electric vehicles does not face barriers to their adoption, MaaS can also be an enabler of higher demand for electric vehicles. Unless MaaS becomes a more explicit part of integrated solutions for mobility system transitions, its effect on emission reduction risks to be structurally limited. Similar to the case of connected and autonomous vehicles, an effective broad sustainable mobility strategy is important to manage the potential undesirable effects of MaaS (ITF, 2021e).

The current scale of application of MaaS solutions is also still rather small, in part because shared mobility services experienced a rather substantial hit after the COVID-19 pandemic. This is also shown also by a tendency towards more consolidation in a sector that saw the dynamic development of several start-ups and is now marked by mergers and restructuring (M2050, 2024).

4.9.2. Competitiveness, supply chain and deindustrialisation

Several business models have been created around MaaS, with examples of cross-border expansion. Key organisational models include a commercial integrator setup, reliant on a commercial actor providing the service following bilateral negotiations with mobility service providers; a framework where a public transport operator or the public transport authority has taken the integrator role; and cases where public authorities provide the shared integration platform that all private MaaS providers may use for their digitally-enabled services (ITF, 2021e). All approaches intend to leverage opportunities from asset sharing to offer access to mobility at competitive rates, taking a total cost of ownership and use perspective, especially in comparison with the traditional model enabled by personal vehicle ownership.

The idea is grounded on the capacity of digitally-enabled MaaS platforms to enhance rate of use of public transport infrastructure, enabling better utilisation of transport systems overall, thanks to digital technologies, ultimately leading to net savings with respect to a counterfactual without it.

Notwithstanding remaining questions on who extracts the commercial value from this system optimisation (and which part ends up in net savings for users) - also relevant for other global markets (including the United States and China), the solidity of this rationale enabled MaaS could be moving past the idea of a "leap of faith" for its key stakeholders, including users, operators and public authorities (ITF, 2021e). By now, MaaS includes several pilot programmes, complementing other approaches also for the availability of seamless, digitally-enabled ticketing. This includes examples not only in EU cities (European Commission, 2022), but also in other global locations, including 41 cities in China (Chen et al., 2023).[35] Challenges still exist, as shown by the recent stop in operation of an iconic privately-owned MaaS platform allowing users to book public transport, shared mobility such as e-scooters and e-bikes, taxis and rental cars all in one platform (Musa, 2024).

While internationally scalable models are possible, especially with regulated data infrastructure models, due to the independence of the platforms from specific local public entities, supply chains for MaaS tend to be local rather than international, as the provider of transport services integrated in MaaS platforms need to operate locally. MaaS integrators dealing with the technical coordination of services, however, can be located in different parts of the world - not requiring local presence.

As they are largely reliant on existing infrastructure and as they aim to enhance their efficiency, MaaS services can be part of a set of solutions that reduces risks of early stranding of existing assets (and related deindustrialisation). For the same reason, MaaS is also less vulnerable to supply chain disruptions, beyond the shortages of technologies or components that face electric vehicles more generally.

4.9.3. Security

The strategic importance of transport for the economy and national security makes the sector a target of cyber-attacks. Evidence suggests that transport organisations are more vulnerable to cyber-security threats as attacks on databases and IT systems increase (ITF, 2023b).

MaaS increases reliance on digital infrastructure, as it is based on well-functioning and seamless internet systems, which means that cyberattacks or malfunction is a security risk.

Part of the security challenges faced by MaaS also relate with data governance, as MaaS concerns the sharing of potentially sensitive commercial data among stakeholders, including both private entities and public authorities, raising privacy concerns (ITF, 2021e).[36]

[35] A case in Beijing also integrated the possibility to connect MaaS with the carbon market (Song and Zhong, 2023).

[36] The same concerns are also the basis of fears among market actors and public authorities that the MaaS providers become "gatekeepers" of the relationship between transport service providers and other parties, including users and public authorities, potentially exposing stakeholders to risks of reputational damage and related financial losses (ITF, 2023b) and meaning that it is crucial that all actors trust the data-sharing architecture (ITF, 2021f).

4.9.4. Societal acceptance and justice

MaaS generally does not suffer from major social acceptance problems, as its visible effects on the surrounding society is limited to car-sharing schemes' parking scape use (which has raised some opposition). Existing acceptability challenges are mainly associated with the fact that MaaS represents a break with past aspirations for individual mobility in many global contexts (ITF, 2021f).

Some acceptability challenges are specifically related with new mobility modes that have been enabled by MaaS, such as shared electric scooters and/or bikes/e-bikes. Part of the reason stems from delays in the development of a regulatory framework for novel transport modes (e-scooters in particular). These include early deployment choices – fuelled by venture capital – based on "wild west", unregulated deployment strategies, mainly aimed at quick market share gains, paired hardware models designed for retail, lacking the durability necessary for a shared service setup, coming into urban areas that lacked capacity to manage and develop infrastructure to control this phenomenon. Even if this is something that, by now, has changed, it resulted in public opposition, as clearly documented by the choice of specific municipalities, in particular the city of Paris (Euronews, 2023), to actually ban e-scooters.

Social acceptance may also vary depending on whether MaaS is considered a niche product. e.g. aimed at a segment of society or tourists, or as an offer for everyone travelling within a region (ITF, 2021e).

That said, MaaS uptake is still very small and there does not yet appear to be a groundswell of societal enthusiasm that could drive the wider diffusion of MaaS. This is underscored by economic viability problems of some MaaS options and forerunners, offering an integrated solution for planning and booking different modes of transport via a single platform (M2050, 2024).

The operation of MaaS is not only dependent on the agreement between the aggregating digital platform and mobility service providers, but also (and above all, taking a demand perspective) by the existence of a large enough group of people or households to subscribe to the service. Therefore, acceptance to subscribe is important. Acceptance is higher in people with lifestyles that have previously included no car ownership and multi-modal transport, while car owners are harder to attract (Kim and Rasouli 2022).

Organisational models and data governance approaches can also have impacts on the acceptability of MaaS, with data sharing frameworks and payment interfaces as open as possible and as constrained as necessary likely better suited to enable MaaS to deliver social, welfare-enhancing outcomes (ITF, 2021e; Schneider and Koska, 2023; ITF, 2023b).

4.9.5. Research and innovation actions

Overall, opportunities and challenges paired with MaaS call for a reflection on business models and deployment strategies, accounting for collaboration between the various players (public, private, start-ups, major groups) and adaptation to the real needs of citizens (M2050, 2024).

4.9.5.1. Basic research

Basic R&I activities should focus on fostering progress for key enablers not only of MaaS but also of a variety of other digitally-enabled services. Key examples include all fundamental elements underpinning digital technologies, including global positioning and communication devices.

Basic R&I can also focus on the role, applicability and potential of MaaS solutions as part of broader transport and mobility system transitions, which look at the reconfiguration of mobility in a way that tackles multiple policy challenges (emissions and resource use, competitiveness, and fair mobility of people). For instance, what does a future European transport system look like and what role does MaaS play and how could MaaS be scaled up to benefit transport demand reduction and the acceleration of the electrification of transport.

MaaS can also benefit significantly from progress enabled by basic R&I activities regarding the broader set of data exchanges characterising the digital transformation and/or the legal basis for the sharing (and reporting) of data while respecting personal privacy and proprietary data rights, in the broader context of digital and communication technologies. Other examples of R&I activities that are broader than just MaaS include those focused on minimal but sufficient capabilities needed to achieve interoperability of data, systems, and services between buyers, suppliers and regulators across different governance levels.

Basic R&I work that would improve understanding of the dynamics of mobility choices, including reasons why a mobility-oriented perspective has prevailed so far, could be beneficial for future developments of MaaS. This could focus on the relevant actors, institutional arrangements and power dynamics that underpin the developments leading to the current characterisation of urban, sub-urban and rural transport systems and how they could evolve. Other key areas of R&I include the dynamics of transport integration through mobility hubs, supporting trip planners and integrated ticketing as the glue between different modes that ensures uninterrupted and convenient travel chains (ITF, 2021h).

4.9.5.2. Applied research

Applied R&I should address the governance and organisational barriers to the diffusion of MaaS solutions, given past experiences of resistance to MaaS from traditional transport system actors

Applied R&I topics also include impacts of MaaS on accessibility and travel choices for users, optimal MaaS regulation approaches (also with respect to different organisational models and the relevance of possible options across different EU urban areas), and the impact of MaaS on public authorities' existing functions and policy levers (ITF, 2021e).

Applied R&I can also cover data governance in a way that has greater sector-specific relevance, leveraging on broader developments from basic R&I activities, also covering other sectors. This concerns the sharing of potentially sensitive commercial data among operators and with MaaS providers, privacy considerations and the sharing of customer data and the reporting of data to public authorities (ITF, 2021e). Specific R&I programmes in this area can include the development of open access technical standards, as key facilitators of opportunities to deliver social, welfare-enhancing outcomes.

Digital integration is not only relevant in cities, but it can also help better link local rural services and the core network (ITF, 2021g). Rural MaaS is an area that can significantly benefit from R&I activities, leading to net improvements in the way public transport services can be offered in low density areas, with potential for energy and cost savings, as well as emission reduction (although probably at limited scale) through the encouragement of users to become prosumers (“producing customers”), in order to help increase the supply of transport options and integrating them with the core transport network. Priorities include the assessment of local services that can be combined with shared mobility to achieve a sustainable business model (ITF, 2021g).

4.9.5.3. Deployment

R&I activities geared towards commercialisation and deployment need to address remaining challenges faced by specific business models. This includes (but is not limited to) improved understanding of the needs for financial support and subsidies and making shared mobility modes part of long-term planning tools and exercises (OECD, 2021).

Other deployment-oriented seek R&I activities can focus on the way MaaS platforms could be (at least in part) supported by schemes that subsidise public transport. This matters the most for the public MaaS and regulated data infrastructure models, as they both draw on public funds (ITF, 2021e).

5. Conclusions on R&I priorities and wider policy recommendations

5.1. Conclusions on R&I priorities

We draw the following conclusions and specific recommendations on R&I priorities with regard to the nine pathways that can help achieve the vision for future energy and mobility systems, discussed in Chapter 4.

5.1.1. First pathway: Digital technologies and system integration

The first pathway, digital technologies and system integration use sensors, dataflows, autonomous data-processing, machine-learning and AI to improve interactions between modular innovations in energy and mobility systems, leading to enhanced efficiency or more decentralised systems. Digital technologies, which can also enable integration across energy carriers (e.g. electricity, hydrogen, heat), infrastructures, and end-user sectors (industry, buildings, mobility), have significant potential to accelerate low-carbon transitions, but their deployment and diffusion is still in early stages. Although Europe is lagging the United States and China in digital hardware and software, the competitive race for the use of digital platforms in energy and mobility systems is still open, offering economic opportunities for European firms. Increased use of digital platforms in energy and mobility systems enhances security risks of and vulnerabilities to cyber-attacks, which could have significant social and economic consequences. Social acceptance problems are still relatively limited but could increase if digital technology applications increase inequalities (between income groups or urban and rural areas) or create data security problems (e.g. inadvertently sharing private or confidential data).

In light of these challenges, research and innovation actions should have the following priori focus. Basic research should focus on: (a) improved cybersecurity and data privacy; (b) technical and social dimensions of the ‘machine-to-machine economy’ (where autonomous devices interact and exchange data without human intervention); and (c) positive and negative sustainability effects on energy and mobility systems (and how to shape these). Applied research and innovation should focus on specific uses of digital technologies in urban transport, car-sharing, public transport (e.g. inter-modality), freight transport (e.g. logistics, vehicle connectivity), automated vehicles, mobility services, electric vehicle charging, vehicle-to-grid systems, smart grids, smart meters, demand-side management, road pricing, and grid pricing. Deployment actions should focus on the use of digital technologies to further drive the transitions towards distributed energy resource management systems, DERMS (based on integrating solar panels, wind turbines, battery storage, and electric vehicles), towards sustainable connected, autonomous, shared, and electric (CASE) vehicles, and new mobility services, including car-sharing.

5.1.2. Second pathway: infrastructural innovations

The second pathway, infrastructural innovations, considers developments that are crucial to adapt the European asset base to changes induced by the technology developments and the transformations in productive activities and behaviours that accompany a low-carbon, secure, economically competitive, just and socially acceptable transition. Key advances include the adaptation of industrial capacity to technology shifts, to accommodate increased electricity demand and supply variability (with renewables), to enhance electricity grids (including but not limited to interconnectors) and to enable use of low-carbon hydrogen in energy intensive industries. For mobility, they include street redesign and road space reallocation towards more sustainable and affordable transport modes. Security-related developments need to ensure resilience in case of conflicts, address climate-related hazards and enable its preparedness with respect to cyberattacks.

Basic research and innovation actions for infrastructural innovations should focus on the assessment of economic costs and benefits related with infrastructure deployment. They should support a better understanding of responses to investment choices regarding the use of hydrogen as a tradable energy carrier and strengthen foresight exercises. Applied R&I can be instrumental to address administrative and cost-related barriers for the deployment at scale of key energy infrastructures, such as HVDC interconnectors or high-capacity charging for heavy duty road vehicles. They can support the identification of best practices to simplify permitting while maintaining environmental, safety requirements and secure societal support for their construction. Applied R&I can support improvements in the use of existing infrastructural capacity (including via enhanced flexibility, e.g. for electricity grids). Planning can also have specific relevance for the intersection between energy and mobility, including for supply chain analyses. Remuneration and pricing structures for different types of infrastructure services, during and after the transition required to meet carbon neutrality objectives, are also relevance applied R&I priorities. Deployment R&I actions can improve the efficacy of stakeholder engagement, improve coordination across stakeholders and include project-specific tasks, with the aim to streamline implementation and installation.

5.1.3. Third pathway: decarbonising electricity production with solar PV and wind

The third pathway, decarbonising electricity production with solar-PV and wind, refers to technologies that are widely regarded as a key pillar of low-cost, low-carbon energy systems. These technologies also come with a key energy security advantage, offered by the quasi-universal availability of solar resources and by a widespread potential availability for wind energy – but with other security challenges to be resolved, e.g. access to critical raw materials and, in the case of wind, improved institutional and technical solutions to the interactions between wind turbines and defence air surveillance. Solar PV manufacturing is strongly characterised by a competitive advantage acquired by China, while the EU leadership in wind turbine manufacturing is eroding. While the possibility to deploy low-carbon energy production capacity at lower cost is key to support a competitive system in a net-zero transition, over-dependency on Chinese supplies of these technologies exposes risks of weaker resilience, industrial capacity losses and/or missed growth opportunities.

Opportunities and challenges linked with solar PV and wind also come from strong differences in energy production costs between areas with high endowment and low endowment in solar and wind resources, as this has direct implications for industrial and economic competitiveness. In terms of social acceptance, solar PV and wind energy tend to enjoy a favourable perception, but they also face greater challenges where climate and energy diversification advantages are not paired with industrial development. Additionally, social acceptance risks may increase when benefits are not distributed equitably.

Due to the relevance of these technologies for the acceleration of the EU energy transition, managing challenges and seizing opportunities requires a careful balance between market openness and R&I and industrial development strategies. Basic R&I actions should focus on areas offering opportunities to reverse the existing gap between the EU and its competitors, seeking a competitive advantage with a focus on advanced technologies such as solar cell technologies with high conversion efficiency, new/alternative materials (such as perovskites silicon-based tandems), bifacial cells and modules, panels enabling more material efficiency, advanced fabrication/manufacturing processes and recycling technologies to extract secondary raw materials from end-of-life PV panels. Applied R&I for solar PV can leverage the combination of public and private funding for the creation of new, specialised ecosystems to foster positive dynamics, as these are capable to reduce costs and increase competitiveness, also in the deployment phase. For wind, applied R&I programmes can support the EU industry to leverage its expertise and innovation capacity beyond turbines, for the construction and maintenance of offshore capacity. Applied R&I efforts - also related with batteries, digital technologies and system integration - are also important to address remaining challenges due to supply variability of solar and wind energy, especially for periods of low wind or sun, requiring energy storage, interconnections and readily available power generation capacity (and related primary energy) to ensure system resilience. Other specific applied R&I priorities include the end-of-life management of solar PV and wind electricity generation devices. specific applications of solar PV and wind for mobility and, in the area of defence, technical challenges regarding the interaction of solar PV and wind with air surveillance systems. R&I on governance and enhanced social acceptance is a priority to enable both solar PV and wind electricity to accelerate their commercialisation and increased deployment, alongside the development of policy instruments that enable greater certainty of demand to favour investments in large-scale supplies for highly performing subset of solar PV and wind technologies.

5.1.4. Fourth pathway: low- and medium-temperature heat in buildings and industry

The fourth pathway, low and medium heat in buildings and industry, entails the use of electric heat pumps or boilers for heat below 400 ºC and electric furnaces for heat up to 1,000 ºC. Despite their potential for decarbonisation and efficiency improvements, these technologies are not yet diffusing at a rapid pace (because of high upfront costs, regulatory barriers, skilled labour shortages, supply chain challenges, and inadequate thermal building insulation). Europe still has a sizeable share of global manufacturing capacity in heat pumps (Figure 2) and is global leader in the air-to-water heat pump segment. Nevertheless, China and the US produce more in total because of their lead in other types of heat pumps (Figure 2). Although global competition in heat pump manufacturing is increasing, Europe has good chances to increase its global share (Figure 3). While heat pumps can reduce Europe’s energy security risks (because of reduced fossil fuel imports and low critical raw material needs), they somewhat increase supply risks because European firms import compressors and semiconductors (for control systems) from a handful of countries. Increased heat pump use could increase inequalities because upfront costs may be too high for financially vulnerable groups.

In light of these challenges and the economic opportunities for European firms, research and innovation actions should have the following priority focus. As heat pumps are a well-established technology, there is limited need for basic research, although some research could be done on new refrigerants, heat transfer fluids, and materials that could improve performance and heat recovery. Applied research and innovation should focus on heat pump component optimisation, better integration techniques of heat pumps (with district heating, energy storage, thermal networks), modular heat pump designs (which could enhance scalability and system compatibility), and improved manufacturing techniques (including 3D printing) for heat pump components. Deployment actions should focus on innovative business models and supportive policies that can accelerate heat pump diffusion and adoption (e.g. purchase subsidies for lower income households), training and certification programs for installers, inclusion of heat pumps in broader renovation and building retrofit programs. It is important that R&I also investigates what explains the large differences in heat pump deployment and diffusion in different EU member states, find ways to promote diffusion in areas where it has been slow, and also to support governments in better understanding impacts of increased reliance on reversible systems already installed in homes for air conditioning, also for heating purposes.

5.1.5. Fifth pathway: electric vehicles and electric vehicle batteries

Electric vehicles and batteries are at the core of the fifth pathway, as they offer opportunities for major GHG and pollutant emission savings, energy efficiency improvements and energy diversification. Currently subject to significant growth globally, electric vehicles and batteries could be steered towards being an asset rather than a liability for electricity grids thanks to digital technologies for better system integration. China was particularly successful in developing advanced and highly competitive electric vehicle and battery industries, including the related supply chains, pairing them with major production facilities. As in the case of solar PV, China thus gained a competitive advantage with respect to the EU. Because the automotive sector has traditionally been a stronghold for the European industry (contrary to solar PV manufacturing), ensuring that the future transition towards electric vehicles is also an industrial development opportunity for the EU, and not just for China, is essential for jobs and social stability. This is also important for strategic reasons, due to the relevance of the automotive and battery and industries (alongside semiconductors) not only for civil use, but also for military applications. Similar to solar PV and wind, electric vehicles tend to enjoy favourable public perceptions due to alignment with climate change mitigation and energy diversification goals. However, they are recently becoming more divisive, especially in countries with automotive industry subject to competitiveness pressure. Problems risk to increase if the EU struggles to improve its competitiveness profile and address risks of overdependency. Other challenges that may further exacerbate acceptability issues relate to equity considerations, e.g. due to high purchase prices and an early market deployment strongly focused on premium models. Equity challenges also relate with access to (and pricing) of charging, as challenges to access affordable charging are stronger in communities that do not have access to private parking.

Due to the structural disadvantage accumulated by the EU in terms of competitiveness on batteries, basic R&I action should focus on the acceleration of the readiness of advanced and material-efficient battery technologies (such as bipolar batteries), batteries reliant on advanced chemistries (i.e. advanced and low-cobalt anodes, advanced cathodes solid state, lithium sulphur, or involving sodium, potassium, magnesium and calcium), and on technologies and processes capable of delivering productivity increases in battery manufacturing and in upstream steps of the battery value chain. Basic R&I can also strengthen the emergence of an industrial capacity for the cost effective and environmentally sustainable recovery of valuable minerals and an improved understanding of the barriers faced by EVs, batteries and their supply chains in society. Applied R&I activities should keep supporting the definition of clear pre-requisites for the e-mobility transition, including in technical standards regarding safety, durability and environmental requirements for EVs, batteries and charging infrastructure (also needing action on interoperability). Applied R&I should also support product innovation (e.g. in new mobility and in software-defined vehicles). Battery-related research can foster progress in new pack architectures, support advanced manufacturing processes, recycling and the extraction of secondary raw materials, with positive spillovers for local industrial development and job creation. Deployment R&I actions should also support progress in trucks and related charging technologies. They can help govern the challenges for the stability of governmental revenues of the EV transition. They can also focus on instruments supporting affordable access to electric vehicles and related infrastructures (including the “right to plug”) in communities disproportionately affected by the technology transition.

Regarding electric vehicles and batteries, and similar to solar PV, it is important to underline that enabling an industrial transformation, including a surge in EU-based supply is unlikely to be solely enabled by R&I efforts. Policies accompanying the mobilisation of public R&I investments should support an increase in private investments may need to include a mix of trade tariffs or price undertakings and conditional access to policies supporting electric vehicle demand and supply, reversing the tools deployed over the past decades in China to acquire its current competitive advantage. Securing a resilient and cost-effective market shift can also benefit from the development of joint ventures or technology transfer agreements with companies not headquartered in the EU (but rather in China, Japan or Korea) whose battery manufacturing experience is strong. Increased diversity in value chains (needed for EU-based production, given the current concentration, with most of the processing and manufacturing taking place in China) also requires the declination of the concept of open strategic autonomy in trade policy. Policies promoting responsible material sourcing practices could also be instrumental to steer investments in material sourcing and processing.

5.1.6. Sixth pathway: biofuels

Biofuels, our sixth pathway, are already part of the road transport fuel mix and are likely to play a growing role in long-distance transport, where they are only marginally used today. The capacity of biofuels to abate emissions depends strongly on specific technical pathways and feedstocks. Significant abatement of life-cycle GHG emissions are achievable with feedstock derived from sustainable agriculture, forest management and land restoration practices. Significant risks exist for cases not reliant on low-carbon process energy and sustainable feedstock sourcing practices. Current biofuel production has been driven by policy action and is largely reliant on food and feedstocks. This was capped on the basis of undesired effects on land use change, also undermining GHG emission reductions from a life-cycle perspective. Despite significant policy efforts to scale up advanced biofuels, not based on food/feed, success has been limited. Biofuels offer the opportunity to avoid asset stranding for combustion-based technologies, this is only relevant if these technologies are not outcompeted by electrification and if their deployment is feasible sustainably and at scale. This is not guaranteed, as biofuels have low energy returns on energy invested. They also come with significant land use requirements, competing with agriculture and leading to energy and food security risks, especially in case of conflicts or other external factors constraining land productivity (such as shortages of fertiliser supplies). Social acceptance of biofuels is generally positive but can be negative if unintended consequences are significant.

In light of these opportunities and challenges, basic R&I should support sustainable practices enabling the sustainable provision of biomass resources (also in light of a broader transition towards resource- and energy-efficient practices). Basic R&I can enhance understanding of impacts of economic activities having sizable land use footprint, including land-use competition between energy, food and feed and other biomass-based products, the use non-farmed land the reversal of biodiversity loss. Applied R&I activities should help reduce uncertainties on the sustainability of specific biofuel feedstock and bioenergy conversion pathways. Applied R&I should also foster the utilisation of concentrated streams of CO_2 of biogenic origin with renewable and other low-carbon forms of hydrogen for the production of carbon-bearing e-fuels/RFNBOs. Deployment-oriented R&I should focus on sectors that have a high adoption potential for sustainably produced biofuels with low life-cycle emissions, but are also currently not priority markets. Aviation and shipping are clearly amongst the top priorities.

5.1.7. Seventh pathway: hydrogen and hydrogen derivatives

Hydrogen and its derivatives are the focus of the seventh pathway. Hydrogen production is currently almost entirely reliant on natural gas and paired with high levels of CO_2 emissions. Without a technology switch, hydrogen is not a low-carbon option. Low-carbon hydrogen production is technically feasible and, under specific circumstances, it can offer opportunities for energy diversification. Alternative pathways to produce low-emission hydrogen include electrolysis, if based on low-carbon electricity (either from nuclear or renewables), or CCS, to manage emissions from fossil-based technologies. Low-carbon hydrogen may also be derived from biomass, but this faces constraints related with its sustainable supply at scale. Hydrogen-derivatives (renewable fuels of non-biological origin, RFNBOs) include carbon-bearing fuels (methane, methanol and hydrocarbons) produced combining hydrogen and CO_2 of biogenic origin (e.g. from concentrated sources), ammonia, and other synthetic, carbon-bearing fuels, obtained sourcing carbon from direct air capture of CO_2. Low-carbon hydrogen stands good chances to compete cost effectively with alternative decarbonisation technologies (e.g. based on carbon capture) for the decarbonisation and the reduction of fossil energy demand in hard-to-abate energy end-use sectors such as chemicals and fertilisers and in cases where it is a key processing input (e.g. for low-carbon steelmaking, as a reducing agent). In other end-uses, including buildings and land transport, several assessments point towards far lower energy efficiency than direct electrification for hydrogen, also likely paired with higher costs. In long-distance aviation, hydrogen or its derivatives compete with biofuels. In shipping, specific ammonia production pathways are seen as possible low-carbon alternatives to biofuels. Hydrogen and its derivatives (in particular ammonia) may face social acceptance problems in consumer-facing end-uses because of safety and environmental risks and limited concrete experiences. High electricity needs for electrolytic hydrogen production may also create social acceptance challenges related to visual impacts and nature loss (as already mentioned for solar PV and wind) or - for nuclear electricity - face other social acceptance barriers.

Basic R&I should focus on new materials and chemistry that can reduce the cost of production of hydrogen and its derivatives, including technologies needed for direct air capture of CO_2, electrochemical CO_2 reduction and highly integrated fuel synthesis processes. Basic R&I should also explore and improve system-wide opportunities where hydrogen can make a difference in a resilient manner. Applied R&I should focus on cost reductions in electrolytic hydrogen, while supporting competitiveness based on quality, energy efficiency and lower operational costs. Applied R&I for hydrogen from fossil fuels could also leverage private R&I investments for technologies (e.g. autothermal reforming of natural gas) with very high CO_2 capture rates. Methane pyrolysis also needs R&I, including for an effective use of carbon black in non-combustion applications. Other applied R&I activities should address transportation, storage and distribution challenges. System-wide research should focus on integrations that deliver energy efficiency, cost saving and emission reductions for industrial clusters already using hydrogen (hydrogen valleys). In transport, applied R&I should support the exploration of the use of hydrogen as an energy carrier in short-range aviation, where hydrogen competes with sustainable bio- and synthetic aviation fuels. R&I is also needed to foster the energy efficient use of synthetic hydrocarbons and/or ammonia in aviation and long-distance shipping. Applied R&I is also relevant to further develop technical standards on environmental performances, safety and emergency responses. Deployment-oriented R&I should support a phase-in of low-carbon hydrogen, especially in energy end-uses that cannot be decarbonised cost-effectively through direct electrification and for which the availability of biomass-based alternatives is constrained. Further assessments could offer new insights on the role of hydrogen (and possibly also its carbon-bearing derivatives) in heavy-duty, long-distance road transport, as a complement for direct electrification. On the infrastructure side, the way hydrogen transport and distribution network could develop needs careful consideration, due to important risks (and therefore barriers) in the repurposing of natural gas infrastructure. R&I activities for demonstration projects around industrial hydrogen valleys or clusters could also offer important learning opportunities (including, eventually, decisions to not pursue further with the use of hydrogen as an energy carrier, in applications where this technically too costly and not competitive).

5.1.8. Eighth pathway: social innovations

Social innovations and their role in sustainable energy and mobility transitions have gained increasing interest based on an understanding that technological development on its own is insufficient to solve the challenge of decarbonisation. Social innovations offer potential to address institutional and user-based barriers for sustainable transitions and suggestions for more radical transformation of societies. Many well-documented social innovations, such as community energy initiatives (or energy communities) and car-sharing may have been characterised by slow diffusion to date and/or limited opportunities to upscale. However, social innovation can be associated with novel policy and institutional innovations (e.g. novel forms of citizen participation and more transformative policy mixes) or organisational innovations with potential to make practices around governing energy and mobility systems more sustainable, hence, having important transformative potential for mobility and energy sectors. Some social innovations like degrowth or sufficiency also advance more radical visions of the future, which open up the scope for debate but may not resonate with wider publics or mainstream political debates. Empirical evidence on scalable effects of social innovation is still limited and, hence their role in large-scale emission reduction is uncertain. Some forms of social innovation are not compatible with standard approaches to competitiveness and are critical of it. Yet, social innovations (e.g. one-stop shop business models and energy cafes) may help scale up technological innovations. Social innovations offer security advantages through reduced demand of energy and resources and by being less dependent on international trade and supply chains. As they are often initiated at the local level or by civil society actors, their social acceptance tends to be high although radically different propositions, such as degrowth, may have negative socio-economic implications and meet societal resistance.

Basic R&I is needed to better understand and conceptualise social innovation, its dynamics, conditions of scaling and diffusion and the interactions between technical and social innovations (e.g. service-oriented business models, the ways in which digitalisation connects to social innovation and enables/limits access to it). Further R&I is needed on how social innovations can benefit just transitions and create synergies between environmental sustainability and European competitiveness. Applied R&I is needed to provide more empirical examples of the effects and potential of social innovation for large-scale emission reductions, e.g. by focusing on their direct and indirect cascading effects, and how policy instruments can support social innovation in its different stages. Deployment R&I should focus on examining barriers to diffusion, what policy support is needed, and questions of power and politics associated with social innovation.

5.1.9. Ninth pathway: Mobility as a Service (MaaS)

Mobility-as-a-Service (MaaS) is a social, technical, and business model innovation, based on the concept of a single, digital customer interface to source and manage travel-related services. It aims for the integration of public transport modes with commercial transport services (e.g. ride sourcing, bike- and car-sharing and taxis), into a comprehensive, digitally-enabled, mobility offer. MaaS is discussed among the umbrella of sustainable mobility services as an enabler of lower greenhouse gas emissions thanks to the improved value proposition, but whether these emission reductions are effectively delivered depends on the effective capacity of MaaS to enable a lower use of privately-owned personal combustion engine vehicles or the individual use of ride hailing services. MaaS can also be an enabler of higher demand for electric vehicles. Unless MaaS becomes a more explicit part of integrated solutions for mobility system transitions, its effect on emission reduction risks being structurally limited. Because supply chains tend to be local rather than international, MaaS is less vulnerable to supply chain disruptions, beyond the shortages of technologies or components that face electric vehicles more generally. MaaS increases reliance on digital infrastructure, as it is based on well-functioning and seamless internet systems, which means that cyberattacks or malfunction is a security risk. MaaS generally does not suffer from major social acceptance problems, as its visible effects on the surrounding society is limited to car-sharing schemes' parking scape use (which has raised some opposition). MaaS uptake is still very small, in part because shared mobility services experienced a substantial hit after the COVID-19 pandemic, and there does not yet appear to be a groundswell of societal enthusiasm that could drive the wider diffusion of MaaS.

Basic R&I should focus on fostering progress for key enablers not only of MaaS but also of a variety of other digitally-enabled services. It should also investigate the role, applicability and potential of MaaS solutions as part of broader transport and mobility system transitions, which look at the reconfiguration of mobility in a way that tackles multiple policy challenges (emissions and resource use, competitiveness, and fair mobility of people). For instance, what does a future European transport system look like and what role does MaaS play and how could MaaS be scaled up to benefit transport demand reduction and the acceleration of the electrification of transport, and how MaaS should be regulated in this context. R&I should also look into why many MaaS initiatives have failed, looking at ticketing interfaces, institutional arrangements and power dynamics underpinning the developments. Applied R&I topics include governance and organisational conditions for MaaS diffusion, accessibility and travel choices, data governance, and rural MaaS. For deployment, R&I needs to analyse how to improve conditions for commercialisation, any potential for export, financing, and experiences with different business models.

5.2. Wider policy recommendations

Addressing the four challenges from Chapter 2 -requires wider adjustments in European R&I policy and the institutional landscape besides the changes in R&I priorities discussed in Chapter 4 and summarised above. The wake-up calls from Letta and Draghi, which Chapter 2 reinforced for energy and mobility systems, emphasise the scale and urgency of the current challenges, which, in our view, also require several urgent and significant changes in R&I policy. Key policy changes, which we elaborate on in the sections below, include:

- Increasing public R&I support strategically, with a focus on achieving price/performance parity to leverage the power of markets.

- Finding a new balance between the protection of existing assets and the creation of new assets for environmentally and socially sustainable growth, taking a forward-looking, transformative and systemic approach.

- Aligning basic research for disruptions, applied R&I as a key enabler of change and transformative deployment actions to scale up resilient innovations.

- Aligning R&I actions with other strategic, infrastructure-related choices, correcting market failures, targeting better competitiveness.

- Taking specific R&I actions regarding social innovations with environmental and security benefits and better understanding the dynamics of system transitions.

- Considering institutional changes to leverage large-scale opportunities, including better EU/Member States coordination.

- Fostering the contributions of new stakeholders, moving the attention beyond incumbents, to better leverage the potential of startups.

5.2.1. Increase public R&I support strategically, with a focus on achieving price/performance parity to leverage the power of markets

To accelerate the low-carbon transition, improve competitiveness in the global innovation race, and reduce security risks, Europe should increase R&I funding as a percentage of GDP, which is lagging behind the US and China, both overall (Figure 4) and for clean-tech in energy and mobility (Figure 6). The main challenge is to increase private R&I funding, which is a long-standing European problem that is particularly salient for energy and mobility.

R&I is especially important to accelerate the transition in cases where it can foster technology developments towards price/performance parity. The reason is that price/performance parity is a key mobiliser of market dynamics, necessary to drive the transition at the required scale and speed, and therefore also an enabler of greater private investments in innovation, supplementing public resources.[37]

To that end, policymakers could increase financial incentives for firm-level R&I, e.g. through targeted subsidies or tax incentives. These instruments could be combined with conditionalities on the capacity to achieve price/performance parity of clean and sustainability-aligned technologies. Increased funding on sustainability-aligned R&I would be coherent with the articulated action already undertaken on regulatory requirements aiming to accelerate technology transitions in energy and mobility, complementing other policy tools to help enable implementation actions. Requirements for matching investments by the private sector to access public funding could also complement this funding increase, with a multiplier effect.

R&I policy should also move beyond a 'science push' focus on R&I funding, as the literature on innovation systems (Malerba, 2002, 2004; Hekkert et al., 2007; Bergek et al., 2008) has long shown. Innovation is not only driven by resource inputs such as R&I funds, but also by adoption (through a 'market pull', including the mobilisation of private investments) and a related increase in scale, learning by doing and continuous improvements, also enabled by

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[37] A focus on price and performance parity is not only important to mobilise market dynamics, but also to reduce inflationary pressures, an aspect that is particularly important in the context of the current geopolitical tensions.

increased knowledge flows between relevant actors (e.g. universities, research centres, firms, consultancies), institutions, supported by strengthened networks between relevant actors to stimulate collaboration and knowledge flows (Figure 15).

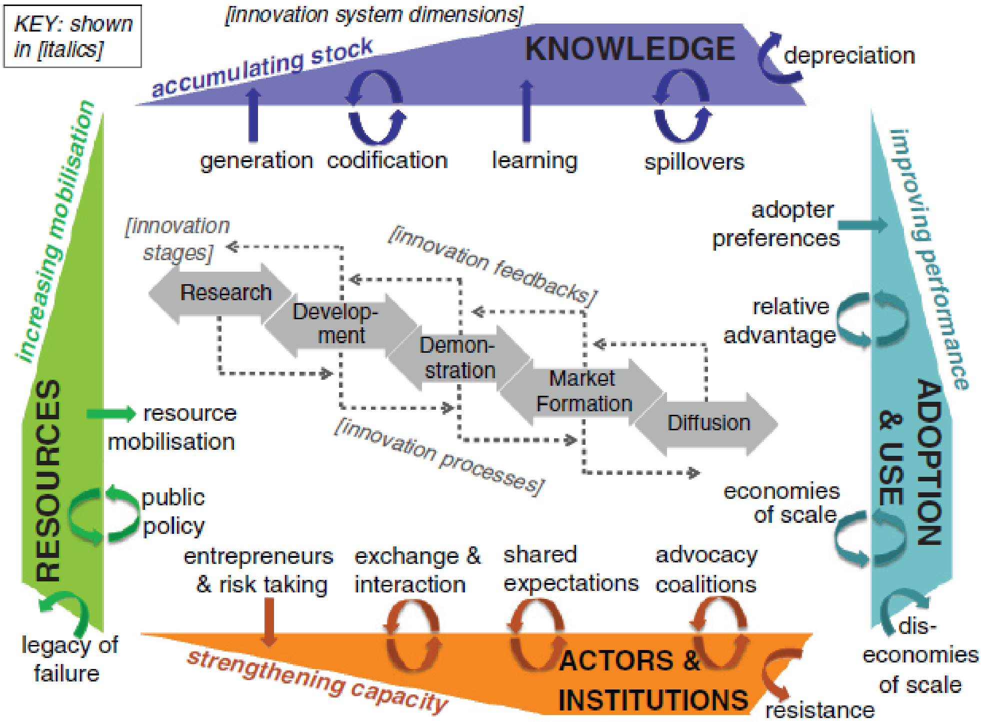

Figure 15. The energy technology innovation system (Wilson and Grubler, 2014: 13).

European R&I policy should therefore combine public spending with a parallel focus on strengthening the power of market dynamics. R&I policy should stimulate a shift and scale up of investments in assets that are necessary for the EU to maintain its competitive edge where that exists (e.g. some of the aspects of system integration) and regain it where it does not.

This cannot happen in isolation, meaning that R&I policy should be aligned with the ambitious regulatory requirements and pricing mechanisms recently introduced. It is beyond any doubt that the EU will continue to benefit from the large-scale deployment of low-carbon electricity supplies and greater reliance on energy end-use electrification (including with EVs and heat pumps). R&I policy should foster a gain in competitiveness for the EU in these strategic growth areas.

Non-discriminatory and objective non-price criteria in technology sourcing practices can help support the EU to mobilise private investment in industrial-scale manufacturing of clean technologies, but they should be aimed at reducing margins for complacency and maintain a competitive environment to avoid ending up supporting the creation of industrial assets that are stranded by design. Achieving this can require the use of sunset clauses for these criteria, as the industrial capacity grows.

Joint procurement of raw materials from stakeholders adopting sustainable mineral sourcing standards and practices can also reinforce the effect of regulations, pricing and incentive mechanisms, supporting the development of the EU net-zero industrial capacity and industrial productivity by enabling access to the materials needed by the manufacturing sector at lower costs.

A genuine buy-in by all Member States in the overall EU policy (as opposed to conditional buy-in to the availability of EU funds, and limited to that) is also crucial to improve the broader enabling environment of innovation systems. Due to scale effects, this can reinforce efforts taken by Member States on their own, enabling mutual benefits (better alignment reduces investment risks for the deployment of clean technology at scale, better leveraging the potential of capital markets and also the power of EU market integration).

Because company R&I also relates to strategic perceptions of risk and future growth markets, policymakers should specifically help shape markets, reduce regulatory burdens (by harmonising rules and regulations between member states), and make Europe more attractive as an investment destination.

R&I efforts also need to strengthen their broader transformative focus in a way that aligns efforts to address the four key challenges: sustainability, competitiveness, security, and social acceptance and justice. A strong focus on driving clean technologies towards price/performance parity is particularly relevant for the competitiveness dimension, whereas security and sustainability require broader systemic approaches seeking improved policy coordination and coherence between R&I and other sectoral policies (e.g. cohesion policy, climate policy, energy policy, transport policy, foreign and security policy).

5.2.2. Find a new balance between the protection of existing assets and the creation of new assets for growth, taking a forward-looking approach

To improve competitiveness and reduce supply chain vulnerabilities, Europe should develop a more strategically targeted R&D funding strategy that finds a new balance between:

1. Supporting new technologies, services and industries where Europe can potentially compete internationally.

2. Supporting innovations that can transform existing assets and industries that are important for European jobs and economic vitality (e.g. automotive industry).

3. Supporting technologies and industries that can mitigate supply chain risks, even if these technologies and industries may struggle to compete internationally.

We particularly stress the importance of the first point and suggest that European R&I policy should develop a more ambitious forward-looking focus on supporting new technologies and new industrial capacity, even if these may be more disruptive for existing systems. In this context, especially technologies and industries that also support improved environmental and social sustainability and societal resilience should be favoured, in line with other EU policy choices.

R&I support should not remain primarily focused on technologies that can enhance existing assets. While this is relevant for competitiveness, it bears the risk to lock the EU industrial base out of new, emerging technologies, with high growth potential, and with detrimental effects for its future economic development. This is especially important right now, in a phase of great power competition globally, and requires swift moves, with no delays.

As discussed in Chapter 4, key examples of technologies having this strong growth potential in the energy and mobility areas, due to scalability and/or stark energy efficiency/decarbonisation advantages, especially in a context of economic circularity, or both, include:

- Applied digital technologies for energy and mobility, including AI (with a need for policy steering for their alignment with sustainability and public purpose).

- Renewable energies like solar PV and wind (already shown to be cost competitive, including storage, despite remaining challenges for long-term storage, narrowed by digital technologies and other solutions, from pumped hydro to demand response).

- Energy demand reduction and very efficient energy end-use devices (starting from heat pumps).

- EVs and other energy storage (e.g. batteries) related business models, despite challenges for the supply of critical minerals, also for geopolitical reasons, with diminishing risks as deployment grows, from economic circularity.

- Integrated EV and Mobility as a Service (MaaS) models.

For sectors in which electrification struggles to achieve price/performance parity and energy efficiency falls short of enabling a net-zero transition, this includes also low-carbon fuels/energy carriers. These comprise biofuels and hydrogen and/or hydrogen derivatives, with the latter mattering the most where they can achieve price/performance parity and in case of constrained sustainable bioenergy supplies, and competing with nature-based and geological options for carbon sequestration, also needed to address residual emissions.

5.2.3. Align basic research for disruptions, applied R&I as a key enabler of change, and deployment actions to scale up resilient innovations

To accelerate low-carbon transitions and to compete in the currently unfolding global innovation race, R&I policy should combine and align basic research, applied R&I and deployment actions to scale up resilient innovations.

The balance of R&I policy should focus relatively more on the commercialisation and deployment of technologies that are closer to the market, even if applied research remains important to achieve technology cost reduction, including through demonstration and basic research is necessary to enable potential breakthroughs.

In the area of deployment, it is important to underline that European R&I policy should align better with green and socially just technological and social developments, as these are at the core of EU policy goals and, as such, also domains where a variety of policy tools will mobilise scale increase.

Coherence between R&I actions and other policy priorities is important to enable systemic benefits, and therefore also as a way to foster an acceleration in investments in areas - including digital and clean technology manufacturing - where the EU has already lost early-mover advantages.

Catching up on deployment aligns well with the growing relevance of industrial policy and strategic resilience. It also requires a combined focus on those technology areas with high growth potential, clearer pathways towards price/performance parity (especially if assessed against structural, physical limitations) and where Europe really stands a chance of being able to compete with China and the United States (which also requires a deeper analysis of competitors).

The discussion elaborated in Chapter 4 provides suggestions for specific technology areas and R&I actions that are most relevant in this context. These include:

- Digital technologies that enable systemic improvements, delivering energy- and material-efficiency (including through and for economic circularity) as well as cost savings (as in the cases of digitally-enabled system integration and MaaS).

- Disruptive technologies, enabling energy efficiency improvements, energy diversification and cost savings at once (as in the case of heat pumps and e-mobility).

- Complementary technologies in cases facing greater chances to shift towards increased reliance on electricity, including low-carbon hydrogen as a feedstock and for high-temperature heat applications in industry, and sustainably produced biofuels and low-carbon hydrogen derivatives as aviation and shipping fuels.

Aligning deployment-oriented R&I policy with industrial development also requires a greater focus on the demonstration and commercialisation of energy and mobility technologies with higher technology readiness. This could also help address the so-called ‘valley of death’ for climate-relevant innovations, which is the gap between funding for R&D and commercialisation (Figure 16). To bridge the valley of death, there is significant need for funding for pilot and demonstration projects.

Enabling funding for deployment also requires applied R&I actions on technical standards, as they are key prerequisites for the large-scale deployment of technological innovation (enabling their safe and environmentally-aligned operation). Key examples in this area include safety and durability requirements for automotive batteries to stationary and on-board storage devices for gaseous fuels, to charging and refuelling protocols, specifications for fuel quality after-treatment devices to abate tailpipe emissions of local pollutants and communication, safety features for EV chargers and electric road systems and protocols for connected vehicles (amongst many others).

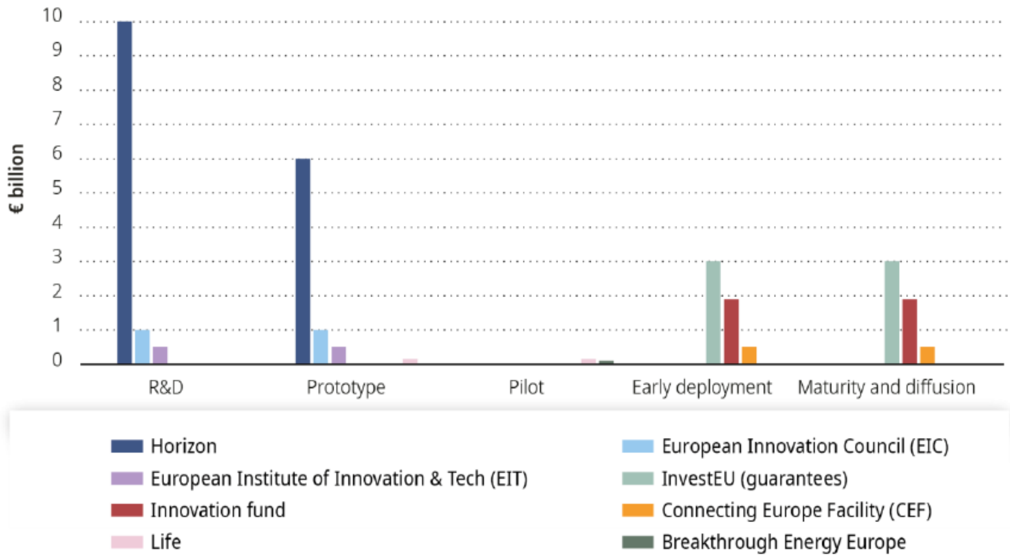

Figure 16. Available European public funding (in billion EUR) for climate-relevant innovations across stages of the innovation chain (ESABCC, 2024: 262)

5.2.4. Take specific R&I actions to reduce supply chain over-dependency, in conjunction with other policies

To reduce over-dependency risks, R&I policy should stimulate, specifically, innovations and broader transformative changes that can reduce reliance on excessively concentrated supply chains. Different types of solutions can enable this, including the development of energy- and material-efficient low-carbon energy technologies like batteries, wind turbines or solar panels. They also include the integration of better repairability in technology design, to facilitate re-use and economic circularity, and they encompass technology designs that are devising new recycling options.

These innovations are important as enablers of higher productivity in an area where Europe faces headwinds to compete internationally, due to pressures to increase its energy costs, the need to rely on imports of raw materials, higher labour costs than in emerging economies and losses in the competitive advantages that it had in terms of industrial capacity that already paid off its capital and knowledge base.

For these reasons, enabling early scale up of manufacturing capacity in the EU and the development of related supply chains, needed to achieve greater resilience in these areas, will require other policy tools, and not just R&I support. These include:

- Non-discriminatory, non-price criteria such as those already foreseen in the Net Zero Industry Act.
- A focus on economic circularity (as secondary materials are inherently less energy intensive to produce, on the top of being based on materials already in the EU economy, and while also reducing waste streams).

- The use of tariffs or price undertakings to counter unfair competition (even if these will require sunset clauses to avoid fostering the development of activities that are structurally not competitive).

- The development of a foreign policy that will continue to be based on open exchanges, investments in partner countries, responding to a genuine agenda of development. EU foreign policy should arguably become more assertive towards countries that do not play by the same internationally agreed rules and introduce protective measures and stronger industrial policies when this is reasonable.

Dedicated R&I actions can be enablers of better policy developments in these areas and should also be fostered, alongside programmes that enable the use of R&I for multilateral research programmes, not limited to EU Member States, but open (eventually with co-funding conditionalities) to global EU partners.

5.2.5. Align R&I actions with other strategic, infrastructure-related choices, correcting market failures, targeting better competitiveness

As markets alone tend to deploy technologies giving priority to profit maximisation, and not necessarily to resilience, R&I actions need to leverage other policy choices, enabling the achievement of price/performance parity for options with high growth potential. This is especially important in the case of strategic infrastructure if it can lead to systemic advantages in terms of competitiveness.

Strengthening electricity grids with interconnectors and a scale-up of pumped hydro storage where feasible (and/or other technologies, from batteries to compressed or liquid air to electro-thermal energy storage) is a concrete example in this regard, and it should be scaled up, in terms of importance, to the level of the hydrogen backbone. The reason why this is a major priority lies in its capacity to facilitate progress on the cost-effective integration of low-cost, low-emission variable renewables like solar PV and wind, end-use technologies providing demand response instruments alongside major energy efficiency and energy diversification enhancements - including heat pumps and EVs. By doing so, and also by creating a platform enabling a more homogeneous access to low-cost, low-carbon electricity (and an access that can help bridge variability in production profiles), this can significantly reinforce the R&I actions discussed in this Reflection Paper. Strengthened electricity grids can also leverage digital technologies and at the same time complement their use for system integration, helping to deliver cost cuts and enhanced competitiveness.

Other infrastructures - namely the envisioned EU hydrogen backbone - are also strategically relevant. Greater challenges, however, lie in the larger distance between hydrogen-enabled technologies and price/performance parity needs, meaning that specific care should be paid to this issue. Infrastructure-related investments regarding hydrogen should be focused on cases that can effectively justify high rates of utilisation, as these are necessary to bring down unit costs for hydrogen end-users. These are more likely where hydrogen has a higher probability to be the least cost option capable of responding to policy goals, and much less so if it is only the second or third best, behind direct electrification and/or CCS.

This means that hydrogen-related infrastructure investments will probably need to start from industrial clusters already using hydrogen, as these can have sufficiently high willingness to pay to decarbonise existing demand (especially if they can leverage major revenue streams from capital investments that have already paid off during the transition, while also being better protected by the EU Carbon Border Adjustment Mechanism). These may also include long term storage facilities, especially in cases where pumped hydro storage and demand-side management risk not being sufficient to manage risks from variable electricity supplies and seasonal differences with demand profiles.

Expansions of the hydrogen transport and distribution network can effectively leverage R&I activities, as they help lower production costs, as long as there are applications where hydrogen use can outcompete the higher energy efficiency of low-cost, low-carbon direct electrification pathways.

5.2.6. Take specific R&I actions regarding social innovations and better understanding of the dynamics of system transitions

To bridge social acceptance and justice gaps, R&I policy should also stimulate more social science and humanities research on various forms of innovation (including social, business model and governance innovation) and to understand factors that support and hinder the diffusion of digital and low-carbon innovations and system transitions (including business strategies, user adoption, public policies, social acceptance, global implications of European investment decisions).

To better understand the dynamics of system transitions in energy and mobility, R&I policy should also focus more on the co-evolution between technologies, markets, policies, public debates, business strategies, and users. Although it is ultimately the interaction between these dimensions that drive system transitions (Geels, 2005; Köhler et al., 2019), R&I funding policies have, so far, focused mostly on more isolated topics such as individual technology areas, social acceptance and justice, or business model innovation.

However, while deep understanding of isolated topics remains important, broad analyses of co-evolutionary processes in system transitions are especially relevant in the current stage of transitions.

5.2.7. Consider institutional changes to leverage large-scale opportunities, including better EU/Member State coordination

Stronger coordination with Member States, who spend the bulk of European R&I funding (about 90%, compared to 10% of funding from the Commission (Clemens et al., 2024: 46), is essential to improve Europe’s competitiveness, as it enables scale effects and cost reduction.

Strengthened coordination also aligns well with the key messages developed throughout this Reflection Paper about the relevance of scale and policy coherence to de-risk investments capable of accelerating innovation in clean and affordable energy and mobility, and enabling Europe (if paired with a coherent and more efficient set of R&I actions) to catch up with global competitors, reduce over-dependencies, and strengthen resilience.

Coordinated R&I actions between the EU and Member States on energy and mobility are also in line with the proposals from the recent Letta report (‘Much more than a market’) to create a ‘fifth freedom’ in the EU focused on research, to include energy in the perimeter of the Single Market, and to enhance interconnectivity (which is a mobility enabler) between EU neighbouring countries.

The concept of ‘auctions-as-a-service’, introduced in the European policy framework with the hydrogen bank could be expanded to research and innovation policy, e.g. enabling far greater coherence by allowing Member States to contribute their own financial resources for awarding support projects located on their territory, while relying on EU-wide allocation mechanisms to identify the most relevant projects.

R&I policy should also consider making institutional changes, such as the creation of specific agencies focused on disruptive innovation (such as the Advanced Research Projects Agency-Energy (ARPA-E) in the United States), strengthening tools specifically focused on deployment such as IPCEIs (Important Projects of Common European Interest) and also including specific tools that can foster disruptive forms of innovations, and enabling a better funding environment for startups, and not solely focusing on incumbents. The reason for making this suggestion is that the current policy and institutional landscape for European R&I policy has some significant shortcomings.

For example, the European Innovation Council (EIC), which was created in 2017 to drive radical innovation with an annual budget of about EUR 1.4 billion, does not appear to be working very well. A recent report titled EU Innovation Policy: How to Escape the Middle Technology Trap (Clemens et al., 2024) suggests that the EIC allocates too little funding towards supporting radical innovations with lower Technology Readiness Levels and too much to innovations with higher TRLs. This report also suggests that much of the funding is directed towards projects by mature mid-tech companies rather than to projects from startups. This is likely because the management of the EIC was allocated to an existing body (the Executive Agency for Small and Medium-Sized Enterprises) whose task was to support SMEs.

Although the EIC was officially inspired by the American ARPAs, the report (Clemens et al., 2024) concludes that the EIC is far less effective in driving radical breakthrough innovations for a range of reasons (related to governance, funding, and the orientation towards incumbents).

A more general criticism of the current EU R&I policy landscape is that the successive layering of different instruments (often in response to particular criticisms) has led to a fragmented and sometimes opaque policy mix. Table 2, which summarises the main policy tools and instruments, shows that Horizon Europe is the main funding instrument, but that several deployment-oriented instruments also focus on innovation. Focusing on green innovations, Tagliapietra et al. (2023:177-178) conclude that: '*there remains a long way to go to achieve a green industrial policy. Notably, strong governance, which can ensure the consistency of green industrial policy, is missing. Instead, the EU green industrial policy strategy seems more like a scattered collection of energy, climate, innovation, and social policy initiatives, rather than a coherent industrial policy framework.*'

Research & Innovation	**Deployment**	**Framework conditions**
Horizon Europe (about EUR 11 billion/year), spend through three pillars	European Alliances aimed at promoting public-private partnerships (e.g. European Battery Alliance, European Clean Hydrogen Alliance, European Raw Material Alliance)	Trade and investment policies

Research & Innovation	Deployment	Framework conditions
Pillar 1: basic and applied research (about EUR 3.25 billion/year) - European Research Council (about 2/3 of funding) - Marie Curie Actions - Research Infrastructure	IPCEIs (Important Projects of Common European Interest), which involve multiple EU countries and private funding. IPCEIs include: - one for micro-electronics - two for batteries (both with EUR 3.2 billion public funding and EUR 5 billion private funding) - two for clean hydrogen (`both with about EUR 5 billion public funding and EUR 7-8 billion private funding)	Competition policy
Pillar 2: Global challenges collaborative projects (about EUR 7.33 billion/year, focused on six clusters (Health; Culture, Creativity and Inclusive Society; Civil Security for Society; Digital, Industry and Space; Climate, Energy and Mobility; Food, Bioeconomy, Natural Resources, Agriculture and Environment)	EU Innovation Fund (about EUR 4 billion/year) to stimulate projects between industry, research organisations, and other stakeholders	Environmental standards
Pillar 3: Innovative Europe collaborative projects (EUR 1.5 billion/year): - European Innovation Council (aimed at driving radical innovation through three programs focused on different TRL-levels: Pathfinder (TRL 1-4), Transition (TRL 3-6), Accelerator (TRL 5-9) - European Institute of Innovation and Technology - European Innovation Ecosystem	European Investment Bank	Climate policy
	EU Cohesion Funds (about EUR 8 billion/year)	Energy policy
	NextGenerationEU (EUR 750 billion for 2021-2026 period)	Development policy
	Single market rules	

Table 3. Europe's main R&I and green industrial policies (Tagliapietra et al., 2023: 171; Clemens et al., 2024).

5.2.8. Foster the contributions of new stakeholders, moving the attention beyond incumbents, to better leverage the potential of startups

As implicitly indicated in the second suggestion in Chapter 5, our more general view is that EU R&I policy has been strongly oriented towards supporting innovations that benefit incumbent firms in established (mid-tech) industries. Many policy tools and platforms (like the European Alliances, the global challenges projects, the European Innovation Council, and Joint Undertakings) tend to be oriented towards or dominated by incumbent actors, who have vested interests and major amounts of capital invested in the existing system. In this context, challenges faced by Europe to compete globally on clean technology suggest that grant funding to corporations against in-kind R&I efforts struggled to address the commercialization challenges.

This strong focus on incumbent players has often led to an R&I policy focus on single technologies and existing sectors rather than a significant engagement with whole system transitions and innovations that may blur the boundaries between existing sectors. It also led to a focus on innovations that gradually upgrade and reconfigure existing industrial assets (e.g. CCS, hydrogen), rather than favouring the development and scale-up of disruptive technologies.

While this is valuable to reduce exposure to asset stranding challenges, it also risks delaying investment growth in startups that can drive radical innovations with the potential to spawn entirely new industries.

A key example is Northvolt, an independent battery manufacturer headquartered in the EU which commissioned its first large-scale manufacturing plant in 2021, seven years after the first Tesla gigafactory in Nevada and 10 years after the establishment of CATL (currently the main EV battery manufacturer globally) in China.

We thus conclude by suggesting that European R&I policy should make more efforts to support and engage with new entrants like startups, pioneers, and innovative entrepreneurs and make more efforts to examine existing or future regulations, in order to ensure that it is not blocking the commercialisation of innovation. This could be done by developing new instruments or platforms that are specifically tailored to their needs. The recently launched European Tech Champions Initiative (ETCI) of the European Investment Bank is an example. It could also be done by including more new entrants in (the governance of) existing or new platforms. One example is the creation of a technology advisory body - comprising leading academics, established and emerging corporate actors, start-ups, as well as venture capital investors - can also help both the European Commission and the Member States to identify the latest and most promising technology development trends and game changers to support with R&I actions.

The increasing attention for public-private European partnerships (e.g. through the IPCEIs and European Alliances) is very welcome, because this stimulates knowledge flows, exchange, and collaborations in technology innovation systems (see Figure 15). But more can be done to include new entrants in these partnerships, as this can spur incumbents and introduce ‘out of the box’ ideas and business models. Furthermore, these partnerships should focus on ‘action’ as well as ‘talk’. To increase the likelihood of ‘action’, participating firms should make significant private R&I investments and not just rely on public R&I investments.

5.3. Concluding thoughts

This report agrees with the recent Letta and Draghi reports that the world is changing fast and that Europe faces multiple challenges, including deteriorating competitiveness, rapidly advancing climate change, social justice and acceptance problems associated with new technologies, and escalating security risks. These contextual changes demonstrate the complexities and multiple dimensions involved in promoting and achieving low-carbon energy and mobility transitions that will also improve the EU's competitiveness, security and social justice. Europe needs to act fast to address these challenges.

Our report identifies and analyses nine essential innovation pathways for energy and mobility systems, and proposes R&I priorities for them. Overall, our message is that European R&I actions have a vital role to play in enabling progress that is environmentally, socially and economically sustainable – and such R&I actions need to take into account the rapidly changing global context of the 2020s.

We articulate a prudent view on what can be achieved with hydrogen and biofuels, compared to direct electrification, with the exception of specific application domains where direct electricity struggles to deliver better results (namely long-distance aviation and shipping, at the interaction of energy and mobility).

We observe that Europe has fallen behind China in most clean technology areas. This declining competitiveness is problematic because, if unaddressed, it will reduce the fiscal space to support greater social justice, increased spending on security, and stronger EU cohesion. Our analysis, therefore, indicates which pathways and technologies Europe should focus to regain international competitiveness, where it may have fallen behind too far to catch up, where security, jobs and industrial vitality arguments warrant more support despite limited international competitiveness opportunities, and what R&I can do to strengthen the selected pathways.

We suggest that it is important to deepen our analysis of these issues. We also suggest that further analysis should deepen the understanding of how Europe can effectively seize its chances and opportunities. While we agree about the value of the Single Market, as highlighted by Letta and Draghi, we think that Europe needs a wider and better focused set of instruments to effectively respond, as a Union, to the size of the challenges. Tackling multiple crucial policy objectives simultaneously – especially those addressing climate change, competitiveness, security and justice – is not easy, but should be a key focus of coordinated and cross-sectoral policy efforts. While our report focused on R&I priorities, we do not think that R&I policies alone will be able to address these challenges. We rather see the need for a whole-of-government and whole-of-the-EU mobilisation to succeed. While this approach is challenging for the siloed EU policy landscape, it will be essential to address the challenges in the coming years.

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‘Addressing European Research and Innovation Challenges for System Transitions in Energy and Mobility’ is an independent expert report prepared by four experts. The purpose of this reflection paper is to offer recommendations and ideas on challenges and priorities for research and innovation (R&I) in the areas of clean energy and mobility. The paper sets out a vision for future energy and mobility systems that is aligned with the EU’s long-term ecological, economic and social objectives, in particular the aim to become climate-neutral by 2050. In order to bring about this vision, the paper explores nine ‘innovation pathways’ in energy and mobility systems, selected on the basis of their expected impact to achieve the vision. The pathways are assessed against four contemporary challenges affecting energy and mobility systems. These challenges stem from four macro-level contextual changes. The paper also provides broader policy recommendations for EU R&I, beyond energy and mobility systems.

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