European Commission

Study on energy technology dependence

Broad Brush Assessment Results (Task 3)

D3 Report

Independent
Expert
Report

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Research and Innovation

Study on energy technology dependence

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Broad Brush Assessment Results (Task 3) D3 Report

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1 Overview

This report (Task 3 – D3 Report) summarises the results of the broad-brush assessment which was undertaken as part of the Energy Technology Dependence (ETD) assessment developed for DG RTD under Framework Contract PP-02161-2014.

The broad-brush assessment was carried out following the methodology set out in the broad brush assessment step-by-step manual (see Appendix 0) for the following energy technologies, and their variants indicated in brackets:

- Solar Energy (Photovoltaic, concentrated solar power, solar heating & cooling);
- Wind Energy (on shore, off shore);
- Hydropower (run-of-river, reservoir, pumped storage);
- Bioenergy (biochemical, thermochemical, algae);
- Geothermal Energy (dry steam, flash steam, binary steam, enhanced geothermal);
- Ocean Energy (wave, tidal, ocean thermal conversion, salient gradient);
- Hydrogen & Fuel Cells (renewable hydrogen, proton-exchange membrane fuel cells (PEMFC), solid oxide fuel cell (SOFC));
- Energy storage linked to renewable energy systems (heat, mechanical, chemical and electrical);
- CO2 capture (pre-combustion, post-combustion, oxy-fuel combustion);
- CO2 storage (depleted gas and oil fields, deep saline aquifers, enhanced hydrocarbon recovery);
- CO2 utilization (carbonate mineralization, CCU fuels);
- Flexible conventional thermal power plants (gas engine-based, gas turbine-based and pulverized coal plants);
- Heat pumps (air, water and ground source).

The results of the broad-brush assessment are presented in section 2 of this report:

- **Section 2.1**: A summary paper on key issues of critical dependence (i.e. EU reliance on non-EU supply, and associated market concentration), for each energy technology family;
- **Section 2.1**: List of specific elements (e.g. components, raw materials, equipment) identified as potential critical dependencies;
- **Section 2.2:** Indication of each energy technology family/variant importance for EU security of supply and for EU leadership;
- **Section 0:** Recommendations on the critical energy technology families/variants to be assessed in-depth in Task 4.

Details of the sources used and analysis principles adopted during the broad-brush assessment are discussed in section 3 of this report.

2 Results

2.1 Identification and assessment of critical dependencies (Stage 1 results)

The Energy technology summary papers (provided in Appendix A1) highlight key issues of energy dependence - i.e. EU reliance on non-EU supply and market concentration - for each energy technology family and its selected variants. Summary papers focus on dependencies in the physical flow of goods and services including components, raw materials, equipment, machinery and services. The detail provided in each summary paper is an input for selecting which energy technology families/variants (see results of this selection in section 0) will be studied in-depth in the detailed assessment during Task 4.

Key insights from the summary papers are concluded below:

- Aggregation of energy technology family variants (section 2.1.1);
- Critical dependence elements, either specific to an energy technology family/variant or multiple energy technology families/variants (section 2.1.2).;
- Energy technology families/variants critical dependency score (section 2.1.3).

Full summary papers can be found in Appendix **Error! Reference source not found.**.

2.1.1 Aggregation of energy technology family variants

Energy technology family variants are identified in each summary paper, and conclusions are drawn on whether energy technology family variants should be considered as separate technologies or whether they should be combined as one energy technology family. Generally speaking, where critical dependencies are common across all variants, variants are combined as one energy technology family; where critical dependencies are unique to a variant, variants are considered as separate technologies.

Table 1 lists each energy technology family, and its variants, considered during the broad-brush assessment. It summarises the rationale for either combining or separating of variants, and highlights (indicated using a checkmark) how technologies have been aggregated for assessment during the broad-brush assessment.

Table 1 Summary of variant aggregation

Energy technology families considered	Variants considered	Separate	Aggregate	Key rationale for aggregation
Bioenergy	Thermochemical conversion	✓		Variants are largely independent e.g. different feedstock and primary equipment.
	Biochemical (including algae) conversion	✓		
CO2 capture	Pre-combustion capture	✓		Variants are unique technologies with varying value chains.
	Post-combustion capture	✓		
	Oxy-fuel combustion	✓		
CO2 storage	Depleted oil reservoirs		✓	Differences not substantial.
	Depleted gas reservoirs and aquifers			

Energy technology families considered	Variants considered	Separate	Aggregate	Key rationale for aggregation
	Enhanced hydro carbon recovery			
CO2 utilisation	Carbonate mineralization	✓		Variants are based on unique technologies.
	CCU fuels	✓		
Energy storage	Compressed air energy storage (CAES)			All variants listed were considered. However, only Li-ion technology was analysed during the broad brush assessment due to its leadership in terms of performance characteristics, maturity level, current market share and predicted market growth potential.
	Flywheels			
	Li-ion batteries	✓		
	Redox flow batteries			
	NaS batteries			
	Lead acid			
	Super caps			
	Hydrogen storage			
	Thermal Energy Storage			
Flexible conventional thermal power plants	Gas engine based energy plants	✓		Variants have unique dependency issues.
	Stationary gas turbine based energy plants	✓		
Geothermal energy	High enthalpy: dry steam geothermal and flash steam geothermal	✓		Variants have been categorised into high enthalpy and low enthalpy technologies due to a common critical dependency issue for dry and flash steam geothermal.
	Low enthalpy: binary cycle geothermal plants	✓		
Hydropower	Run-of river hydropower plants		✓	Variants are combined – components and materials are common.
	Reservoir hydropower plants			
	Pumped storage plants			
Hydrogen & fuel cells	Renewable hydrogen (RH)	✓		Variants are considered separately – unique in their technology requirements, processes and dependencies.
	Proton-Exchange Membrane Fuel Cells (PEMFC)	✓		
	Solid Oxide Fuel Cell (SOFC)	✓		
Ocean energy	Wave energy		✓	Variants are combined
	Tidal energy			
Solar energy	Photovoltaics (PV)	✓		Variants are considered separately – dependency issues identified are unique to each variant.
	Concentrated solar power (CSP)	✓		
	Solar heating and cooling	✓		
Wind energy	Offshore energy		✓	Variants are combined – share the same critical dependency issues.
	Onshore energy			
Heat pumps	Ground source		✓	Variants are combined – no evidence of critical dependency issues unique to each variant.
	Air source			

2.1.2 *Critical dependence elements*

Critical dependency is defined by the extent of EU reliance on non-EU suppliers and the concentration of those suppliers. A definition of critical dependence (see Figure 1) was drafted as part of the ETD project and is detailed in the Interim Report (Task 1 and 2).

Figure 1 Definition of critical dependency

In the context of European energy technology dependence, we define ***dependency*** as:

> *Reliance on an energy technology good, service, component or input that is primarily supplied from outside Europe.*

We further define a ***critical dependency*** as:

> *Where the extent of the external dependence is high and where the supplier market is concentrated in the hands of few firms or countries, giving them market power and the ability to influence availability and price.*

A critical dependency creates the conditions for potential *threats* to European energy technology interests, defined as:

- Increasing the cost of meeting European climate and energy objectives.
- Reducing productivity and employment in the European energy industry.
- Limiting the potential for European technology leadership.

The potential for critical dependence on non-EU supply was assessed for each of the energy technology families and variants listed in Table 1. This assessment followed the methodology set out in stage 1 of the broad-brush assessment step-by-step manual (see Appendix 0).

A variety of critical dependence elements (e.g. raw materials, equipment and components) were identified, some of which are unique to single technologies and some of which are common across multiple technologies. Each critical dependence element is scored in terms of its extent of critical dependency (i.e. high, medium and low). Recall that the extent of critical dependency relates to EU reliance on non-EU supply and market concentration (see Figure 1). Further details on the assessment criteria e.g. indicators of critical dependency can be found in stage 3.1 of the broad-brush assessment step-by-step manual (see Appendix 0).

Figure 2 shows the quantity of critical dependency elements, and their extent of critical dependency (i.e. high, medium and low), identified for each energy technology assessed as part of stage 1. For example, five critical dependency elements have been identified for battery storage where three are scored as high i.e. high extent of critical dependency. It is concluded that 10 energy technology families/variants (i.e. storage-batteries to CO2 reuse) present a supply disruption risk due to critical dependence on one or more elements in their value chain (see Figure 2).

Figure 2 - # of critical dependence elements, and extent of critical dependence, by energy technology

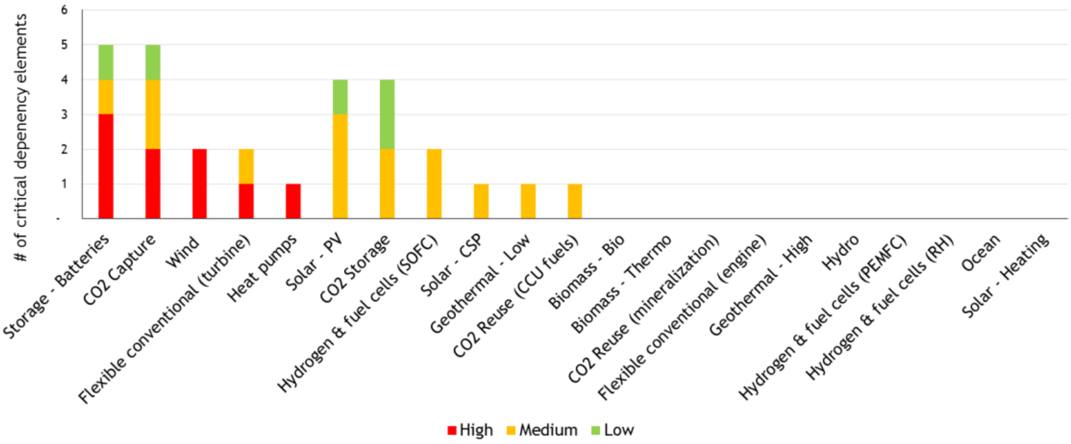


Figure 3 lists all of the critical dependency elements identified by energy technology and indicates their extent of critical dependency (i.e. red is high, orange is medium, and green is low). Cross-energy technology critical dependency elements have been identified, specifically critical raw materials which are common across multiple energy technology value chains (e.g. cobalt and iron ore).

Figure 3 Summary of critical dependencies by energy technology and element

	Biomass - Bio	Biomass - Thermo	CO2 Capture	CO2 Reuse (mineralization)	CO2 Reuse (CCU fuels)	CO2 Storage	Flexible conventional (engine)	Flexible conventional (turbine)	Geothermal - High	Geothermal - Low	Heat pumps	Hydro	Hydrogen & fuel cells (PEMFC)	Hydrogen & fuel cells (RH)	Hydrogen & fuel cells (SOFC)	Ocean	Solar - CSP	Solar - Heating	Solar - PV	Storage - Batteries	Wind - All variants
Component																					
Battery cell																					
Elastomers																					
PV cell																					
PV module																					
Equipment																					
Electrical submersible pumps (ESP)																					
Gas turbine																					
Raw material																					
Chromium																					
Cobalt																					
Dysprosium																					
Gallium																					
Iron ore																					
Magnesium																					
Neodymium																					
Phosphate rock																					
Ruthenium																					
Silicon																					
Silver																					
Tungsten																					
Vanadium																					
Yttrium																					
Zirconium																					

2.1.3 Energy technology families critical dependence score

A team of experts scored each energy technology family/variant based on the quantity and extent of critical dependency elements identified (see results in section 2.1.2 above) and have been summarised in Figure 4 below, following the broad-brush methodology (see stage 3 in Appendix 0). In summary, wind energy, storage-batteries, and CO2 capture stand out as technologies with a high extent of critical dependency.

Figure 4 Critical dependence score for each energy technology family/variant

Broad brush assessment - Summary table	**Critical dependence (Criterion 1)**
	Extent of critical dependence
Explanation	Measure of the threat of supply disruptions for the EU
Technology family or variant	High/medium/low
Solar - Photovoltaic	Medium
Solar - Concentrated solar power	Medium
Solar - Heating & cooling	Low
Wind - All variants	High
Hydro - All variants	Low
Biomass - Thermochemical conversion	Low
Biomass - Biochemical conversion	Low
Geothermal - High enthalpy	Low
Geothermal - Low enthalpy	Medium
Ocean - All variants	Low
Hydrogen & fuel cells - Renewable hydrogen	Low
Hydrogen & fuel cells - Proton-exchange membrane fuel cells	Low
Hydrogen & fuel cells - Solid oxide fuel cells	Medium
Storage - Batteries	High
CO2 Capture - All variants	High
CO2 Storage - All variants	Medium
CO2 Reuse - Carbonate mineralisation	Low
CO2 Reuse - CCU fuels	Medium
Flexible conventional - Gas engines	Low
Flexible conventional - Gas turbines	Medium
Heat pumps - All variants	Low

2.2 Importance for EU security of supply and technology leadership (Stage 2 results)

Stage 2 of the broad-brush assessment aims to provide quantitative data for the different technology families and variants which serves as an input for selecting the technologies that will be studied in detail in the detailed assessment. Furthermore, it provides an indication on where mitigation measures and policies should be focused.

The stage 2 assessment covers indicators that are grouped per the two overarching EU objectives: security of supply and leadership in renewables.

For security of supply the following indicators have been selected:

1. Current installed capacity in the EU: provides an indication of the current reliance on the energy technology for meeting the EU's energy demand. It also indicates the expected replacement volumes;
2. Net capacity additions until 2030 in the EU: provides an indication of the additional capacities that need to be acquired over the coming years to safeguard fulfilling the EU future energy demand.

For leadership in renewables the following indicators were selected:

1. Current installed capacity globally: provides an indication of the current global scale of deployment of the energy technology, also indicating the expected replacement volumes. A higher global deployment indicates a higher export market which makes the technology more important for the EU's global leadership ambitions;
2. Net capacity additions until 2030 globally: provides an indication of the expected volumes purchased globally over the coming years. A higher volume indicates a higher potential export market;
3. EU share of patent applications: provides an indication of the strength of the EU knowledge position. A stronger knowledge position indicates better chances of securing a global leadership position;
4. EU share of global publications: provides an indication of the strength of the EU knowledge position. A stronger knowledge position indicates better chances of securing a global leadership position.

This mix of indicators provides an overall view on the importance of managing dependencies for the respective energy technology. Technologies with high current and expected capacities in the EU and globally as well as a strong EU knowledge position justify stronger efforts to mitigate critical dependencies than technologies with only limited capacities and /or a weak knowledge position, because of their higher relevance for the security of supply and global leadership objectives.

It should be stressed that this assessment aims to deliver figures that provide a rough indication of the differences between the technologies on the selected indicators. For the broad-brush assessment it is important to be aware of the order of magnitude of the deployment of the different technologies and the approximate strength of the EU knowledge position. However, if the installed capacities are 20% higher or lower or if the share of patents is a few percentage points higher or lower is less relevant for selecting the most important technologies. Hence, the assessment takes a pragmatic approach which delivers figures that are approximately right, without aiming to be exactly right.

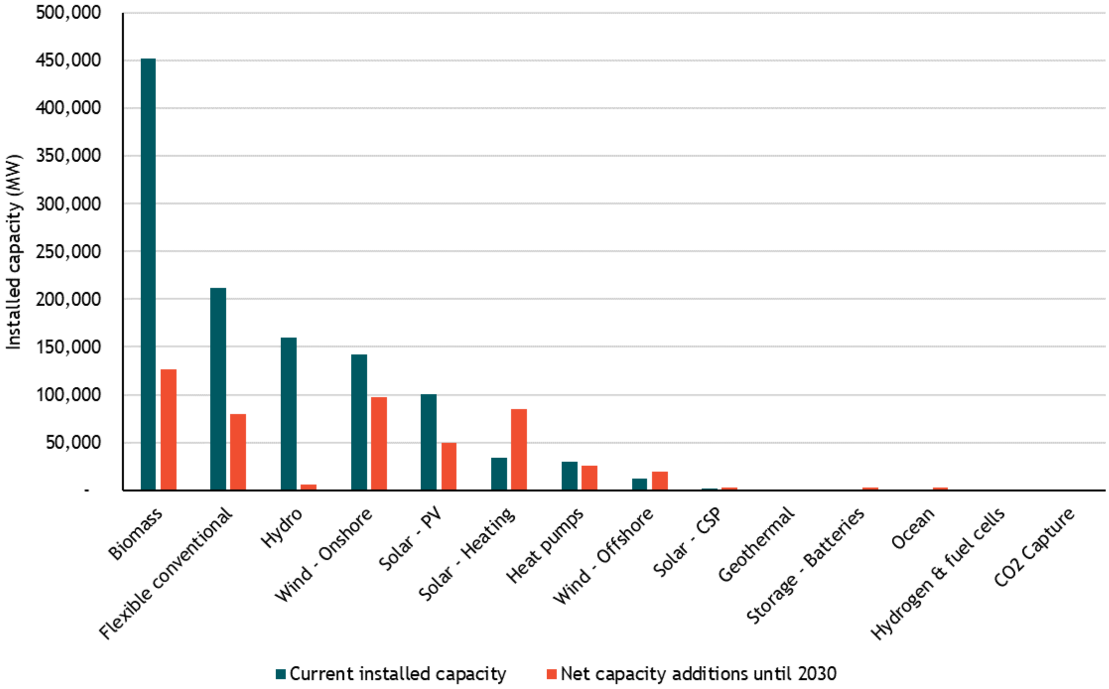
2.2.1 EU capacities

The current installed capacities and expected net capacity additions until 2030 for the EU are shown in **Error! Reference source not found.**. It should be noted that those capacities not o nly include electrical capacities but sometimes also include capacities for heating. This is driven by the scope of technologies assessed in stage 1, where for biomass technologies for heating are also assessed[1] (hence capacities for heating are included) but flexible

[1] Electricity generation capacities for biomass are less significant (currently at 37 000 MW).

conventional, only includes technologies for gas-fired power plants (hence capacities for gas-fired heating are excluded).

Figure 5 EU[2] current[3] installed capacities and net capacity additions until 2030 per technology



Sources for current installed capacity: IRENA (2017) – Renewable capacity statistics 2017, except for solar heating (Stanford University (2016) – 2016 spreadsheets), Biomass and heat pumps (Greenpeace energy revolution (2015)), battery storage (expert assessment), flexible conventional (IEA (2016) – WEO 2016).

Sources for net capacity additions until 2030: Calculated based on 2030 installed capacity estimates from IEA (2016) – WEO 2016, except for solar heating, biomass and heat pumps (Greenpeace energy revolution (2015)), battery storage (expert assessment) and CO2 capture (EU reference scenario 2016).

The data shows that biomass, flexible conventional (gas power plants) and hydro are the dominant technologies, with onshore wind and solar PV following as the main newcomers. For the expected capacity additions, a mixed picture emerges with significant capacity additions foreseen for most of the top five technologies mentioned before (except hydro), as well as for solar heating and to a lesser extent heat pumps and offshore wind. For the remaining technologies the current and expected capacities are negligible compared to the top eight technologies. However, for some of those, the outlook is highly uncertain, and the actual growth may greatly exceed the expectations. Still, the scale of deployment is expected to remain minor compared to other technologies, at least until 2030.

We conclude that the top eight technologies (i.e. biomass to offshore wind) are expected to play a significant role for EU security of supply. For the purpose of safeguarding security of supply, mitigation measures should be focused on dependencies for those eight technologies.

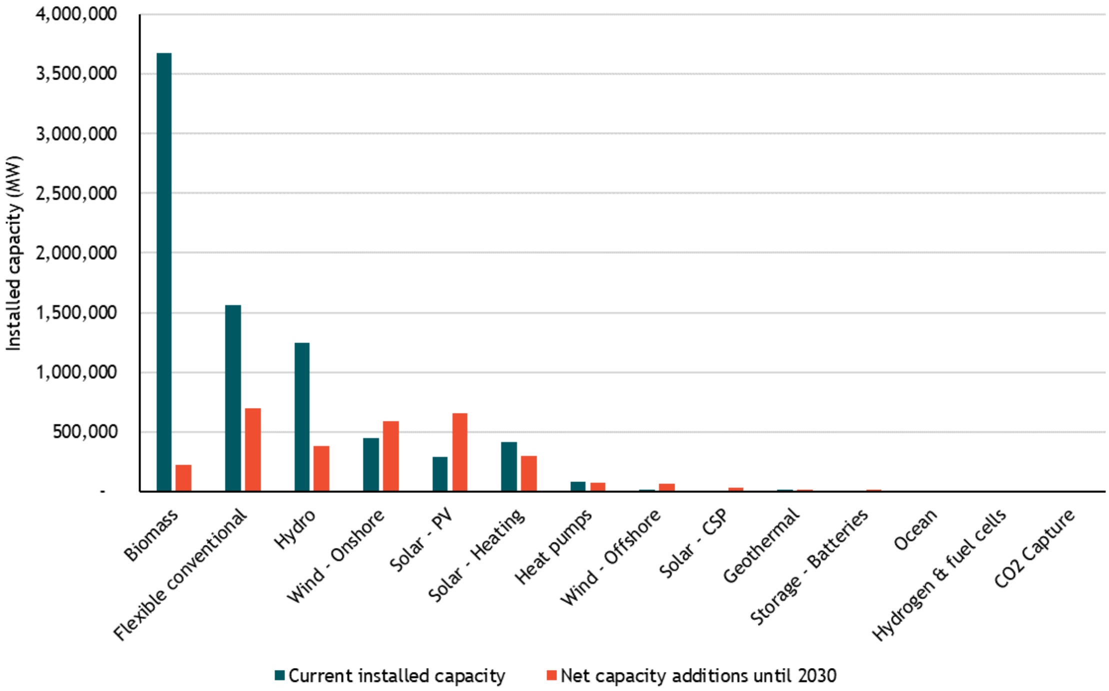
2.2.2 Global capacities

2 Capacities are for OECD Europe instead of the EU for data from Greenpeace energy revolution 2015.
3 Current installed capacity is for 2016 except for solar heating (2015), biomass and heat pumps (2012) and flexible conventional (2014).

The current installed capacities and expected net capacity additions until 2030 for the world are shown in Figure .The global current capacities exhibit the same pattern as the EU capacities, with the largest current capacities for biomass (excluding traditional biomass[4]), flexible conventional (gas power plants) and hydro power. Onshore wind, solar PV and solar heating follow at a somewhat larger distance than for the EU and heat pumps and offshore wind are almost negligible compared to the other global capacities. The expected capacity additions also show a more mixed pattern with significant additional capacities forecasted for onshore wind, solar PV, solar heating, hydro and flexible conventional. The current and expected scale of deployment of the remaining technologies is limited globally.

We conclude that the top six technologies are expected to cover the majority of global capacities but note that flexible conventional cannot be considered a renewable energy technology and would therefore be of lesser relevance for the EU leadership in renewables objective. Mitigation measures on dependency issues for the other five technologies in the global top six should be prioritised from the perspective of global leadership in renewables. Furthermore, we note that while the capacities for the remaining technologies are minor in the global picture, these volumes could still be significant in absolute terms. Therefore, it may still be worthwhile to include some of those in the detailed assessment.

Figure 6 Current[5] global installed capacities and net capacity additions until 2030 per technology



Sources for current installed capacity: IRENA (2017) – Renewable capacity statistics 2017, except for solar heating (Stanford University (2016) – 2016 spreadsheets), Biomass and heat pumps (Greenpeace energy revolution (2015)), battery storage (expert assessment), flexible conventional (IEA (2016) – WEO 2016).

[4] Capacities for traditional use of biomass include for instance stoves for heating and cooking. Those capacities are very large globally, but are not considered relevant for the objective of global leadership in renewable energy technology because EU exports would most likely focus on more advanced technological applications. Hence, those capacities are not taken into account.
[5] Current installed capacity is for 2016 except for solar heating (2015), biomass and heat pumps (2012) and flexible conventional (2014).

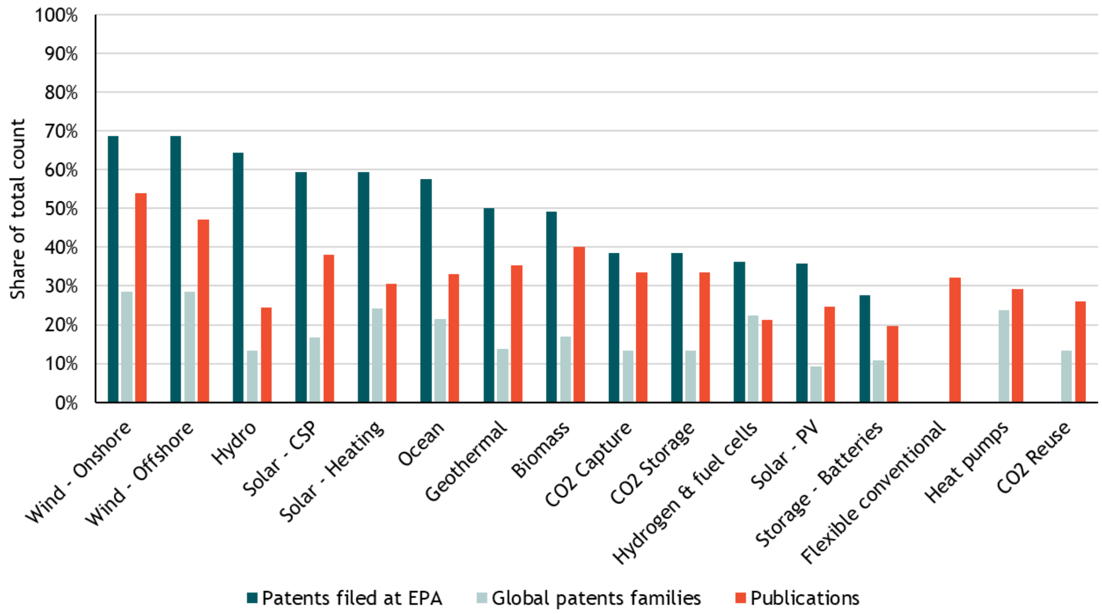
Sources for net capacity additions until 2030: Calculated based on 2030 installed capacity estimates from IEA (2016) – WEO 2016, except for solar heating, biomass and heat pumps (Greenpeace energy revolution (2015)), battery storage (expert assessment).

2.2.3 Patents and publications

For assessing the strength of the EU knowledge position, we look at patents and publications (see Figure). For patents we use both data for patents filed at the European Patent Office (EPO) and for patents filed globally from the JRC as both cover different technologies, which aids in providing a more complete picture on all technologies in scope. The EPO data only considers patents that are filed in Europe and should therefore not be interpreted as the share of the total number of patents filed worldwide. The JRC data does represent patents filed worldwide.

We conclude that the EU knowledge position for wind energy technologies is especially strong with about half of all publications and also a relatively high share of patents stemming from Europe. This provides a strong basis for maintaining and further developing a position of global leadership. For a range of other technologies (hydro, solar CSP, solar heating, ocean, geothermal, biomass, heat pumps) we also find high scores on one or more indicators and conclude that the knowledge position provides a sound basis for global leadership. Hence, from the perspective of realising global leadership in renewables, it would be recommended to actively mitigate critical dependencies for all those technologies.

Figure 7 EU share of number of patent applications to the European Patent Office (2010-2013), globally (2010-2013) and the share of global publications (2014-2016)



Source for patents filed at the EPA: Eurostat - Energy technologies patent applications to the EPO by priority year [pat_ep_nrg]. Source for global patent families: JRC(2018) based on Patstat data (Autumn 2017 edition). Source for publications: Web of Science - Thomson Reuters (2016). Web of Science Core Collection, keyword search in title or topic of the publication, years 2014-2016. List of keywords per technology available in a supporting Excel sheet.

2.3 Priority technology families/variants (Stage 3 results)

An in-depth assessment of critical dependency issues (to be carried out during Task 4) is recommended for the following energy technology families/variants:

Firm recommendation:

- Solar PV;
- Wind energy (includes off and onshore);
- Lithium ion battery storage.

Secondary recommendations

- Concentrated solar power (CSP);
- Low enthalpy geothermal;
- CO2 capture;
- Flexible conventional – gas turbines.

The energy technology families/variants listed above were selected by a team of five experts following the methodology set out in the broad-brush assessment step-by-step manual (see stage 3 in Appendix 0). In summary, the recommended technologies were selected with consideration of the following criteria:

- Critical dependence (see stage 1 results in section 2.1).
- Importance for EU security of supply (see stage 2 results in section 2.2).
- Importance for EU leadership in renewables (see stage 2 results in section 2.2).

Further detail on the selection process i.e. rationale for selection, is also provided in section 3.3.

Figure 8 summarises each energy technology family/variant considered during the broad brush assessment, its scores and data sets against criterion 1 through 3, as well as our final recommendation i.e. green is firm and orange is secondary.

A brief explanation on the selection of each firm and secondary recommendation is provided in the subsections below.

Figure 8 Broad brush assessment summary table

Broad brush assessment - Summary table	Critical dependence (Criterion 1)	Importance for EU security of supply (Criterion 2)		Importance for EU leadership in renewables (Criterion 3)					Priority of managing dependence
	Extent of critical dependence**	Current installed capacity - EU	Net capacity additions until 2030 - EU	Current installed capacity - World	Net capacity additions until 2030 - World	EU share of EPA patent applications	EU share of global patent families	EU share of global publications	Expert assessment based on scores on criteria 1, 2 and 3
Technology family or variant*	High/medium/low	MW	MW	MW	MW	%		%	
Solar - Photovoltaic	Medium	100,414	49,436	290,791	658,426	35%	9%	25%	Firm
Solar - Concentrated solar power	Medium	2,308	2,569	4,873	29,376	59%	17%	38%	Secondary
Solar - Heating & cooling	Low	34,357	84,541	416,675	297,049		24%	31%	
Wind	High	154,283	116,974	466,505	652,622	69%	29%	48%	Firm
Hydro - All variants	Low	159,562	39,792	1,242,961	679,088	64%	13%	24%	
Biomass - Thermochemical conversion	Low	409,953	127,000	3,388,266	223,606	56%	21%	40%	
Biomass - Biochemical conversion	Low	42,047		288,582		42%	13%		
Geothermal - High enthalpy	Low	814	945	12,628	18,651	50%	14%	35%	
Geothermal - Low enthalpy	Medium	64							Secondary
Ocean - All variants	Low	248	2,513	537	5,299	57%	22%	33%	
Hydrogen & fuel cells - Renewable hydrogen	Low	Negligible	Negligible / Uncertain	Negligible	Negligible / Uncertain	36%	22%	21%	
Hydrogen & fuel cells - Proton-exchange membrane fuel cells	Low								
Hydrogen & fuel cells - Solid oxide fuel cells	Medium								
Storage - Batteries	High	350	2,650	1,400	12,600	28%	11%	20%	Firm
CO2 Capture - All variants	High	Negligible	1,083	Negligible	Uncertain	38%	13%	33%	Secondary
CO2 Storage - All variants	Medium	Not applicable	Not applicable	Not applicable	Not applicable			33%	
CO2 Reuse - Carbonate mineralisation	Low	Not applicable	Not applicable	Not applicable	Not applicable	Not available		26%	
CO2 Reuse - CCU fuels	Medium	Not applicable	Not applicable	Not applicable	Not applicable	Not available			
Flexible conventional - Gas engines	Low	212,280	79,512	1,562,558	699,818	Not available	Not available	32%	
Flexible conventional - Gas turbines	Medium					Not available	Not available		Secondary
Heat pumps	Low	30,000	26,000	84,000	76,000	Not available	24%	29%	

* Level of aggregation driven by expert assessment in summary papers

Wind energy (offshore and onshore)

Wind energy stands out as a technology with relatively high current installed capacities and high expected capacity additions both for the EU and worldwide. Furthermore, the EU knowledge position for wind energy is very strong with approximately 50% of publications originating from Europe, signalling a sound basis to maintain a position of global leadership for this technology. Furthermore, the dependency on neodymium and dysprosium pose a significant dependency risk, especially for offshore wind. Therefore, an in-depth assessment of wind energy critical dependence issues is firmly recommended. Because the critical dependencies for onshore and offshore wind are common, it is suggested the two technology variants be considered at the energy technology family level (wind energy).

Solar PV

Solar PV stands out as a technology with relatively high installed and expected capacities additions. The 25% share of global publications does not indicate such a dominant knowledge position as for wind energy, but still provides a strong knowledge basis to build a globally competitive industry on. Based on these considerations, an in-depth assessment of solar PV critical dependence issues is firmly recommended.

Lithium ion battery storage

Battery storage stands out as having several critical raw material dependencies and also a critical dependency on cell manufacturing capacities. Combined with the uncertain but potentially strong increase in capacities, an in-depth assessment of lithium ion battery storage critical dependency issues is firmly recommended.

Concentrated solar power (CSP)

CSP stands out with a medium extent of critical dependence signalling no major dependence risk but some dependencies that may still be worth paying attention to. The installed and expected additional capacities are modest and the EU knowledge position is strong. Based on these considerations, an in-depth assessment of CSP critical dependency issues could be considered.

Low enthalpy geothermal

Like CSP, low enthalpy geothermal stands out with a medium extent of critical dependence signalling no major dependence risk but some dependencies that may still be worth paying attention to. The installed and expected additional capacities are modest and the EU knowledge position is strong. Based on these considerations, an in-depth assessment of low enthalpy geothermal critical dependency issues could be considered.

CO2 capture

CO2 capture stands out with numerous critical raw material dependencies. Combined with a potentially significant increase in capacities, but with due consideration to the low level of maturity of this technology, an in-depth assessment of CO2 capture critical dependency issues could be considered.

Flexible conventional – gas turbines

For flexible conventional gas turbines, the expected additional capacities for gas-fired power plants are still large globally and some potential critical raw material dependencies have been identified (i.e. cobalt which has also been identified as a critical dependence issue for batteries, CO_2 capture and various other non-energy technologies). However, gas turbines are not a renewable energy technology and would therefore not contribute to the EU objective to be a leader in renewables. Taking this into account, an in-depth assessment of flexible conventional gas turbines critical dependency issues could be considered.

3 Sources and analysis

3.1 Literature sources and expert input (Stage 1 analysis)

Energy technology experts researched dependency issues across all energy technology families/variants (as listed in Table 1) focusing on two key topics: EU reliance on imports and market concentration. Stage 1 was standardised to ensure that a consistent level of research was carried out across each of the energy technology families/variants, and that this research met a minimal standard in terms of quantity and quality of sources. Further detail on the methodology followed during stage 1 assessment is set out in the broad-brush assessment step-by-step manual stage 1 (see Appendix 0).

A wide variety of sources were used including websites, reports, journal articles and books (see Table 2). Reports were the most common source of information followed by websites. A complete list of sources can be found in the bibliography of Appendix **Error! Reference source not found.** – Energy Technology Summary Papers.

Table 2 Number of sources by source type for each energy technology family

	Report	Website	Journal Article	Book	Database	Interview	Patent	Brochure	Slide deck	EC	White paper	Government	Grand Total
Bioenergy	6	13	3	5		2							29
CO2 capture	5	1	8										14
CO2 storage	6	7		2	3	2				2		1	23
CO2 utilization	3	3	7				4						17
Energy storage	16	2	3										21
Flexible conventional thermal power plants	10	17	6	3				2	1		1		40
Geothermal	2		3	1	1								7
Heat pumps	4	7			1								12
Hydrogen & fuel cells	10	17	5	3		1							36
Hydropower	10	7						1					18
Ocean	9	2											11
Solar	9		6		1				1				17
Wind	13	2	6	1									22
Grand Total	103	78	47	15	6	5	4	3	2	2	1	1	267

To optimise the level of research across each of the energy technology families, the first searches carried out for each energy technology family/variant used common databases and search engines, and search terms, as detailed in Appendix 0. Further research was carried out as required.

Furthermore, a minimal standard was set for quantity and quality of sources ensuring that sources were current and credible and that there was adequate coverage of the key topics: EU reliance on imports and market concentration. Table 3 indicates the number of high, medium and low-quality sources used for each energy technology family summary paper. The method for scoring sources can be found in the broad-brush assessment step-by-step manual stage 1 (see Appendix 0).

Table 3 Energy technology family summary paper sources by quality of source i.e. high, medium, low.

	High	Medium	Low	Total # of sources
Bioenergy	15	13	1	29
CO2 capture	13	1		14
CO2 storage	19	4		23
CO2 utilization	11	6		17
Energy storage	15	6		21
Flexible conventional thermal power plants	13	18	9	40
Geothermal	6	1		7
Heat pumps	7	4	1	12
Hydrogen & fuel cells	18	17	1	36
Hydropower	12	6		18
Ocean	10	1		11
Solar	4	13		17
Wind	7	14	1	22
Grand Total	150	104	13	267

3.2 Data collection principles (Stage 2 analysis)

3.2.1 Level of aggregation

The appropriate level of aggregation of the data is informed by the summary papers delivered for stage 1 of the broad-brush assessment. If the experts indicated that the variants of a technology family should be assessed separately because of marked differences in their dependencies, the data collection is also performed at the variant level (e.g. for solar, which is broken down into PV, CSP and heating). If the experts indicated that the variants do not exhibit clear differences in dependencies and could therefore be assessed as one technology family, we collected the data at the technology family level (e.g. for hydro).

3.2.2 Selection of sources

Our selection of sources was driven by:

- **Realism**: especially for 2030 installed capacities we chose to rely on central scenarios that focused on the expected developments rather than the developments that would be needed to reach a certain goal. We used for instance the IEA's New Policies Scenario instead of the more ambitious 450 Scenario which is made to comply with a maximum of 2-degrees warming;

- **Coverage:** we first selected sources that covered as many of our technologies in scope as possible at the required level of aggregation (EU and global figures, broken down into variants when needed). This way, consistency of the data on the respective indicator is safeguarded as much as possible;
- **Time:** we used data sources from the last two to three years where possible and have been careful not to skew data when filling data gaps with slightly older data;
- **Credibility: w**e aimed to use trustworthy and credible data sources where possible. In practice, this resulted in using datasets from the IEA, IRENA and Eurostat in most cases.

We managed to find a select number of data sources that complied with the criteria above and allowed us to populate the majority of the data points. Still, for a few missing data points we needed to use alternative sources. The sources used are identified in the results section.

3.2.3 Exceptions

In some cases, we had to deviate from the data collection principles outlined above: see Table for an overview. These deviations have only a minor impact on the overall purpose of the broad-brush assessment as they concern technologies with limited relevance for mitigation of dependencies (in case the technology is not yet mature or in case no critical dependencies have been identified in stage 1) or have a back-up indicator that provides sufficient information (in case of publications and patents).

Table 4 Overview of deviations from the overarching data collection approach

Technology	Indicator	Issue	Approach
Ocean, geothermal, biomass, flexible conventional	Current and future installed capacities	Not all capacity indicators available at technology variant level	Capacities reported for the whole family
CO2 Storage, CO2 Reuse	Current and future installed capacities	Concept of 'installed capacity' does not apply as it does not concern an energy generation technology	Indicator not reported for technology family
All	Patents	Data not available at variant level	Reported at technology family level
CO2 Reuse, flexible conventional	Patents	No patent data available from central source	Indicator not reported
CO2 capture and CO2 storage	Patents, publications	Patent data reported for Carbon Capture and Storage. No breakdown into the two families	Consolidated indicator reported
All	Publications	No central data source with publications data for multiple technologies	Own research performed on web of science database

The full data set is available in Appendix **Error! Reference source not found.**

3.3 Analysis of energy technology families against criteria (Stage 3 analysis)

As stated in section 0, the energy technology families/variants were selected by a team of five experts following the methodology set out in the broad-brush assessment step-by-step manual (see stage 3 in Appendix 0). Overall, the selection considered the following criteria:

- Critical dependence (see stage 1 results in section 2.1);
- Importance for EU security of supply (see stage 2 results in section 2.2);
- Importance for EU leadership in renewables (see stage 2 results in section 2.2).

During the selection process, the team of experts reached a consensus on the final selection of energy technology families/variants. An overview of their rationale is as follows:

1. Issues of critical dependence are the primary focus of this study. As such, only energy technology families/variants with medium or high extent of critical dependence (see Figure 4) were considered.
2. Impact of critical dependence on EU security of supply is of significant importance. As such, technologies which will play a significant role in achieving EU energy supply targets (as measured by EU current installed capacity additions as seen in section 2.1.1) – and which satisfy point 1 above i.e. are identified as critical dependence issues – were considered as a firm recommendation. Note that flexible conventional gas turbines have been demoted to a secondary recommendation on the basis that it is not a renewable energy technology.
3. Impact of critical dependence on EU leadership is also of significant importance. As such, technologies which will play a significant role in achieving EU leadership in renewables (as measured by current installed capacity and net capacity additions, EU share of global patent applications and EU share of global publications (see section 2.1.2 and 2.1.3) – and which satisfy point 1 above i.e. are identified as critical dependence issues – were considered as a firm recommendation.

Appendice - A1 Summary papers

TABLE OF CONTENT

1 Bioenergy

1.1 Description of bioenergy technologies

Bioenergy covers energy from biomass and energy from renewable wastes. The conversion from biomass and renewable wastes to the final energy products - electricity and heat - can follow many routes, and subsequently follow many different (interlinked) value chains. Therefore, different literature apply different classification methodologies for biomass and bioenergy (IEA, Technology Roadmap, Bioenergy for heat and power, 2012), (ETIP, 2017), (AEBIOM, 2017).

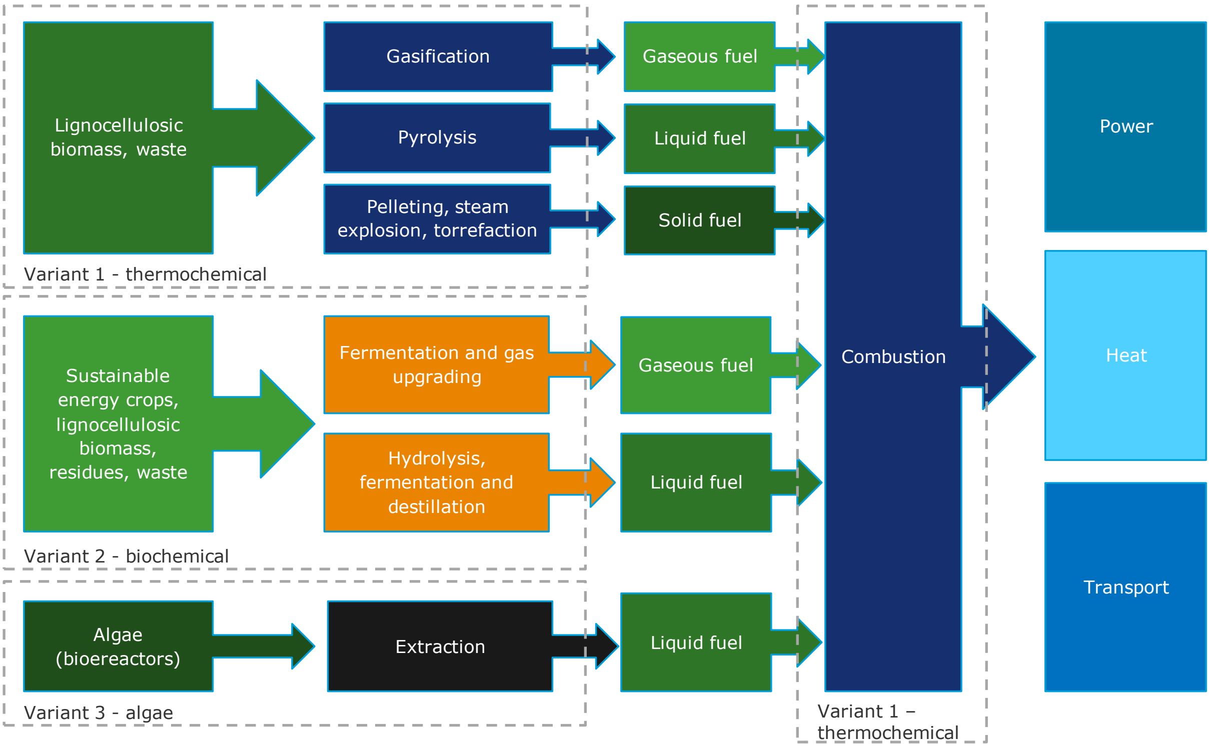


Figure 9 Classification of the energy technologies in the three variants

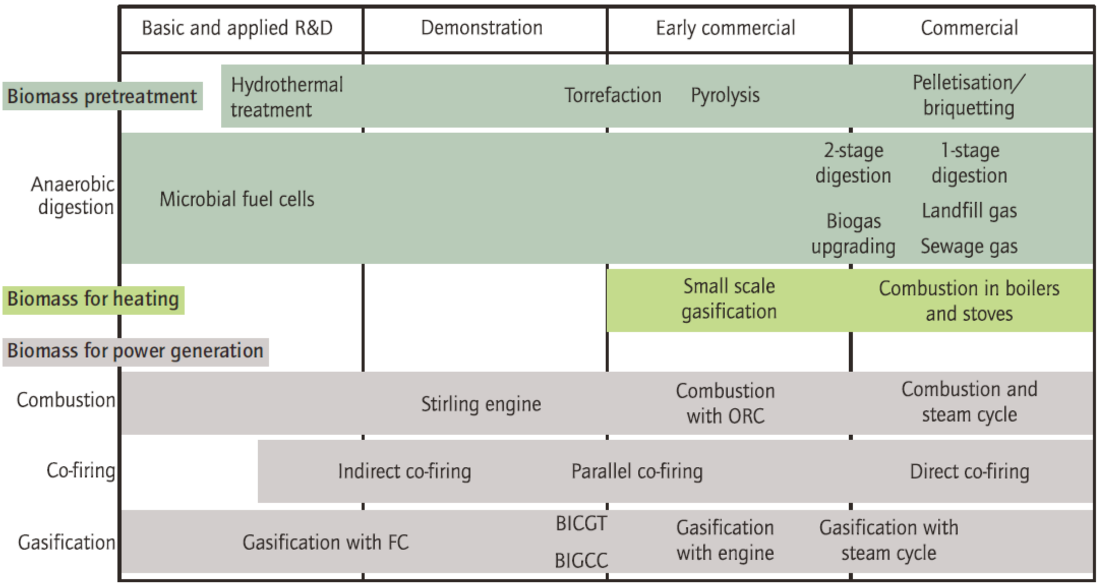
Figure 9 provides an overview of the classification we apply in this summary paper. The three variants of Bioenergy are:

- Thermochemical conversion;
- Biochemical conversion;
- Algae.

1.1.1 The variants

The first variant is thermochemical conversion. This variant includes biomass thermochemical pre-treatment facilities, biomass-fired heat boilers, and combined heat and power plants, and gasification. Thermochemical techniques can be found in Figure 10. The variant is discussed in section 1.2.

The second variant is biochemical conversion in which biological mechanisms convert raw biomass into gaseous or liquid fuel. This is mainly the production of biogas by digestion or bioethanol by fermentation and hydrolysis. The variant is discussed in section 1.3.



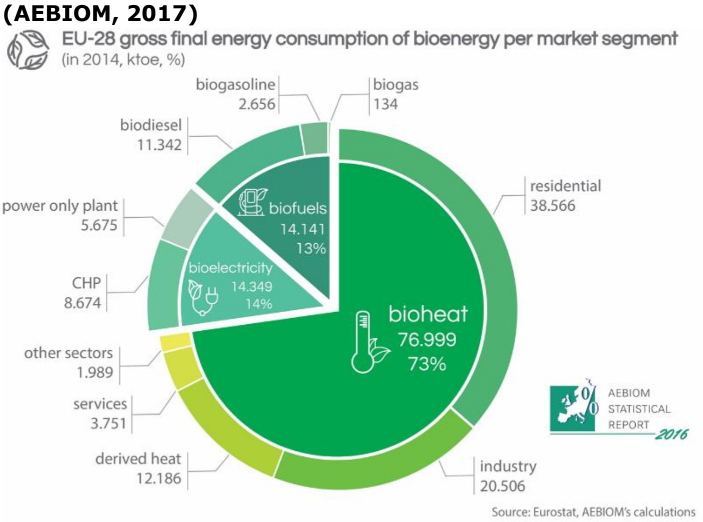
Note: ORC = Organic Rankine Cycle; FC = fuel cell; BICGT = biomass internal combustion gas turbine; BIGCC = biomass internal gasification combined cycle

Source: Modified from Bauen *et al.*, 2009

Figure 10 Overview of conversion technologies and their current development status (IEA, Technology Roadmap, Bioenergy for heat and power, 2012)

The third variant includes technologies that produce algae and convert it to an algae-based fuel. Algae-based biofuels can be used to replace fossil fuels in the transportation and energy sectors. Much has been published on algae recently (Pires, 2017), (Elliot, 2016), (Ehimen, 2016), (ExxonMobil, 2017), (Fuel4Me, 2017). A variety of conversion technologies are under development. These are developed by companies and institutes such as: Sapphire Energy Inc., Algonel Biotech LLC, Genifuel/Reliance, Mudadel Pty. Ltd, and the University of Sydney (Elliot, 2016). Conversion technologies have been demonstrated only at a laboratory and demonstration scale. Currently no large-scale continuous conversion scheme appears to be operational globally (Ehimen, 2016). The FUEL4Me project (Fuel4Me, 2017) shows that the TRL level is currently still far below TRL9. Therefore, we exclude this variant from further analysis.

Figure 11 EU-28 gross final energy consumption of bioenergy per market segment (AEBIOM, 2017)



In 2014, the total biomass and waste fuel production (primary energy production by biomass and renewable wastes) in EU28 Member States accounted for 124 Mtoe (AEBIOM, 2017). The gross final energy consumption from biomass and renewable wastes was 106 MToe (see Figure 11). Gross final energy consumption[6] is energy that is produced as heat or electricity, or energy from biofuels that is used in vehicles. The majority (73%) was for bioheat, followed by electricity (14%). Bioheat accounts for 77.0 Mtoe (3.2 EJ / 895 TWh). Bioelectricity accounts for 14.3 Mtoe (169 TWh).

1.2 Thermochemical conversion

1.2.1 *Description of thermochemical conversion*

Thermochemical conversion techniques include the direct combustion of biomass fuels in boilers and stoves (biomass for heating), or in steam production plants (biomass for production of steam and/or electricity). They also include the (co-)firing of biomass (wood pellets in coal fired power stations) and gasification (for injection of biogas in the gas grid). Finally they include the thermochemical pre-treatment of biomass feedstock to a solid or liquid fuel by e.g. torrefaction or pyrolysis.

Feedstock (lignocellulosic feedstock)

Figure 12 A typical bioenergy value chain, focusing on raw feedstock

A typical bioenergy value chain includes feedstock harvesting as a first step.

Pre-treatment (gasification, pyrolysis, torrefaction, steam explosion)

Figure 13 A typical bioenergy value chain, focusing on pre-treatment

After feedstock harvesting, raw material is converted into a biofuel (pre-treatment). As shown in Figure 10 various pre-treatment options exist, depending on the type of biofuel to be produced. The most important pre-treatment technologies include pelleting, steam explosion, torrefaction, pyrolysis, and gasification:

- Pelleting includes the drying, milling and pelleting of mainly lignocellulosic feedstock. The most important component that will be discussed in the dependency section is the pelletizer;
- The steam explosion process works by thermo-mechanical breakdown of biomass, for which a (batch-type) steam explosion reactor is required. This reactor operates with steam as an operating medium, at temperatures around 200-230ºC;
- The torrefaction process converts, as with the steam explosion process, fibrous biomass to a brittle product. The torrefaction reactor has hot inert gas as a

[6] Gross final energy consumption is defined in Directive 2009/28/EC as the sum of: final energy consumption + consumption of electricity and heat by the energy branch for electricity and heat generation (own use by plant) + losses of electricity and heat in transmission and distribution

processing medium, and operates at temperatures between 240 and 300ºC. The torrefaction technology also has a cooler that needs to prevent the torrefied product from igniting once it is brought in contact with air;

- The pyrolysis process converts a solid biomass into a liquid biomass in a pyrolysis reactor at temperatures typically around 500ºC;
- A gasifier operates at temperatures around 800ºC and a gasification reactor that will be considered.

Conversion (combustion)

Figure 14 A typical bioenergy value chain, focusing on conversion of a raw biomass or biofuel to final energy

Any type of installation that converts biomass or a biofuel into electricity and/or heat is in the conversion step. This is done by the combustion of the biofuel. The main equipment for these installations are a combustor and flue gas cleaning equipment. Furthermore, auxiliary equipment such as wood lines, steam turbines, and generators are needed. These are partly also relevant for the pre-treatment technologies, but will be discussed under the conversion section.

1.2.2 Issues of dependency – Thermochemical conversion

Feedstock (lignocellulosic feedstock)

Thermochemical conversion is dominated by the use of woody feedstock, such as wood chips and wood pellets. As such this section governs:

- The import of wood chips from outside of the EU28 where they are consumed untreated or processed (pelletized) within the EU28;
- The import of wood pellets when they are produced outside of the EU28 and imported to the the EU28.

For residential heating and cooling European (ENPlus) pellets are most generally used (ENPlus, 2017). These are standardized quality pellets. On the whole, these pellets are from local European pellet mills, or pellet mills from neighbouring countries within the EU28 (intra-European trade).

Industry and utility scale steam generators apply wood chips and pellets sourced and produced within the EU, as well as imported wood pellets from outside of the EU. Countries with utility and industry sector biomass or co-firing plants rely on the import of wood pellets.

Currently, Europe is a net importer of wood fuels (Figure 15). Import, however, accounts for less than 3% of total solid biofuels consumption in Europe (AEBIOM, 2017).

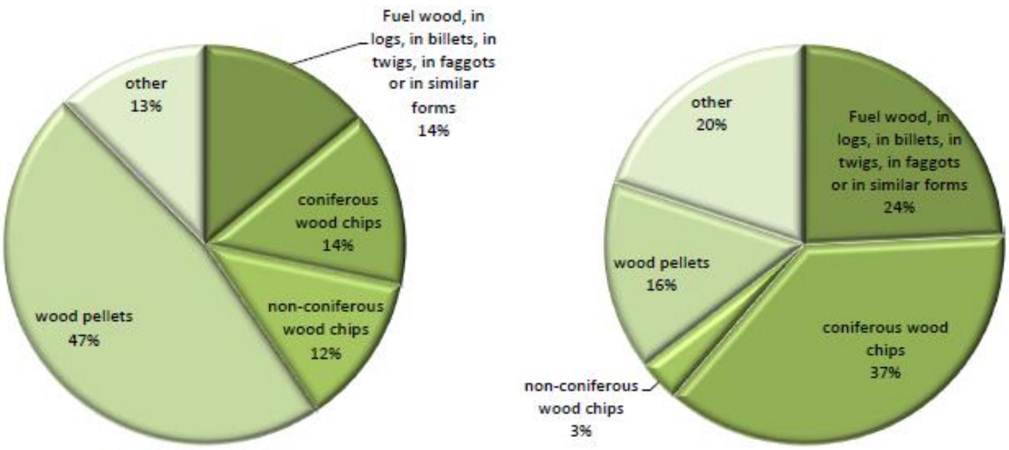
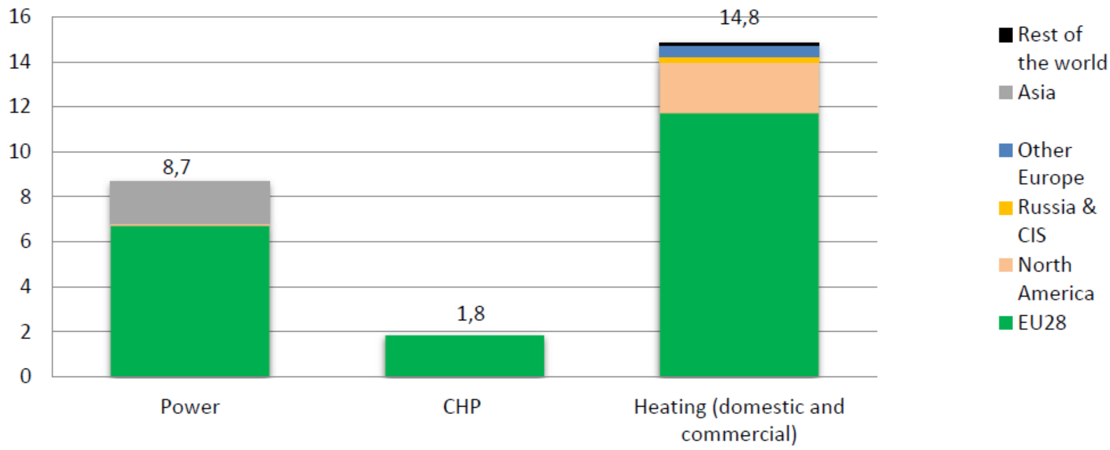


Figure 15 EU28 wood fuels import from third countries in 2013 (left, 12.86 million tons) and wood fuel exports to third countries in 2014 (right, 0.86 million tons total) (AEBIOM, 2017)

The total imports in 2013 were 12.86 million tonnes from outside of the EU28. Figure 15 provides an overview of imports of lignocellulosic biomass. A relatively small share was imported as wood chips, and therefore we consider that the EU28 has no substantial reliance on the import of wood chips. Most the imports were in the form of wood pellets for the industrial and utility sectors. A potential import dependency on wood pellets will be discussed below.



Source: EPC survey

Figure 16 World wood pellet demand in 2015 - power, combined heat and power (CHP), and heating (million tonnes) (AEBIOM, 2017)

Figure 16 provides an overview of world wood pellet demands for the different applications. The power application relates mainly to co-firing of wood pellets pulverized coal fired power plants (dominantly in the UK), whereas heating is mainly for residential heating.

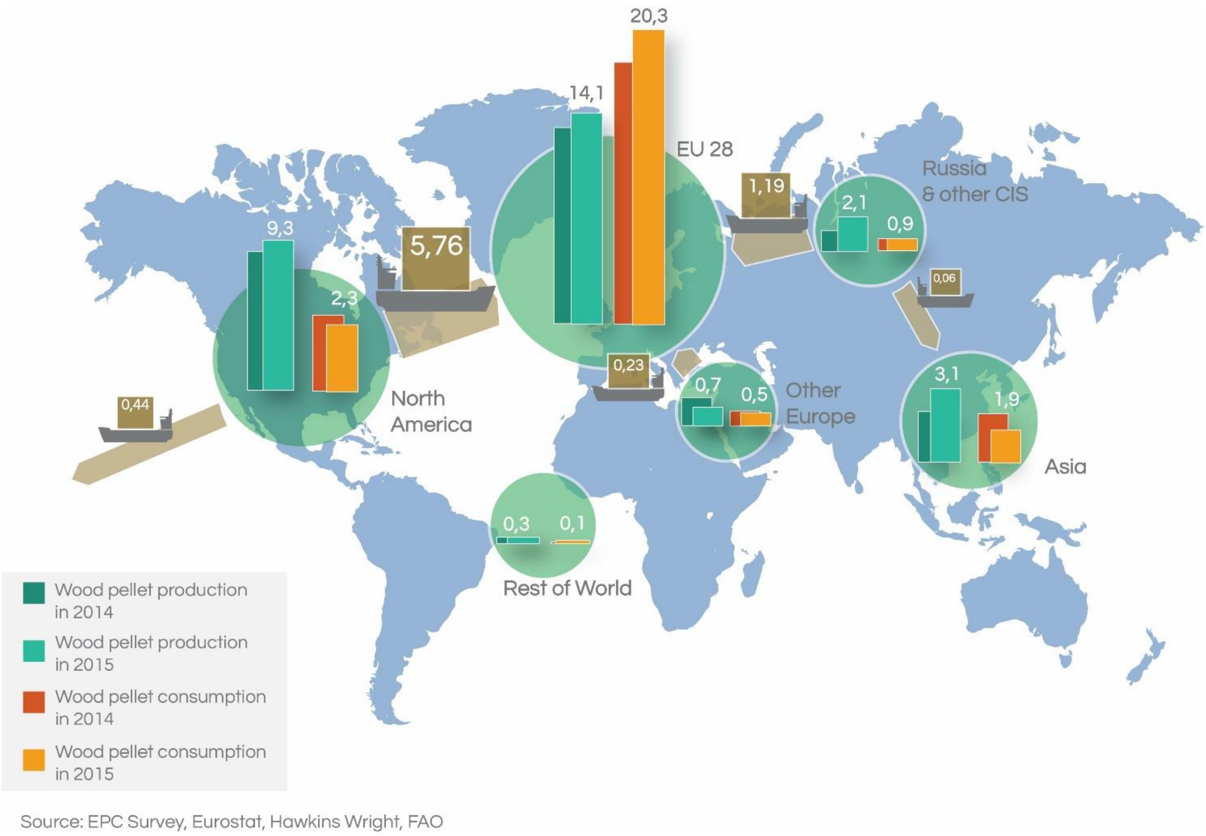


Figure 17 World pellet map and tradeflow (in 2015, million tonnes) (ENPlus, 2017)

Figure 17 confirms that more pellets are consumed in the EU28 than there are produced. Hence, we consider that there is currently partly an import dependence of wood pellets.

Market concentration of the pellet mills outside of the EU28 is around countries like Canada, the USA and Russia. Major companies that trade wood pellets on the international markets include for example Enviva (USA), Rentech (USA), and Pinnacle (Canada). A major European pellet producer is Graanul (Estonia). All of these companies produce pellets for the utility and industrial markets (industrial pellets).

Pre-treatment

Table 5: Thermo-chemical pre-treatment options

Pre-treatment option	Critical equipment	Biofuel	Development stage (IEA, Technology Roadmap, Bioenergy for heat and power, 2012)	Selected technology providers and (country)
Wood pelleting	Pellet mills	Solid biofuel (pellets)	Commercial (>10 mton/a)	Pellet presses, e.g. C.F. Nielsen (Norway), Amandus Kahl (Germany), CPM Europe (Netherlands), Muench Edelstahl (Germany)
Steam explosion	Reactor	Solid biofuel (pellets)	Demonstration (<< 1 mton/a)	Arbaflame (Norway), Zilkha (USA)
Torrefaction	Reactor	Solid biofuel (pellets)	Demonstration (<< 1 mton/a)	CEG (Netherlands), Torrcoal (Netherlands), Airex (Canada), Blackwood Technology (Netherlands), River Basin Energy (USA),

Pre-treatment option	**Critical equipment**	**Biofuel**	**Development stage (IEA, Technology Roadmap, Bioenergy for heat and power, 2012)**	**Selected technology providers and (country)**
				CMI (Belgium), TSI (USA)
Pyrolysis	Reactor	Liquid biofuel (oil)	Early commercial (< 1 mton/a)	Ensyn/Honeywell (Canada/USA), BTG (Netherlands), Fortum (Finland)
Gasification		Gaseous biofuel (gas)	(Early) commercial (not defined)	Valmet (Finland), Andritz Oy (Finland), Babcock & Wilcox (USA), Amec Foster Wheeler/Wood Group (

Table 5 provides the most common pre-treatment options. The next paragraphs will discuss each of the pre-treatment options.

Wood pelleting

For wood pelleting, pellet presses are the most important piece of equipment. There are numerous EU28 companies that provide pellet presses (first row in Table 5). The other equipment is treated in the conversion paragraph (below), and therefore is not further discussed here. The EU28 has several companies that can build wood pellet plants as well as several suppliers of the main equipment needed (e.g. Andritz).

Steam explosion

For steam explosion, there is a reliance on non-EU28 technology providers. Currently, only Zilkha (USA) and Arbaflame (Norway) are known technology providers, incurring a technology (IP) risk. Both are non-EU28 companies. The steam explosion technology is currently at demonstration scale with limited quantities produced. It is therefore uncertain how the market for this product will evolve. As the main developers are outside of EU28 a technology reliance exists. In addition, market concentration is high. However, given the relatively low TRL level and the uncertainty on future market demands by the EU28 (steam explosion pellets are a substitute for wood pellets), this element of the value chain is currently considered as non-critical.

Torrefaction

For torrefaction, there are numerous developers. They apply different technologies (fluid bed, screw, rotary drum, etc). The development status of the individual developers ranges between lab scale and demonstration scale/early commercial scale (IEA_Task_32, 2015). The main equipment used in torrefaction are reactors and coolers. These are mostly fabricated of structural steels and stainless steel (to protect against the corrosive nature of the condensables in the torrefaction gases). As many of the IP, developers, and equipment manufacturers are located in Europe, and by the low reliance risk on materials, no critical dependencies are expected. Furthermore, future market demands by the EU28 countries are uncertain (torrefaction pellets are a substitute for wood pellets). Therefore this element is currently considered as non-critical.

Pyrolysis

Equipment that differentiates a pyrolysis plant from other biofuel producing plants include a pyrolysis reactor, a cyclone, and bio-oil recovery installation and storage tanks. This covers all main equipment for producing raw pyrolysis oil, in line with the current early commercial state-of-development. The corrosiveness of the pyrolysis oil (condensed) requires equipment to be fabricated from stainless steel. Technologies for upgrading raw pyrolysis oil to a gasoline or diesel fuel are under development but have not yet been proven at demonstration scale. Equipment required for converting the raw pyrolysis oil into a diesel or gasoline fuel includes a hydrotreating/hydrocracking facility as a minimum. In order to regenerate hydrogen (needed for the hydrocracking facility) and for the production of a fuel gas, a gas separator, reformer, and pressure swing absorption system can be installed. The current stage of development is, however, only at laboratory or (early) demonstration scale. Two of the three main technology developers are located in the EU28. A major developer (Evergent Technologies: a joint venture between Ensyn and Honeywell) is located in North America. For the production of raw pyrolysis oil, currently no reliance on equipment, materials or suppliers of technologies (specific to a pyrolysis plant) have been found. For the production of upgraded pyrolysis oil into a biodiesel/biogasoline the TRL level is still low, and these biofuels are primarily aiming at the transportation sectors rather than the bioenergy sector.

Gasification

For gasification, a number of technologies exist (Task33, 2017), depending on scale and application. These are fixed bed (small scale), fluidized bed (medium scale) and entrained flow reactors (large scale). Gasification technology is considered as commercial. Technology providers include EU28 companies like Valmet (Finland) and Foster Wheeler (United Kingdom). Europe is an exporter of gasifiers, e.g. to Indonesia (Valmet, 2017). Currently no reliance on equipment, materials or suppliers of technologies (specific to a gasifier) have been found.

Conversion (combustion)

In the conversion step the raw or pre-treated biomass (solid, liquid or gaseous) is converted to electricity and/or heat. We can categorize them by size and type.

Stoves and boilers for residential heating

Residential heating includes boilers and stoves for houses and residential applications. The boilers are manufactured by numerous European companies, and mainly have plate steel as materials used. For wood stoves cast steel is frequently used, but also plate steel (Hartmann, 2017). Most boilers that are sold in the EU are also manufactured in the EU (e.g. in Austria). Several stove manufacturers have their production abroad, e.g. in India (Hartmann, 2017). As such residential boilers and stoves are not considered to have critical dependencies.

Hot water boilers and steam generators and steam driven heat and power plants

The main elements for heat boilers include materials for the boilers, materials for steam turbines, catalysts for flue gas cleaning, materials for generators, manufacturers of major components for power plants, and service companies.

European EPC contractors of biomass plants benefit from a large variety of suppliers providing the main equipment items. These are discussed below.

Boiler suppliers for small or mid-size boilers are various and include for example Valmet (Finland), Vyncke (Belgium), WES (UK), KARA (Netherlands) and Mawera (UK). Large boilers are supplied by European manufacturers like Andritz (Austria), BWE (Denmark), Stork (Netherlands) and Valmet (Finland).

Table 6 Chemical composition of the alloys in biomass and waste to energy boilers, investigated by (Viklund, 2013)

	Alloy designation:		Fe	Cr	Ni	Mo	Mn	C	Other
Ferritic	13CrMo44	EN 1.7335	Bal.	0.9	0.1	0.5	0.5	0.12	
Ferritic-martensitic	HCM12A	-	Bal.	11.3	0.5	0.5	0.5	0.11	B, V, W
Austenitic	Esshete 1250	EN 1.4982	Bal.	15.5	9.3	1.1	6.3	0.08	Nb,V
	304	EN 1.4301	Bal.	18.2	8.4	0.4	1.7	0.02	
	304L	EN 1.4306	Bal.	18.2	10.1	-	-	0.02	
	Super 304	EN 1.4567	Bal.	18.0	9.0	-	0.8	0.03	Cu, Nb
	317L cladding	EN 1.4438	Bal.	18.5	14.5	3.1	1.7	0.03	
	310S	EN 1.4845	Bal.	25.1	19.4	0.1	1.0	0.05	
	Sanicro 28	EN 1.7380	Bal.	26.6	30.6	3.3	1.6	0.09	Cu
Nickel-base	Hastelloy C-	EN 2.4675	1.2	22.5	Bal.	15.7	0.2	0.00	Cu
	625 cladding	EN 2.4856	1.0	21.4	64.5	8.5	0.4	0.01	

The EU has published a list of critical raw materials (EU, 2017). This lists indicates that from the materials in Table 6, none are critical.

Steam generators often operate at steam temperatures in the range of 480-540ºC. The exact temperature depends on the corrosiveness of the flue gas (chlorine content in the biomass). This also results in different steel types applied in the various boiler parts (Table 6 for superheater parts, which are most critical). Corrosion is further prevented by a protective layer (cladding). Waste-to-energy assets generally have an (Inconel) cladding. The most commonly used cladding is Inconel 625 (also in Table 6). The main metals used within the alloys are Fe, Cr and Ni. Although the EU28 imports these metals, market concentration is low, and they are abundantly available. For the cladding and nickel based steels Molybdenum (Mo) is also required. Molybdenum production occurs as a by-product of copper production and through primary molybdenum mining. The total world production from mining is around 250,000 tonnes per year. Although the EU28 would rely on the import of Molybdenum, the quantities needed compared to the production capacity is very low. As there are several markets that have sufficient capacity available, the dependency risk is low.

Steam turbines are essential equipment for generating electricity from steam. Suppliers of large steam turbines include Siemens (Germany), General Electric (USA), GE-Alstom (USA/Switzerland), Mitsubishi Hitachi Power Systems (Japan/Germany), Ansaldo Energia (Italy), Bharat (India) and MAN (USA). Smaller steam turbines with a capacity of several MWe are supplied by for example MAN (USA), Dresser-Rand (A Siemens company, Germany), General Electric (USA), Bharat (India). Overhauls and repairs can be performed by companies like Sulzer (Switzerland). For the fabrication of steam turbines Molybdenum is required, which is considered a non-critical dependency.

Biomass plants (>1 MWth) need, at the very least, to be equipped with Selective Non-Catalytic Reduction (SNCR) for reduction of the emission of NO_x. However, local competent authorities tend to require Selective Catalyst Reduction (SCR catalysts). A short-term peak demand on SCR catalysts is expected after 2020 and the global production capacity is expected to be approximately equal to the expected demand. The catalysts are needed for pulverized coal fired plants, but they are also required for other combustion plants. The demand will only be high for a few years. Most of the SCR Catalyst applied in the EU will need to be imported from Cormetech (USA), Mitsubishi Heavy Industries (Japan), Johnson Matthey (UK) and Haldor Topsoe (Norway). Consequently, there is likely to be a reliance on SCR catalyst for a restricted period of time, with the main manufacturers within a number countries (medium market concentration).

An electric generator is a key rotating equipment for producing electricity from the rotational energy provided by a steam turbine. Electric generators use copper (Cu) as their main metal, but can alternatively also use alumina (Al). The supply risk of copper is considered low. Main European suppliers of generators and electrical equipment are Siemens (Germany) and Alstom (France).

The EU28 has various manufacturers of main equipment for biomass combustion installations. These OEMS include Valmet (Finland), Amec Foster Wheeler (UK), Burmeister & Wain Energy A/S (Denmark), Doosan Babcock (UK), and Andritz (Austria) for the wood lines and boilers. No reliance on non-EU28 manufacturers is therefore expected.

As can be concluded from the above, the EU28 has a leadership position for bioenergy and waste-to-energy infrastructures. It is observed that Chinese companies are acquiring European waste-to-energy companies (e.g. E.ON Energy from Waste, AVR). Intellectual capacity building is considered as a main reason for these acquisitions (Wilson, 2016).

1.3 Biochemical conversion (by fermentation and biocatalysts)

1.3.1 Description of Biochemical conversion (by fermentation and biocatalysts)

Industrial biotechnology, also known as white biotechnology, uses enzymes and micro-organisms to improve industrial processes and generate valuable products in sectors as diverse as chemicals, food and feed, healthcare, detergents, paper and pulp, textiles, and energy (BIO-TIC, http://www.industrialbiotech-europe.eu/about-industrial-biotechnology/, 2017). Bioconversion is the conversion of biological or chemical substances into useful products either through fermentation or through biocatalysis where microbially-produced enzymes are used to catalyse industrial chemical reactions.

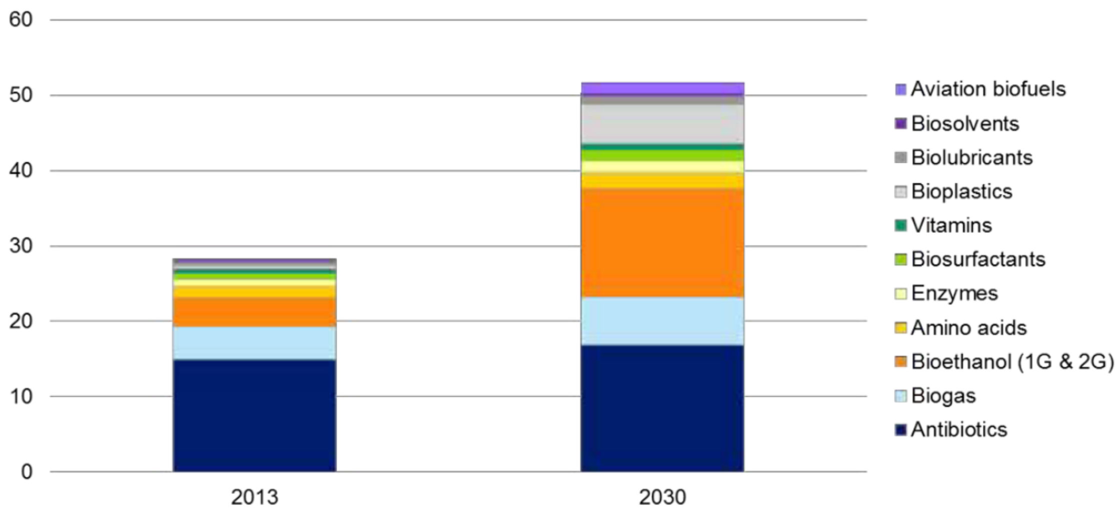


Figure 18 Estimated industrial biotechnology market demand (in billion euros) in the EU up to 2030 (BIO-TIC, The bioeconomy enabled, A roadmap to a thriving industrial biotechnology sector in Europe, 2015)

Currently, the main products from the industrial biotechnology are antibiotics, biogas and first and second generation bioethanol (see Figure 18); the latter two are fuels. Therefore, they are within the scope of the current study (bioenergy), although they will also serve as an ingredient for petrochemical production processes.

According to the BIO-TIC, the industrial biotechnology market will grow to 52 billion euros in 2030 (BIO-TIC, http://www.industrialbiotech-europe.eu/about-industrial-biotechnology/, 2017). The production of biogas is expected to grow slowly, whereas the production of bioethanol is expected to grow rapidly. The rise is mainly contributed to the production of biobased materials (chemical industry) (Eubia, 2017). However, biobased materials are excluded from this summary paper.

The two most important biofuels that are derived from biochemical processes are biogas and bioliquids (biodiesel/bioethanol). Bioethanol is primarily a fuel in the transportation sector. The transportation sector (and subsequently bioethanol) is excluded from further analysis. Biogas, however, will be discussed in more detail below.

Biogas

Biogas (methane and CO_2) is produced by the fermentation of various streams of organic waste materials (organic fractions of waste, sugar rich leftovers from food and feed, manure, etc.). Anaerobic digestion applies anaerobic micro-organisms to produce biogas in a digestor. Cleaning and upgrading of the gas is generally needed to inject the biogas in a gas network. The main equipment required are the digestors and the gas upgrading facilities.

Already throughout Europe, 200 biomethane plants are in operation. Biomethane is the cleaned, upgraded, and conditioned biogas that can be fed into the natural gas grid. This shows that gas upgrading technology is mature and utilised in Europe (Intelligent Energy Europe, 2013).

Dependencies for the digestors and gas upgrading facilities will be discussed in the next section.

1.3.2 *Issues of dependency – Biochemical conversion*

Biogas – digesters

Structures for fermentation (digesters) are primarily made of steel and concrete (Samer, 2012). As such, no dependency risk is expected for these structure, as there is no critical dependency expected for steel and concrete. The roofs (membranes) of digesters are primarily made of plastic (PVC) foil or aluminium. There are no issues of dependency for these materials (Holstein, 2017). Rudders inside the digesters are made from copper, which also gives no issues of dependency.

Germany is the worldwide market leader in the production and operation of digesters (Holstein, 2017) (European Biogas Association, 2011). In Germany, approximately 50 companies of various sizes are active, operating in several countries around the globe. Furthermore, in 2011 Germany was a net exporter of such digesters (European Biogas Association, 2011). The European Biogas Association published a list of leading companies active in the biogas industry and their business areas which clearly indicates that there is an abundance of biogas digester producers in Europe (European Biogas Association, 2016).

Biogas – gas cleaning

Pressure swing adsorption is one of the most frequent techniques of biomethane production. In this technology, CO_2 and H_2S is removed from the biogas by adsorption onto an activated carbon surface or on a zeolite molecular sieve (Biernat & Samson-Brek, 2011). The EU28 is both an exporter and importer of activated carbon (OEC, 2017) with the value of imports only exceeding the value of exports by 4%. Countries that export activated carbon, excluding the EU28, include the USA (largest share), China, the Philippines, India, and Japan. Therefore, no critical dependencies are expected for pressure swing adsorption technology.

Additionally to pressure swing adsorption, the water scrubber, organic scrubber, and chemical scrubber (on the basis of amines) technologies exist. Water scrubbers are widely available. There are also many suppliers of this technology and the necessary equipment (Biernat & Samson-Brek, 2011). This reduces import reliance risk for new projects.

An interview of experts highlighted that the main suppliers of biogas cleaning equipment are based in Europe (e.g. Evonik, DMT, Malmberg) with many of the manufacturers being German companies (Holstein, 2017).

1.4 Conclusions

1.4.1 *Critical dependencies*

Thermochemical conversion

Residential boilers apply domestic high-quality wood pellets from national suppliers or suppliers from neighbouring countries. Hence, there is no reliance on imports for residential pellets. Also wood chips are mostly from local markets and no reliance on wood chips exist. There is a substantial import of industrial wood pellets that are fired in large utility (pulverized coal) fired boilers. Imports of industrial wood pellets are mainly supplied by the USA and Canada, and can potentially also be supplied from South East Asia (Indonesia) or by the Baltics (EU28). There are currently 4 or 5 main suppliers of industrial wood pellets. Market concentration is therefore medium to high.

Residential boilers and steam generating biomass fired boilers do not show critical dependencies for materials, components or suppliers.

The EU28 has a leadership position in the design and construction of biomass fired power plants and heat boilers.

Biochemical conversion

Biochemical conversion includes the production of biogas and bioethanol by fermentation and hydrolysis. We focus on the generation of electricity and heat, as biogas is consumed for these purposes. However, bioethanol is primarily applied for transportation, and therefore its related technologies have not been investigated. Biogas technologies (digestion and gas upgrading) do not show critical dependencies for materials, components or suppliers.

1.4.2 Consideration of variants

Currently, the variants are largely independent. Thermochemical conversion techniques tend to use woody feedstock, where biochemical conversion techniques tend to use sugar rich feedstock. Also the techniques are different by process nature and process conditions. Thermochemical conversion primary equipment includes boilers, turbines, generators, and thermal reactors; whereas the primary equipment for biochemical conversion has biochemical reactors. Few identical components (e.g. dryers) are used across the different variants. Hence, the variants should be treated separately in stage 2 and 3.

2 CO_2 capture

An abundance of CO_2 is created in the conversion of fossil fuels or biomass to electrical power and heat, and also by some other industrial processes. Industry CO_2 emissions made up 26% of global CO_2 emissions in 2013, with 8.9 $GtCO_2$ (International Energy Agency, 2016). Using both chemical and physical separation technologies, CO_2 can be removed from the exhaust gases of combustion and conversion processes, after which it can be stored or utilized. The removal and subsequent storage or utilization of CO_2 is referred to as carbon capture, utilisation and storage (CCUS). Certain CCUS chains, particularly permanent geological storage of CO_2, can decrease the contribution of fossil fuels to global warming, by preventing the emission of CO_2 into the atmosphere. This summary paper is focused on the technologies used to remove the CO_2 from exhaust/waste gases of industrial processes.

Carbon capture variants are pre-combustion, post-combustion, and oxy-fuel combustion. In pre-combustion carbon capture, CO_2 is removed during the process of creating a hydrogen rich fuel. In post-combustion carbon capture, CO_2 is captured and separated from a flue gas created in the combustion of fossil fuels/biomass or in another industrial process. In oxy-fuel combustion carbon capture, a high purity CO_2 stream is captured during the process of burning fuel with oxygen (instead of air).

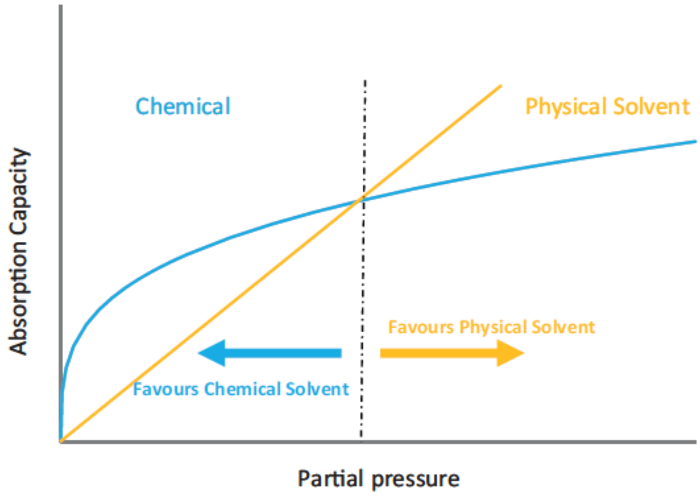
2.1 CO_2 pre-combustion capture

2.1.1 Description of CO_2 pre-combustion capture

Pre-combustion CO_2 capture is one of the three main forms of CO_2 capture. This variant is preferred at higher CO_2 pressures and concentrations (see Figure 1), because physical absorption solvents have a higher absorption capacity than chemical absorbents at higher partial pressures of CO_2. (Jansen, Gazzani, Manzolini, van Dijk, & Carbo, 2015) In pre-combustion, syngas (H_2, CO and CO_2) is created in the gasification of fossil fuels and/or biomass. The H_2 content of syngas can be increased, from CO/H_2 to CO_2/H_2, by a water gas shift reaction with steam. The CO_2 can be subsequently removed leaving a hydrogen rich fuel. (Jansen, Gazzani, Manzolini, van Dijk, & Carbo, 2015)

The main forms of pre-combustion CO_2 capture are physical absorption, adsorption, and membrane technology. The physical absorption process is the most established variant of pre-combustion. In the physical absorption process, CO_2 is dissolved into a solvent. The amount of CO_2 absorbed depends on the specific solvent solubility, which depends on the partial CO_2 pressure that the solvent is exposed to. Therefore the physical absorption technology works more efficiently at higher CO_2 partial pressures (see Figure 19).

Figure 19 : Chemical absorption versus physical absorption. The figure shows that a physical solvent is preferred at higher CO_2 pressures and a chemical solvent is more suitable for lower partial pressures of CO_2 (Jansen, Gazzani, Manzolini, van Dijk, & Carbo, 2015).



In membrane technology, the membranes are designed to form a selective barrier that separates CO_2 from the other components. The membrane is a material that is highly selective for the separation of CO_2, or less selective so other gaseous components such as H_2S and SO_2 are simultaneously separated. A trade-off for the high CO_2 selectivity is a low mass flow of CO_2 removal, which translates into the need of a large membrane area, and elevated costs (Sreedhar, Vaidhiswaran, Kamani, & Venugopal, 2017). Membrane technology is not ready yet for commercialization in the context of CO_2 capture from flue gases.

Solid materials can be used to adsorb CO_2. The adsorbents can then be regenerated by either a pressure or temperature swing process, where the material is exposed to either low pressure or high temperature (Abanades, et al., 2015). At the moment the technology is not ready to be commercially applied in carbon capture plants, because the cycle time is too long and adsorbent capacities are not high enough (Abanades, et al., 2015).

2.1.2 Issues of dependency – pre-combustion CO_2 capture

For pre-combustion carbon capture the essential components investigated are physical absorption solvents, membranes, adsorbents, catalysts for the water gas shift reaction, and turbines for hydrogen rich gas.

For the physical absorption the main component is the solvent.

Table 7 shows the different vendors of the solvents used for physical absorption. These companies are either based in Europe or in the USA. As such, there is a possible dependence on the US for solvents used in physical absorption.

Table 7 : Solvents used for physical absorption and their vendors (Theo, Lim, Hashim, Mustaffa, & Ho, 2016).

Commercial physical absorption process	Chemical	Vendor
Selexol	Dimethyl ether of polyethylene glycol (DMPEG)	Union Carbide (USA)
Rectisol	Methanol	Lurgi and Linde (Germany Lotepro Corporation (USA)
Purisol	N-methyl-2-pyrolidone	Lurgi (Germany)
Morphysorb	Morpholine	Gas Technology Institute (GTI) (USA)
Fluor process	Propylene carbonate	Fluor Daniel (USA)

Figure 20 : Bar graph from (Li, Duan, Luebke, & Morreale, 2013). The Figure shows an overview of the number of patents for membranes, solvents and sorbents by country. Patents valid in Europe are European patent office (EP), Germany (DE), France(FR), Great Britain (GB) and the worldwide patents (WO).

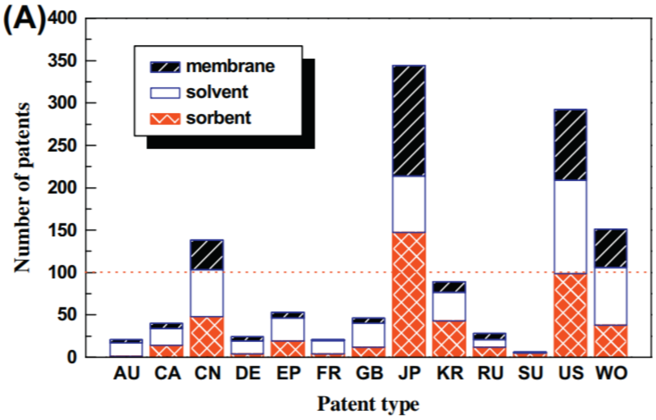


Figure 20 shows the intellectual property rights in different countries for membranes, solvents and sorbents, of which some will be valid in Europe (i.e. EP, FR, DE, GB and WO) (Li, Duan, Luebke, & Morreale, 2013). It appears evident that the majority of patents for membranes, solvents, and sorbents which can be associated with CO_2 capture systems, have been predominantly registered in the countries of Japan, the United States and Canada. Far fewer patents have been registered in European Member States. This could indicated that the EU does not have a leading position in knowledge and intellectual property regarding such technologies. However it would be inappropriate to state that this could lead to a dependency on these technologies from countries outside the EU. In any case, it appears that there are entities in Germany, France and Britain active in the field of membrane, solvent, and sorbent development.

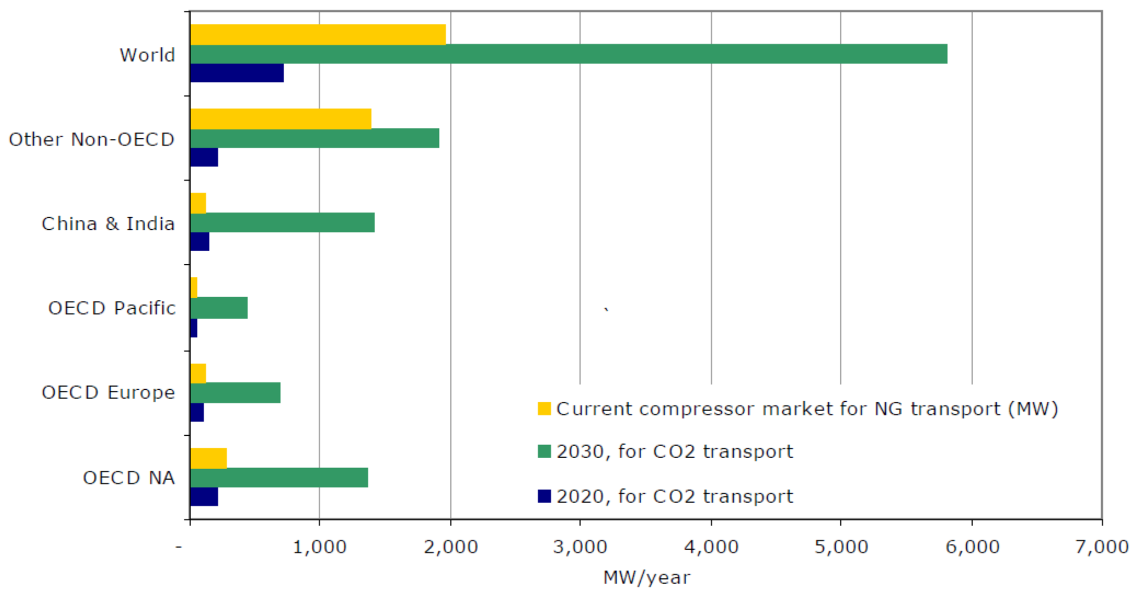
For the water gas shift reaction, where CO and H_2O are converted to CO_2 and H_2, catalysts are necessary. Materials used for the shift reaction catalysts are copper, zinc, aluminium oxide, chromium oxide, copper oxide, sulphide cobalt oxide, molybdenum oxide, and copper-promoted iron chromium oxide (Jansen, Gazzani, Manzolini, van Dijk, & Carbo, 2015) (van Breevoort, et al., 2011). The critical materials for these catalysts are cobalt and chromium, and these elements are on the EU's critical materials list. The EU has a cobalt dependency on the Democratic Republic of Congo (56% of worldwide production) and chromium dependency on South Africa and Kazakhstan (43% and 20% of worldwide production) (Ad Hoc Working Group, 2014).

In the pre-combustion method a hydrogen rich fuel is created. To combust this hydrogen rich fuel and convert it to electricity and heat, a suitable gas turbine is required. The manufacturers that are able to develop and produce these gas turbines are GE, Mitsubishi Heavy Industries, Siemens Westinghouse, and Alstom (van Breevoort, et al., 2011). Commercially available gas turbines exist, but further research and development is necessary for efficient use in carbon capture. GE, Mitsubishi Heavy Industries, and Siemens Westinghouse are the only manufacturers that are involved in R&D aimed at efficient gas turbines for hydrogen rich gas. Considering that the manufacturers operate globally, no dependencies are expected.

Following each carbon capture process, i.e. pre-combustion, post-combustion and oxy-fuel combustion, CO_2 gas must be compressed. Compression technologies have already been developed for the natural gas industry, but will have to be deployed on a large scale for CCS over the next 30 years. Figure 21 shows the predictions of the compressor demand in the current situation, 2020 and 2030. The main producers of compressors are located in Germany, Japan and the USA. (van Breevoort, et al., 2011) There are fewer suppliers for the high pressure compressor systems (Dresser Rand, GE, Man Turbo, Hitachi, Siemens), but most of these are based in Europe.

CO_2 compressors for oxy-fuel combustion and offshore transport do require more research and development, due to contaminations (water, SO_x and NO_x) and high pressure compression (van Breevoort, et al., 2011). Stainless steel is the material of choice for the compressors and this is made of steel together with manganese, nickel, and chromium. As discussed before, in the future chromium might become sparsely available in the EU.

Figure 21 : Compressor market predictions till 2030. (van Breevoort, et al., 2011)



2.2 CO_2 post-combustion capture

2.2.1 Description of CO_2 post-combustion capture

CO_2 post-combustion capture is the most mature form of carbon capture and the only form that has been realized on a commercial scale. The Boundary Dam Unit 3 plant in Canada and the Petra Nova plant in the United States capture 1 Mtpa and 1.4 Mtpa of CO_2 using post-combustion capture technologies (Global CCS institute, 2016). When fossil fuels or biomass is burned CO_2 is created. These CO_2 streams have a low partial pressure and a lower CO_2 concentration, of which post-combustion CO_2 capture is the most suitable capture technique for the removal of CO_2.

Multiple techniques can be used for post-combustion capture, but chemical absorption is the only technique that is currently commercial (Sreedhar, Nahar, Venugopal, & Srinivas, 2017). Chemical absorption uses specific solvents that absorb CO_2. The technique to remove CO_2 and H_2S (using alkanolamines) is already applied in the oil and gas industry. However, it is not completely transferrable to post-combustion carbon capture technologies due to the pressure difference between the petrochemical and the carbon capture processes. In addition, the presence of a relatively high content of oxygen in the flue gas leads to oxidative degradation of the solvents, which further inhibits the transferability of this technique. Research is still ongoing to develop new solvents and optimize the industrial processes for carbon capture; but it is unknown which solvent will be broadly adopted by the industry, should it become necessary to do so.

For the process of absorbing CO_2 and regenerating the solvent there are three main components in the system: solvent, absorber and stripper. The CO_2 is exposed to the solvent in the absorption tower, after which the absorbed CO_2 in the solvent can be removed in the stripping column. The separated CO_2 gas can be compressed and sent to storage.

2.2.2 Issues of dependency – CO_2 post-combustion capture

The dependence of the EU on CO_2 post-combustion capture technology relies on property rights and the commercial scale production of the solvents, and specific suppliers of the industrial equipment.

An essential part of the CO_2 post-combustion capture is the absorption achieved by the solvent. Many different solvents exist and are being developed. Shell has developed the Cansolv technology which is currently applied at the Boundary Dam carbon capture plant and BASF has developed the OASE blue technology, making these solvents commercially available (Koytsoumpa, Bergins, & Kakaras, 2017).

It is unsure which exact solvent will dominate the market in the future and usually specific mixtures or components are protected by patents (see Figure 2). It is not expected that the intellectual property of certain solvents or solvent mixtures is going to be a problem: a lot of solvent variants could still be used and they are produced using abundantly available chemicals such as ammonia, hydrogen, and nitrogen. Tables Table 8, Table 9, and Table 10 show that the base chemicals are widely available and that Europe's dependence on these chemicals should therefore be minimal. However, it is necessary to develop commercial scale production of these solvents for future deployment of CO_2 post-combustion capture.

Table 8 : European Union's export and import of ammonia in 2015 according to (COMTRADE, sd)

Import & Export Ammonia exchange units, 2814					
Event	**Region**	**Trade flow**	**Partner country**	**Trade value**	**Balance of trade**
2015	EU-28	Export	World	0.71 bln $	-
2015	EU-28	Import	World	1.1 bln $	

Table 9 : European Union's export and import of hydrogen in 2015 according to (COMTRADE, sd)

Import & Export Hydrogen exchange units, 280410					
Event	**Region**	**Trade flow**	**Partner country**	**Trade value**	**Balance of trade**
2015	EU-28	Export	World	2.3 million $	+
2015	EU-28	Import	World	0.6 million $	

Table 10 : European Union's export and import of nitrogen in 2015 according to (COMTRADE, sd)

Import & Export nitrogen exchange units, 280430					
Event	**Region**	**Trade flow**	**Partner country**	**Trade value**	**Balance of trade**
2015	EU-28	Export	World	10.6 million $	+
2015	EU-28	Import	World	10.2 million $	

The industrial equipment components that are necessary for CO_2 post-combustion capture are absorption towers, stripping towers, deNOx units, deSOx units, and compressors. The EU's dependence on compressors has already been discussed for pre-combustion CO_2 capture.

In post-combustion capture, using chemical absorption, CO_2 is brought into contact with the solvent in an absorption tower. There are many absorption tower suppliers worldwide such as Fluor (USA), Linde (Germany), Siemens (Germany), Powerspan, Aker Solutions (Norway), MHI, BASF (Germany), HTC Pure Energy, and Alstom (France) (van Breevoort, et al., 2011). There are many European based producers of absorption towers. However, it is not clear whether European based producers are capable of producing the large scale absorption towers necessary for full scale CCS plants.

Absorption towers require a large amount of steel. Large scale introduction of CCS could cause a temporal shortage of steel, corrosion resistant steel and packing materials (van Breevoort, et al., 2011). Furthermore, corrosion resistant steel contains chromium which has been identified as a critical metal for the future in the EU (Ad Hoc Working Group, 2014).

The EU is dependent on South Africa and Kazakhstan (43% and 20% of worldwide production) for chromium.

The regeneration of the chemical solvent requires a stripping tower, for desorbing and separating the CO_2. Stripping towers are widely used throughout the industry and no critical dependence is expected.

A deNOx unit is essential for post-combustion capture. The technology itself is quite mature, but a deNOx unit includes scarcely available catalyst materials such as vanadium and tungsten (van Breevoort, et al., 2011). The supply of these materials is a risk. For the supply of tungsten there is a dependence on China and Russia, considering China is responsible for 84% of the world's tungsten production (see Figure 4a) and Russia is the EU's main source of import (84%, see Figure 4b). For vanadium the exact same dependency applies (see Figure 14c and d).

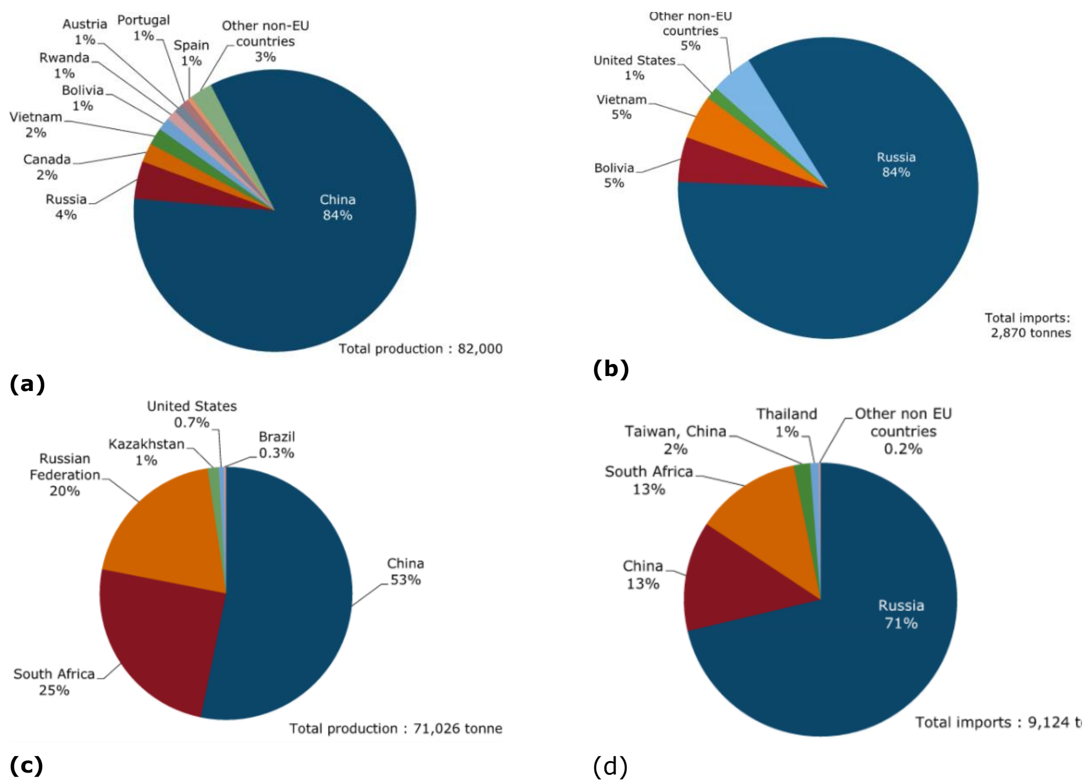


Figure 22 :(a) Global Production of tungsten (b) European import of tungsten (c) Global production of vanadium (d) European import of vanadium (Deloitte Sustainability; British Geological Survey; Bureau de Recherches Geologiques et Minieres; TNO, 2017)

A deSox unit is also necessary for post-combustion capture. This is a mature technology which depends on widely available chemicals such as sodium hydroxide (NaOH) which is used as a scrubbing solution. There are no dependencies expected here.

2.3 CO_2 capture: Oxy-fuel combustion

2.3.1 Description of Oxy-fuel combustion

Oxy-fuel is another variant of CO_2 capture in which fuel is burnt with O_2 instead of the conventional air mixture. Alternatively, oxygen can also be diluted with CO_2 in order to improve the controllability of the combustion. The resulting flue gas contains more CO_2 than in the case of combustion with air. The gas composition is mostly CO_2, H_2O and minor impurities. After removing the impurities and drying the gas stream, the CO_2 can be transported, stored or utilized. At the moment there is no large scale commercial application of oxy-fuel combustion for CCS, but there are several pilot plants (Sreedhar, Nahar, Venugopal, & Srinivas, 2017) (Carrasco-Maldonado, et al., 2016).

The oxy-fuel combustion technology can become a commercial activity in the future, after successful demonstrations of the technology. Subsequently, if the technology did become commercially active, the chemical industry would also need time to adapt their processes.

2.3.2 Issues of dependency – Oxy-fuel combustion

The oxy-fuel combustion technology involves use of air separation units, CO_2 purification units, boilers for oxy-fuel combustion and the use of air as a raw material.

The air separation unit separates the oxygen in air from the other components such as nitrogen. In the global market there are four large suppliers of air separation units with a combined market share of 70-80% (van Breevoort, et al., 2011):

- Air Products and Chemical Inc. (USA);
- L'Air Liquide (France);
- The Linde Group PLC (United Kingdom);
- Praxair Inc (USA).

Half of these providers are based in the EU. In the instance of a large deployment of oxy-fuel combustion, there might be a dependence on the USA.

The resulting flue gas from oxy fuel combustion contains mostly CO_2 and small amounts of Ar, O_2, SO_2, N_2 and NO_x (van Breevoort, et al., 2011). One possibility is to inject this mixture into storage and the other possibility is to separate the CO_2 from the other components with a CO_2 purification unit. The latter has not yet been developed into a mature technology.

Currently, oxy-fuel combustion is not applied at a commercial scale and thus there is no immediate need for CO_2 purification units. The risk of dependency on this technology is low, because existing gas treatment procedures can be used with minor alterations (van Breevoort, et al., 2011).

A special type of boiler is necessary for the combustion of a fuel with nearly pure oxygen (or with oxygen diluted with CO_2), because of the changed temperature profile in the boiler compared to combustion with air. This oxy-fuel boiler is not available on a commercial scale. The current boilers limit the reaction temperature. Future boilers should be made of a nickel based alloy to be more temperature resistant (van Breevoort, et al., 2011). The companies that could start producing these boilers are (van Breevoort, et al., 2011):

- Alstom (France);
- Air Liquide (France);
- Doosan Babcock (United Kingdom);
- Hitachi (Japan);

- IHI Coporation (Japan);
- Clean Energy Systems (India).

For oxy-fuel combustion boilers there seems to be sufficient capacity for developing the necessary boilers, should the technology be needed.

2.4 Conclusions

2.4.1 Critical dependencies

For pre-combustion carbon capture there is a low dependence on non-EU manufacturers of process equipment. The critical dependency for pre-combustion carbon capture is the dependency on countries producing catalyst materials (cobalt and chromium) for the water gas shift reaction, such as the Democratic Republic of Congo for cobalt and South Africa/Kazakhstan for chromium.

For post-combustion carbon capture there is no dependency on manufacturers of specific process equipment, but there is a dependency on China and Russia for vanadium and tungsten which are present as catalyst materials in the deNOx units. It should be noted, however, that deNOx units are necessary for flue gas treatment independent on the deployment of CCS, due to restrictions on NOx emissions.

For oxy-fuel combustion there is a low dependence on non-EU manufacturers of process equipment. No material dependencies were identified for oxy-fuel combustion.

Process equipment is a common dependency across each of the carbon capture technology variants; this is related to the fact that there are only two large commercial scale carbon capture plants operating in the world. A future increase in the use of carbon capture in more large scale projects will need to drive the production of specific process equipment units.

2.4.2 Consideration of variants

The critical dependencies for the three different variants of carbon capture, i.e. pre-combustion capture, post-combustion capture, and oxy-fuel combustion, are unique and need to be treated separately.

3 CO_2 storage technology

CO_2 storage is a main component of the CO_2 Capture and Storage (CCS) chain. It enables clean energy production from fossil fuels (like gas and coal) or from biomass, leading to limited, zero, or even negative emissions from thermal power plants. Capture technology is described in a separate summary paper. Negative emissions can be achieved through the direct capture from the air (DACS) or from capturing CO_2 from biomass combustion (BECCS). CCS is also a promising solution for decarbonizing the energy intensive industries like cement and steel mills. Synergies with CO_2 utilisation are possible like in CO_2-EOR (Enhanced Oil Recovery).

In terms of geological storage media, various types of CO_2 storage can be distinguished: depleted oil reservoirs, depleted gas reservoirs, and aquifers. A specific class of CO_2 storage is the injection of CO_2 in oil fields to enhance oil production, termed CO_2-EOR. This can also be seen as a CO_2 utilisation option. As the supply chains for these various storage options do not differ fundamentally from one another, we will treat CO_2 storage technology as one technology family without subdividing it in separate variants or subfamilies.

3.1 Description of CO_2 storage technology

CO_2 storage implies the injection of pressurized $CO_{2,}$ via one or more wells, into permeable porous media in the deep subsurface at depths of 800 m to several kilometres (Metz, et al., 2005). CO_2 is contained in these geological reservoirs by a thick impermeable rock on top of the reservoir. Injection and storage technology is largely based on the matured technology used in oil and gas exploitation. The market for equipment used in petroleum exploitation is for that reason a good analogue for the incipient European CO_2 storage market.

Storage in depleted oil and gas fields requires very little or no exploration activity. Part of the original infrastructure in terms of wells, interfaces with pipeline infrastructure, and platforms can be re-used for CO_2 storage. Depleted gas fields are often underpressured which makes them very attractive for CO_2 storage. The pressure conditions of depleted oil reservoirs are comparable to aquifers. Pressure management in aquifers may invoke the drilling of pressure relief wells leading to an increase of the storage efficiency ((Global CCS Institute , 2016): Gorgon project offshore West Australia). Combining CO_2 storage with EOR will expand the necessary equipment for the treatment of the produced gas-oil stream, as the CO_2 has to be separated from the produced hydrocarbon stream before it can be re-injected into the oil reservoir (Metz, et al., 2005). There is a considerable difference between the equipment needs of onshore and offshore storage; offshore storage requiring additional large investments in building dedicated drilling rigs, platforms, and optional subsea completions. The necessary compression of the CO_2 is integrated in the capture facility (see carbon capture technology summary paper).

The equipment for the CO_2 storage technology supply chain consists of the following main hardware components[7]:

- Drill rigs;
- Wells (see Figure 23);
- Platforms (offshore);
- Monitoring technology.

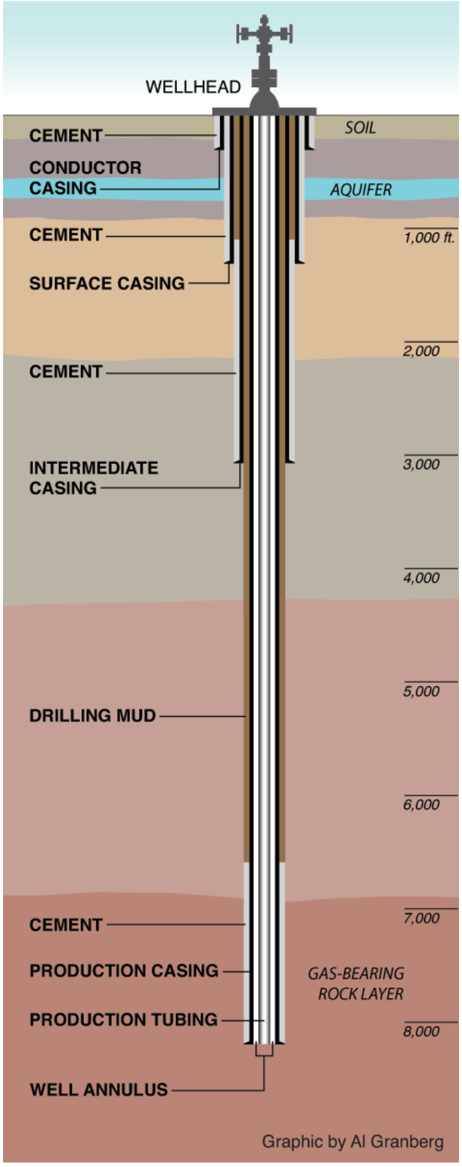


Figure 23 Typical well scheme for gas production as an analogue for a CO_2 injection well (Oil Conservation Division , 2017)

[7] Note that in the oil and gas market a large number of service companies are working on data mining. These organisations provide dedicated trade statistics on oil and gas equipment for commercial tariffs. It is considered to be beyond the scope of this broad brush assessment to acquire this type of information.

3.2 Issues of dependency

The market for CO_2 storage technology in Europe, which largely depends on oil and gas exploitation technology, is very small. GCCSI (2016) reports 2 large-scale storage projects in the Norwegian offshore and three small-scale projects onshore (see Figure 24). To date, October 2017, no further large-scale projects are in preparation for Europe. The Netherlands' new government coalition plans for about 20 Mt storage capacity of CO_2 from industrial plants and from waste incineration by 2030 (VVD, CDA, D66 & ChristenUnie , 2017). The IEA in its 2DS scenario projects that CCS needs to be scaled up by 2 orders of magnitude by 2040 (Global CCS Institute , 2016), which would invoke an enormous acceleration in the deployment of the technology in coming decades.

Statoil in Norway is the operator of the two large storage projects in offshore Europe. The Norwegian Gassnova, a state-owned organisation, advises the Norwegian government on the deployment of CCS in Norway.

CO_2 injection for enhancing oil production is happening in more than 100 sites in the USA (Global CCS Institute, 2016). In Europe CO_2-EOR has been deployed on a small scale in onshore oil fields, e.g. in Hungary and Turkey (Tzimas, Georgakaki, Cortes, & Peteves, 2005); CO_2-EOR offshore in the North Sea region has not been deployed because the required additional infrastructure and CO_2 appears to be too expensive. EOR in the US has been successful as it is onshore where the costs are lower, and on the whole natural geological accumulations of CO_2 have been used.

Figure 24 Global map of dedicated geological CO_2 storage projects that have injected or will soon inject with a size of at least 50,000 tonnes (Global CCS Institute, 2016)

As previously mentioned, CO_2 storage technology is very similar to the technology used in oil and gas exploitation. The availability of this technology, at an affordable price, depends indirectly on the oil price (see (Dumas, et al., 2011). A high oil price implies a high price for equipment like drill rigs, and will thus increase the cost of CO_2 storage projects.

Drill rigs
Given the recent downturn in oil prices, there is currently a surplus of drilling rigs available in the North Sea. Day rates for drilling rigs in the North Sea have fallen considerably from $650,000 in 2013 to $250,000 in early 2016 (Energy Voice , 2016). There are approximately 90 drilling rigs positioned across the NW European Shelf, of which 30 rigs are currently without contract (KL Energy Publishing , 2016). Prominent drilling companies in the North Sea include Transocean (registered in Switzerland), Maersk (Denmark), Ensco (United Kingdom), Seadrill (Norway), and Songa Offshore (Norway).

According to an inventory of drilling companies, 28 were based in Europe (GEOELEC, 2017). In 2015 about 4,000 rigs were available worldwide (EGEC, Market Report 2015 - Fifth edition, 2016), of which 2,337 were deployed (Baker Hughes, 2017). In the same year 117 rigs were in operation in Europe.

Drill rig suppliers in Europe include Bentec GmbH, Deutag KCA, Drillmec, Huisman, Neddrill, and the Trevi Group. Schlumberger with its main office in the US, is also a supplier of drill rigs in Europe.

The current oversupply of drill rigs and the considerable number of European suppliers of drill rigs indicate that there is no critical dependency on drill rigs in Europe.

Wells
Well casing: The EU-28 is a net exporter of casings, tubings, and drill pipes (see Table 11). These steel materials are also referred to with the acronym OCTG or Oil Country Tubular Goods. Vallourec based in France has a leading position; many tens of companies based in Europe deliver tubulars (Global Oil and Gas Directory , 2017). Other companies outside Europe are based in Japan (Sumitomo and Nippon Steel), China, the USA, and Canada (Hopmans, 2017).

As Europe is a net exporter of OCTG there is no critical dependency on this type of equipment in Europe.

Table 11 Trade statistics for EU-28 of casing, tubing and drill pipe (OCTG) of a kind used in drilling for oil or gas, of iron or steel ((UN Comtrade Database , 2017): output 67913)

Casing, tubing and drill pipe of a kind used in drilling for oil or gas, of iron or steel (67913)					
Period	Region	Trade flow	Partner country	Trade value	Balance of trade
2011	EU-28	Import	World	$388,068,142	+
2011	EU-28	Export	World	$2,247,375,367	
2012	EU-28	Import	World	$489,031,472	+
2012	EU-28	Export	World	$2,565,981,457	
2013	EU-28	Import	World	$469,883,156	+
2013	EU-28	Export	World	$2,760,406,295	
2014	EU-28	Import	World	$567,963,481	+
2014	EU-28	Export	World	$2,645,244,263	
2015	EU-28	Import	World	$357,781,871	+
2015	EU-28	Export	World	$1,444,676,653	

Well cement: The EU-28 is a net exporter of cement (see Table 12). The European Cement Association reports a share 5.4% for Europe in global cement production, with the EU-28 producing 167 Mt in 2015. For comparison, China produced 2,350 Mt and the USA 83 Mt of cement in the same period.

Europe is not critically dependent on this commodity as Europe is a net exporter of cement.

Table 12 Trade statistics for EU-28 of Portland cement ((UN Comtrade Database , 2017): output 66122)

Portland cement (66122)					
Period	**Region**	**Trade flow**	**Partner country**	**Trade value**	**Balance of trade**
2011	EU-28	Import	World	$413,762,212	+
2011	EU-28	Export	World	$626,094,310	
2012	EU-28	Import	World	$270,586,706	+
2012	EU-28	Export	World	$780,704,347	
2013	EU-28	Import	World	$134,867,412	+
2013	EU-28	Export	World	$905,173,953	
2014	EU-28	Import	World	$303,585,076	+
2014	EU-28	Export	World	$932,428,363	
2015	EU-28	Import	World	$287,021,728	+
2015	EU-28	Export	World	$818,939,014	

Sealing technology, e.g. packers: These well components are made of elastomers (e.g. rubber), a large share of which is being produced by companies with their main office in the USA, e.g. Seals Eastern, DuPont, Haliburton, Baker Hughes, and Schlumberger. Furthermore, high-quality but expensive packers are produced in Norway (Hopmans, 2017). A company delivering elastomers for the oil and gas upstream industry is Ceetak Ltd based in the UK (http://www.ceetak.com/wp-content/uploads/2011/06/Ceetak-Special-Elastomers-for-Oil-Gas-Sealing.pdf). Not all elastomers used for packers are useful for CO_2 storage as these may swell in the presence of CO_2.

Although sealants are produced and sold by Europe-based companies, a significant part of this product is delivered by companies with European branches but which have headquarters in the USA. This indicates that there is a limited European dependency on non-EU supply of sealants.

Wellheads: Important suppliers of wellheads in Europe are Cameron, owned by Schlumberger (with its HQ in the USA), and Baker Hughes, a GE Company (with HQs in the USA and UK), and Plexus (with its HQ in UK). Suppliers outside of Europe are in China, the USA, Canada (V'NSLimited), and Russia, the companies in the latter having their own standards (personal communication (Hopmans, 2017)).

There is a limited European dependency on the non-EU supply of wellheads, which is similar to the situation for sealing technology (see above).

Platforms

Different types of offshore platforms can be distinguished, e.g. fixed, floating, and submersible. The European market for floating and submersible platforms is quite volatile (see Table 13), which is reflected in the fluctuating import and export trade values. The EU was a net importer of floating or submersible platforms in the years 2012 to 2015; although in 2011 the EU-28 had a net positive trade balance. The European industry for platforms is quite large: a search in the Global Oil and Gas Directory resulted in more than 20 companies delivering with offices in European countries ((Global Oil and Gas Directory , 2017): 4.05.01 Management and Provision of all Facilities Engineering, Modification and Maintenance Services for a Site / Platform).

Between 2012 and 2015 there was a trade deficit in the market of platforms. Yet, the supply of platforms from outside of Europe represents only a limited dependency as there is still a considerable group of Europe-based companies which build and deliver platforms.

Table 13 Trade statistics for the EU-28 of floating or submersible drilling or production platforms ((UN Comtrade Database, 2017): output 890520)

Floating or submersible drilling or production platforms (890520)					
Period	**Region**	**Trade flow**	**Partner country**	**Trade value**	**Balance of trade**
2011	EU-28	Import	World	$350,232,922	+
2011	EU-28	Export	World	$1,094,480,896	
2012	EU-28	Import	World	$1,284,048,498	-
2012	EU-28	Export	World	$158,805,345	
2013	EU-28	Import	World	$1,136,650,061	-
2013	EU-28	Export	World	$395,855,567	
2014	EU-28	Import	World	$423,615,284	-
2014	EU-28	Export	World	$158,527,490	
2015	EU-28	Import	World	$1,195,389,289	-
2015	EU-28	Export	World	$593,204,344	

Monitoring technology

In terms of equipment for geophysical marine seismic monitoring, a number of large USA and EU based companies dominate the market; although no exact figures on market share can be provided. Schlumberger and ION Geophysical are USA headquartered, however Fugro (The Netherlands) and PGS (Norway) also have prominent positions in supplying exploration equipment to the North Sea oil and gas producers.

There is a limited European dependency on the delivery of monitoring technology by companies with their HQs in the USA (see also sealing technology and wellheads).

Services

The service industry for oil and gas exploitation is well suited in providing the services required for CO_2 storage. As the market for CO_2 storage is in its incipient stage, this section will largely be based on the findings for the analogue market for oil and gas services.

The oil and gas service industry offers a broad spectrum of activities which can support all aspects of CO_2 storage technology including engineering, procurement, construction, installation, commissioning, operation, maintenance, decommissioning, and abandonment (Global Oil and Gas Directory , 2017). Also services on consulting, R&D, finance, and insurance are available. Services can be provided as a single activity or can include many activities in an integrated package and be delivered as a turnkey project. Specialized services include activities like directional drilling, seismic surveying, and transportation.

Overall, the required services for CO_2 storage can be delivered by Europe based companies, most of which are located in the UK and Norway. Table 15 shows examples from services for CO_2 storage. The technical services are represented by a large number of companies in contrast to the monetary services. Data from (UN Comtrade Database , 2017) on monetary services (e.g. Comtrade classes: 6 Financial services, 5.3 Other direct insurance, 5.4 Reinsurance) show that Europe is a net exporter of this type of service, which is indicative of a strong market position. Overall the conclusion is that there is no critical dependency on monetary services for the oil and gas industry in Europe. It should be mentioned however, that the banking and insurance needs of CO_2 storage projects are likely to be very different to current practises in the oil and gas sector. Given the infancy of the sector in Europe, it's too early to fully address this point further.

The ten largest oil field and drilling service companies worldwide are listed in Table 14. The top three companies that dominate the market are all headquartered in the USA. Although there is a very wide range of service companies, there are a few that dominate the market, and most of these have their headquarters in the USA. This indicates that there is a limited dependency on the technical services for CO_2 storage.

Table 14 Ten largest oil field and drilling service companies worldwide in 2015 (Mordor Inteligence, 2017)

Number	Name company	Turnover in 2015 (billion USD)	Active in Europe	HQ location
1	Schlumberger Ltd.	35	Yes	USA
2	Halliburton Company	24	Yes	USA
3	Baker Hughes Incorporated	16	Yes	USA
4	Weatherford International plc	9	Yes	Switzerland
5	Transocean Ltd.	7	Yes	Switzerland
6	Seadrill	4	Yes	Bermuda
7	ENSCO plc	4	Yes	UK
8	China Oilfield Services Ltd.	4	Yes	China
9	Noble Corporation plc	3	Yes	UK
10	Helmerich & Payne Inc.	3	No	USA

Table 15 Examples of CO_2 storage services and number of company offices in Europe (Global Oil and Gas Directory , 2017)

Main service group	Type of service	Number of Europe based offices
Drilling	Drilling rigs (semi-submersible/jackups/others)	50+
	Directional drilling	~20
Engineering	Drilling/completion engineering	100+
Decommissioning & abandonment	Well decommissioning and abandonment	100+
Geophysics	2D/3D/4D Seismic data acquisition	50+
Engineering/procurement/construction/ installation/commissioning	Steel/metal/concrete structures/platforms	50+
	Risers	50+

Main service group	Type of service	Number of Europe based offices
	Umbilicals	50+
Integrated services	Storage site development	50+
	Management and Provision of all Facilities Engineering, Modification and Maintenance Services for a Site / Platform	100+
Finance & insurance	Banking	3
	Credit granting	1
	Non-life insurance	2
	Other insurance	10+
	Insurance broking	7

Raw materials

Iron is used for the manufacturing of tubulars. The EU-28 has had a huge trade deficit in iron ore for the years 2014 and 2015 (see **Error! Reference source not found.**). Sweden is the l argest producer of iron ore in Europe, with small contributions from Austria and Germany (EuroGeoSurveys Mineral Resources Expert group , 2014). The EU does however have considerable capacity for primary steel production, the product that is eventually used in construction platforms, drilling equipment, and well casings. It is not considered that the availability of iron ore will restrict the wider proliferation of CO_2 storage projects by 2030 or beyond.

Table 16 Trade statistics for EU-28 of iron ore ((UN Comtrade Database , 2017): output 260111)

Iron ore (260111)					
Period	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Import	World	$8,325,193,797	-
2014	EU-28	Export	World	$123,911,583	
2015	EU-28	Import	World	$4,688,749,256	-
2015	EU-28	Export	World	$20,679,373	

Chromium is used in the manufacturing of steel to make it more resistant to corrosion. Chromium is traded internationally in the form of ferrochromium, an iron-chromium alloy (see Figure 25). Europe has chromium ore resources in Finland and Greece. Finland had a share of 4% in the global trade market of ferrochromium from 2006 to 2016 (see Figure 25).

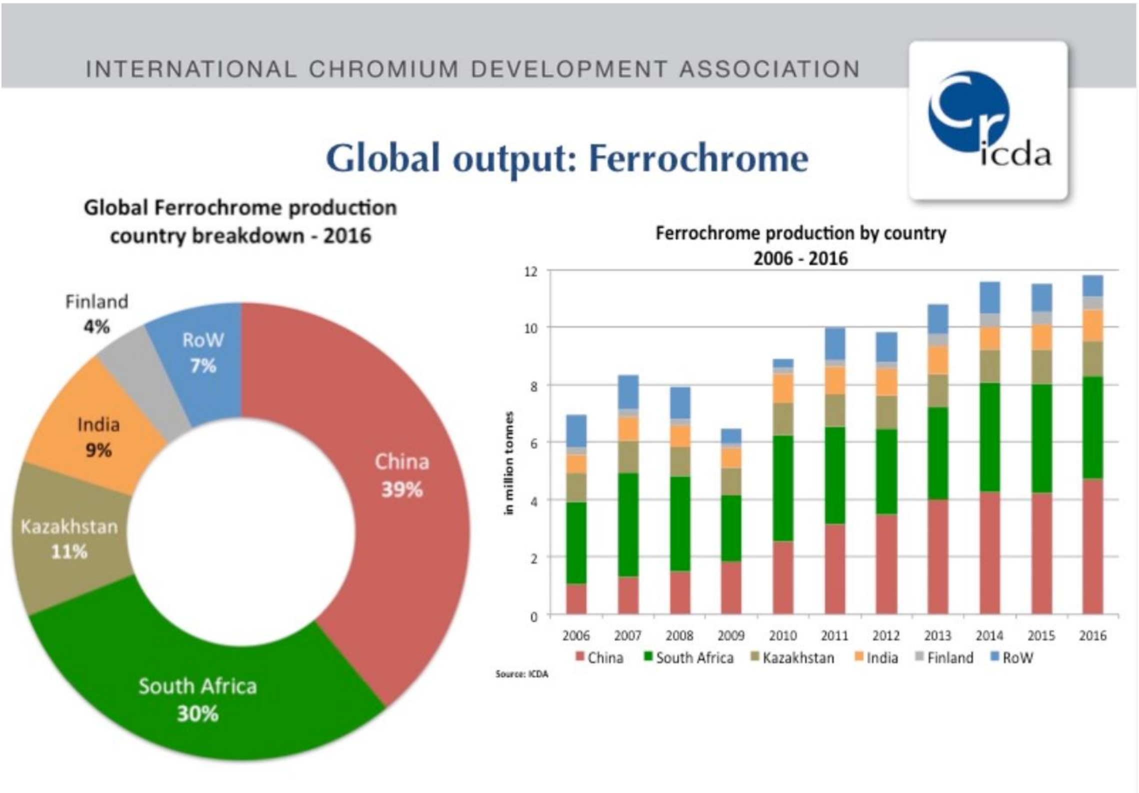


Figure 25 Global production of ferrochrome (ICDA, 2017)

Error! Not a valid bookmark self-reference. shows the dependence of the EU-28 on the import of chromium ore. Chromium was on the EU list of 20 critical raw materials in 2014 (European Commision, 2014), however it does not re-appear on the list of 27 critical raw materials of 2017 (European Commission, 2017). Nevertheless, it is concluded that there is a clear dependency on chromium in Europe.

Table 17 Trade statistics for EU-28 of chromium ore and concentrates (UN Comtrade Database, 2017): output 261000)

Chromium ores and concentrates (261000)					
Period	Region	Trade flow	Partner country	Trade value	Balance of trade
2012	EU-28	Import	World	$123,638,442	-
2012	EU-28	Export	World	$40,655,024	
2013	EU-28	Import	World	$98,525,619	-
2013	EU-28	Export	World	$25,818,353	
2014	EU-28	Import	World	$77,396,665	-
2014	EU-28	Export	World	$15,285,290	
2015	EU-28	Import	World	$80,009,387	-
2015	EU-28	Export	World	$8,381,938	

Limestone including marl and chalk is the most important base material for Portland cement. It is marked by a positive trade balance as shown in Table 18.

Table 18 Trade statistics for EU-28 of limestone ((UN Comtrade Database , 2017): output 252100)

Limestone and other calcareous stone, of a kind used for the manufacture of lime or cement (252100)					
Period	**Region**	**Trade flow**	**Partner country**	**Trade value**	**Balance of trade**
2012	EU-28	Import	World	$3,158,264	+
2012	EU-28	Export	World	$7,658,143	
2013	EU-28	Import	World	$3,216,285	+
2013	EU-28	Export	World	$13,040,317	
2014	EU-28	Import	World	$6,366,219	+
2014	EU-28	Export	World	$12,056,420	
2015	EU-28	Import	World	$9,294,323	+
2015	EU-28	Export	World	$25,302,641	

Tungsten is used as tungsten carbide in drill bits. Turkey produced more than 8% of global tungsten ore in 2012 (Euromines, 2014). Tungsten features on the EU list of 20 critical raw materials (European Commision, 2014), and on the more recent list of 27 critical raw materials (European Commission, 2017). The mineral is classified as critical with regards to a high-supply risk and a high economic importance. The import reliance of Tungsten is 44%. Next to Turkey, there are European producers of Tungsten in Portugal, Spain, and Austria. However, 85% of global production occurs in China, and Chinese production rates can manipulate the global market price. For these reasons, the dependency of Europe on Tungsten is considered critical.

3.3 Conclusions

The European market for CO_2 storage technology is very small; only two large-scale projects are located in Europe, offshore in Norway. However, there is an enormous growth potential for CO_2 storage technology in Europe over the coming decades, in particular in the North Sea region. The technology used for CO_2 storage is very similar to that used in oil and gas exploitation, which implies that the mature oil and gas market can serve as a good analogue for the CO_2 storage market.

3.3.1 Critical dependencies

Raw materials: Some raw materials have been identified as critical dependencies. Limited iron ore resources in Europe makes Europe critically dependent on the import of iron ore. Tungsten (used in drill bits) is recognized by the EC as a critical raw material. The mineral is classified as critical with regards to a high-supply risk and a high economic importance. The import reliance of Tungsten is 44%. Next to Turkey, there are European producers of Tungsten in Portugal, Spain, and Austria. However, 85% of global production occurs in China and Chinese production rates can manipulate the global market price. For these reasons, the dependency of Europe on Tungsten is considered to be critical. Although Chromium is not on the 2017 EC list of critical raw materials, it is concluded that there is a limited dependency on this mineral because of the significant net import in Europe.

Equipment: For the years 2012 to 2015, a trade deficit has been observed in the European market of platforms. Yet, the delivery of platforms from outside Europe is representing a limited dependency as there is still a considerable group of Europe-based companies which build and deliver platforms. Limited dependencies have also been concluded for elastomers used for well sealing, wellheads and monitoring equipment as a number of equipment suppliers in Europe have their HQs in the USA.

Services: Although there is a very wide range of service companies with their basis in Europe, there are a few companies that dominate the market which have their HQs in the USA. This indicates that there is a limited dependency on the technical services for CO_2 storage.

Overall, European dependence on non-EU supply is expected to be limited for CO_2 storage technology.

3.3.2 Variants

CO_2 storage should be considered as a single family, and should be assessed individually. Although there are different forms of CO_2 storage, the differences between them are not considered substantial enough to warrant multiple variants.

4 CO_2 utilization

An abundance of CO_2 is created in the conversion of fossil fuels or biomass to electrical power and heat, and by other industrial processes. Industrial CO_2 emissions made up 26% of global CO_2 emissions in 2013, with a total of 8.9 Gt CO_2. CO_2 can be captured, after which it can be stored or utilized. In utilization the CO_2 is converted to a valuable product (valorisation). The opportunities for CO_2 valorisation methods will increase due to the increased availability of CO_2 from carbon capture technologies. Moreover, in a scenario where fossil feedstocks are less abundantly available, CO_2 may become a relevant carbon source for many industries.

The two main routes of utilizing CO_2 are carbonate mineralization and CCU fuels. The markets for these two utilization routes are able to handle large amounts of CO_2 that will be available from carbon capture technologies. Routes for the utilization of CO_2 as a chemical feedstock (e.g., in polymer manufacturing) will lead to relatively small CO_2 uptake, and are therefore not covered in this paper. Future CO_2 capture and storage will make CO_2 more available and less costly; this will drive further research on developing CO_2-based products.

4.1 Carbonate mineralization

4.1.1 Description of Carbonate mineralization

Carbonate mineralization is the conversion of CO_2 to solid inorganic carbonates using chemical reactions. The mineralisation process can be used to produce building materials, e.g. carbonate aggregates and carbonated concrete (concrete cured with CO_2). Aggregates are coarse materials used in construction as a reinforcement, and are normally acquired by mining. Aggregates consist of sand, gravel, crushed stones, and similar materials. Instead of mining these materials, they can be synthesised by carbonisation of waste materials such as slag, bottom ash, air pollution control residue, galligu, contaminated soils, water treatment sludge, quarry fines, dredges, and soil washing filter cakes (Gökalp, Uz, Emre, Saltan, & Tutumluer, 2017). Carbon8, a company in the UK, is already commercially producing carbonate aggregates (The Global CO2 initiative, 2016).

Concrete curing by CO_2 actually predates concrete curing with water. It was the standard technology until the development of Portland cement in the early 19th century (Zhang, Ghouleh, & Shao, 2017). Companies such as Solidia Technologies and CarbonCure were the first to bring CO_2 concrete curing technology to the (USA & Canada) market (The Global CO2 initiative, 2016).

4.1.2 Issues of dependency – Carbonate mineralization

For the production of carbonate aggregates from CO_2, the essential components investigated are process equipment, CO_2 and industrial waste availability. The necessary process equipment consists of storage silos (for reagents or the aggregate product), a CO_2 storage tank, pelletizer, mixer and a reagent silo/treatment chamber. Figure 26 and Figure 27 show the necessary process equipment for a full-scale demonstration setup and a full-scale plant. There are no dependency issues for the process equipment, considering that this is simple equipment widely used in industry.

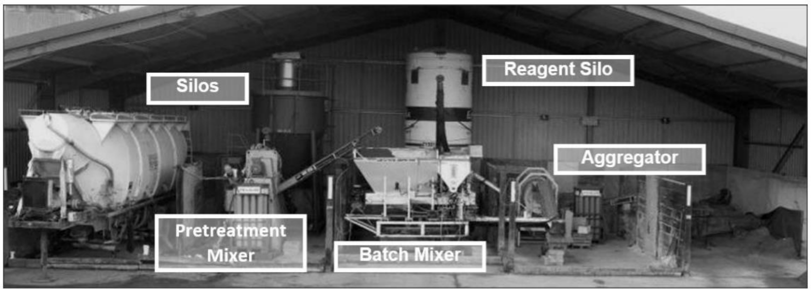


Figure 26: Full scale demonstration setup (Gunning & Hills, 2014)

Figure 27: Plant setup (Gunning & Hills, 2014)

Dependencies on materials for the production of carbonate aggregates are minimal. In the case that carbon capture and storage is adopted in Europe, there will be an abundance of captured CO_2, and the industrial waste products, such as steel slag, are already available in considerable amounts. In the EU, 30 million tonnes of steel slag is produced annually (Gökalp, Uz, Emre, Saltan, & Tutumluer, 2017).

The production of carbonate aggregates using CO_2 from the combustion of fossil fuels is currently minimal. The largest European producer, Carbon8, produced 65,000 tonnes of aggregate products in Europe in 2014 (Carbon8, 2017). Despite the minimal current production, the potential for the technology is large. Figure 28 shows the predicted global utilisation potential for carbonated aggregates for 2020-2030 with a predicted CO_2 uptake by aggregates of 0.3-3.6 billion tonnes, depending on strategic actions from governments.

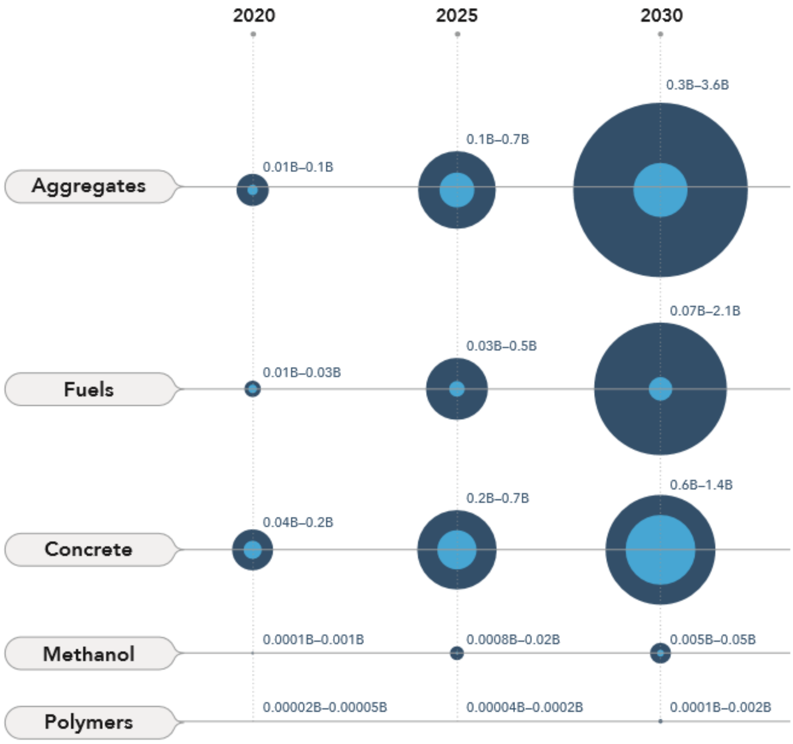


Figure 28: CO_2 reduction potential for different products for 2020, 2025 and 2030 (The Global CO2 initiative, 2016). The inner circle represents the lower limit of the predicted CO_2 uptake potential and the outer circle the higher limit.

There are limited adaptation barriers for concrete curing with CO_2, considering the same equipment and the same or similar materials as the commonly deployed water-curing method can be used (Solidia Technologies, , 2017). The process equipment that is necessary for concrete curing with CO_2 is a CO_2 storage tank and a CO_2 blower. This is widely available equipment for industry and there is no specific dependency on other countries. Solidia technologies and CarbonCure both have US patents on processes for concrete curing with CO_2 (United States of America& Canada Patentnr. US 9221027 B2, 2015) (United States & Canada Patentnr. US 8845940 B2, 2017).

4.2 CCU fuels

4.2.1 Description of CCU fuels

CO_2 that has been separated from industrial processes with carbon capture can be used to produce fuels. In a chemical reaction, the CO_2 is converted into a valuable product. For the utilisation of CO_2 in the production of fuels, it is important that the technology readiness level (TRL) is high enough and that the market is large enough to deal with a significant stream of CO_2 from capture and storage. On the basis of TRL and market size, methane, methanol, and fuels produced from methanol are selected as utilisation products for CCU fuels.

Methane is the main component of natural gas and as such is a widely utilized fuel. Methane can be produced from CO_2 and H_2 using the Power-to-Gas technology developed by ETOGAS (Germany), Audi (Germany), and Electrochea (Germany), which is near commercialization (Bailera, Espatolero, Lisbona, & Romeo, 2017). The technology consumes significant quantities of hydrogen and is based on a scarcely available ruthenium-based catalyst; this has implications on large-scale application.

Methanol is a versatile chemical that can be used as an energy carrier/fuel and an intermediate chemical (Masih, Albinali, & DeMello, 2010). It has a good energy density and is relatively safe. As an energy carrier, methanol can be easily distributed as a liquid, unlike hydrogen. Methanol can also be directly mixed with gasoline for use as a transportation fuel. As a base chemical, methanol is extensively traded worldwide, and there are many commercially mature synthesis pathways to convert it to other chemicals (Masih, Albinali, & DeMello, 2010).

Methanol is commercially produced through a steam methane reforming process, which produces a mixture of H_2, CO_2, and CO (see Figure 4) (Jadhav, Vaidya, Bhanage, & Joshi, 2014). Extra CO_2 is added to the syngas gas mixture to improve the methanol yield. In the presence of a $CuO/ZnO/Al_2O_3$ catalyst and elevated pressure and temperature, the gas mixture is converted to methanol and water.

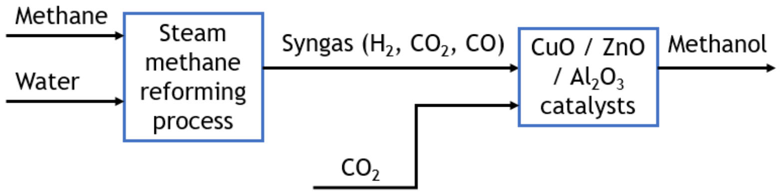


Figure 29: Process diagram for methanol synthesis.

An alternative production method focuses on direct CO_2 hydrogenation to methanol, which would allow more CO_2 utilisation than the steam reforming methane process (process diagram in Figure 29), as well as eliminating the use of fossil methane (Jadhav, Vaidya, Bhanage, & Joshi, 2014). The technical readiness level of direct hydrogenation of CO_2 to methanol is comparable to methanol production from syngas.

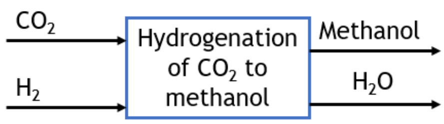


Figure 30: Process diagram for direct hydrogenation of CO_2 to methanol.

After CO_2 is converted to methanol via syngas or the direct hydrogenation process, this base chemical can be converted to dimethyl ether (DME) or even a hydrocarbon mixture.

DME is commercially synthesized from methanol. In a reactor with a $CuO/ZnO/Al_2O_3$ catalyst, methanol is converted to water and DME (Figure 30). The formation of methanol from syngas and subsequent conversion to DME could even be a two-step process in one reactor (Bildea, Gyorgy, Brunchi, & Kiss, 2017). In the CO_2 utilization route, the only change made to the current industrial DME production process is the origin of the methanol. In this new situation, methanol is produced from CO_2. DME can be used directly as a fuel or it can be mixed with diesel.

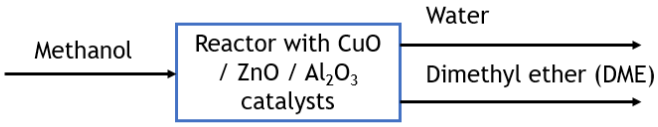


Figure 31: Process diagram for dimethyl ether (DME) production from methanol.

Traditionally, hydrocarbon mixtures (e.g. gasoline) are produced from fossil fuels in the oil and gas industry (Galadima & Muraza, 2015). Hydrocarbon mixtures can also be produced from methanol using commercial technologies like methanol-to-gasoline (MTG), developed by ExxonMobil (Galadima & Muraza, 2015). Figure 32 shows a schematic representation of the MTG process. At the moment, methanol produced from natural gas is used, which would be replaced by methanol produced from CO_2. The MTG reaction mainly uses zeolites as catalysts (Galadima & Muraza, 2015). The necessary process equipment are standard for the oil and gas industry (such as reactors, distillation columns, heat exchangers) and there is no dependency on other countries.

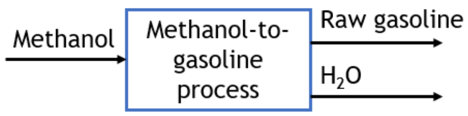


Figure 32: Process diagram of the methanol-to-gasoline process

4.2.2 Issues of dependency – CCU fuels

In the case of methane, the technology that is near commercialisation is based in Europe. The technology would use conventional process equipment widely applied in the chemical industry (reactors, separation vessels, pumps and heaters) and there is no dependency (Wo/European Patent Patentnr. WO 2017162513 A1, 2017). Methane, as a product, could directly be injected in the already existing gas network. The supply of a sufficient amount of hydrogen (that would react with CO_2 to form methane) and ruthenium for the catalyst are more challenging aspects. At the moment Europe does not produce a large amount of renewable hydrogen, but that could change with future developments of renewable energy. Renewable energy sources such as solar or wind energy may, in certain circumstances, produce more electrical energy than required by the electrical grid. This surplus of electrical energy can be stored by producing hydrogen using water electrolysers. Hydrogen is subsequently used as a feedstock in the production of methane (this is also applicable to the other CCU fuels).

The ruthenium catalyst is a critical material for Europe, with South Africa as the main supplier (Deloitte Sustainibility; British Geological Survey; Bureau de Recherches Geologiques et Mineres; TNO, 2017). Figure 33 shows the total global mine production of ruthenium and Figure 34 shows the import statistics for the European Union. It can be seen that there is a large dependency on South Africa for the import of ruthenium. However, in the years of 2010-2014 the EU was a net exporter of ruthenium and iridium, although it is unknown if this was as a primary or secondary material (mining or in a product).

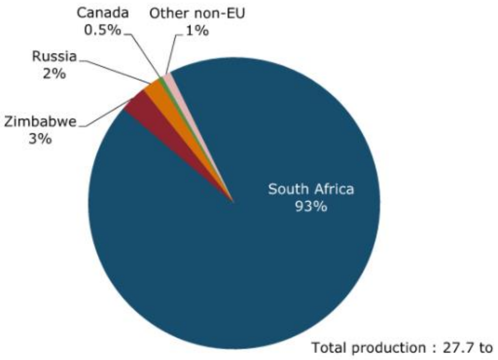


Figure 33 : Total mine production (global) of ruthenium in 2016 (Deloitte Sustainibility; British Geological Survey; Bureau de Recherches Geologiques et Mineres; TNO, 2017)

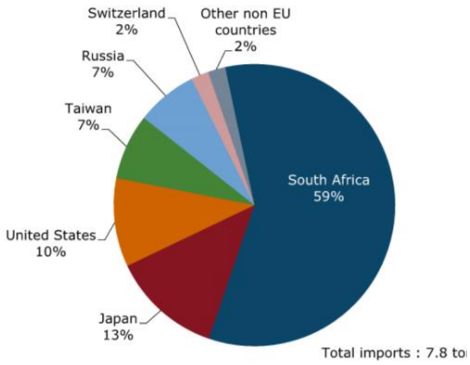


Figure 34: Import of ruthenium and iridium for the EU. (Deloitte Sustainibility; British Geological Survey; Bureau de Recherches Geologiques et Mineres; TNO, 2017)

The same process equipment and catalyst materials for the conventional methanol production could additionally be used for the direct hydrogenation process. The conventional methanol production from syngas uses standard process equipment (reactors, separation vessels, distillation columns, pumps and heaters) widely applied in the chemical industry. In the CO_2-based methanol synthesis, more water is generated as a by-product, which leads to lower efficiency as compared to the standard process. Because of this, a specific and more efficient reactor for the methanol production through direct CO_2 hydrogenation has been patented by Siemens, but this is an improved design for higher efficiencies and not an absolute requirement for running a CO_2-based methanol plant. Both methanol production processes use $CuO/ZnO/Al_2O_3$ based catalysts, for which there is no material dependency.

DME production technology uses standard process equipment (storage tanks, reactors, separation vessels, distillation columns, pumps, and heaters) widely applied in the chemical industry. For this equipment, there are no dependencies on other countries (Ad hoc working group, 2014). The only difference with the current DME production process would be a different methanol feedstock.

The methanol-to-gasoline production process uses standard process equipment (storage tanks, reactors, separation vessels, and heater exchangers). A new tubular fixed bed reactor has been patented in China, which does not hinder the use in Europe (China Patentnr. CN 105154128 A, 2015). This is an improved design and as such standard equipment would still suffice, therefore there is no dependency on other countries. The hydrocarbon production from methanol makes use of zeolite catalysts, which are aluminosilicates, and are not considered critical materials.

4.3 Conclusions

4.3.1 Critical dependencies

For carbonate mineralization there are no significant dependencies on other countries for process equipment or raw materials. The cement industry is established, and the waste materials for producing CO_2-based aggregates are abundantly available. The technology of concrete curing has not yet been applied in Europe, but there are no dependency barriers preventing that.

For the implementation of CCU fuels, there is a dependency on South Africa for the ruthenium catalyst necessary for methane production. For the rest of the catalyst materials for CCU fuels there are no significant dependencies. There is no dependency for process equipment.

If CO_2 capture technologies are broadly deployed, the amount of CO_2 from industrial processes will be abundant. In order to produce CO_2-based fuels, a large feedstock of renewable hydrogen is critical. Only when combined with renewable hydrogen can the use of CO_2-based fuels have a positive impact on the overall reduction of greenhouse gas emissions. The hydrogen supply is connected to the future development of renewable energy in Europe. For this kind of supply, the dependency rests heavily on the speed of the energy transition in Europe and not on specific manufacturers from abroad.

4.3.2 Consideration of variants

The carbonate mineralization and CCU fuels are based on very different technologies and have different dependencies profiles. Therefore, it would be appropriate to treat them separately.

5 Energy Storage

An energy storage system constitutes a system that is capable of converting electrical energy into potential energy (and vice versa) and storing potential energy internally. Several components interact to form an energy storage system, all of which have a significant role to play for its successful operation. The core component of an energy storage system constitutes the storage device that is responsible for storing energy. The way in which the storage device stores energy may differ between various system types. The working principle used can be mechanical (e.g. Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES) and flywheels), chemical (e.g. batteries), thermal (e.g. Thermal Energy Storage (TES), hot water storage) or electrical (e.g. super capacitors). For grid-connected storage systems, a power converter is usually present between the physical storage device and the grid, while a transformer is also used between the energy storage system and the grid.

Each storage technology has different performance characteristics that render it appropriate for specific storage services. Table 19 gives a generic description of the following storage services: bulk storage (1-500 MW) is used to store relatively large amounts of energy for usage at another time than its generation. Storage at transmission (1-100 MW) and distribution level (0,5-10 MW) can support the power grid by reduction of congestion or by deferral of grid updates. Storage at customer level (0,05-10 MW) provides customer services, e.g. by enhancing power quality, by improving reliability, or by realizing additional profit for the customer. Storage for ancillary services (1-100 MW) offers grid support by matching energy demand and supply. Last but not least, storage can also provide several services enabling largescale integration of renewables (1-500 MW). A more extensive description of these storage services can be found in: (GL, 2017).

The choice of which storage technology to utilise for providing a specific storage service relies on the best match between the characteristics and the capabilities of the storage system type and the requirements of the storage service of interest. Therefore, a thorough understanding of the characteristics of the different storage technologies and the conditions under which they perform best is essential. Table 19 provides an overview of the services that can be provided by different storage technologies together with information about the power range and maximum discharge duration of the various technologies (GL, 2017). The exact performance values are in any case project and location dependent. Note that batteries are capable of providing all the available storage services.

Table 19 General characterization of storage services by power range and maximum discharge duration and experienced storage technologies (GL 2017) (Azure International, 2017)

Storage service	Indicative power range [MW]	Maximum discharge duration [hrs]	Storage technologies
Bulk storage	1 – 500	2 – 6	PHS, CAES, batteries
Ancillary service	1 – 100	0,01 - 4	Batteries, flywheels, supercapacitors
Transmission support	1 – 100	1 – 8	PHS, CAES, batteries
Distribution support	0,5 – 10	1 – 4	Batteries
Customer service	0,05 – 10	1 – 8	Batteries, flywheels,

Storage service	Indicative power range [MW]	Maximum discharge duration [hrs]	Storage technologies
			supercapacitors
Renewable integration	1 – 500	1 – 4	Batteries, PHS, CAES, supercapacitors

5.1.1 *Description of energy storage technologies*

A more detailed description of the different energy storage technology variants is provided in the following paragraphs.

Pumped Hydro Storage (PHS) concerns the storage of electricity by pumping water from a lower-altitude reservoir to a higher-altitude reservoir. PHS is widely applied for large-scale energy storage and is currently the dominating market storage system type, in terms of power, with 145 GW installed capacity worldwide (World Energy Outlook 2016, 2016) (Electricity Storage and Renewables: Costs and Markets to 2030, 2017) (Irena, 2017). PHS requires specific geographical conditions, including ground composition, elevation between the reservoirs, and the availability of water (EASE/EERA, 2017). Although there is still some potential for PHS in Europe, the market for PHS is saturated (see summary paper on hydro technologies). There is still a growing market for PHS in South-East Asia, Africa, and Latin America (World Energy Resources E-Storage, 2016). PHS is a mature technology with no dependencies on the R&D sector (see summary paper on hydro technologies). The main components and raw materials used are widely available, and the hydro equipment manufacturing industry is dominated by European companies (VGB, 2017). Pumped hydro storage is not considered in this section since it is covered in another energy family.

Compressed Air Energy Storage (CAES) concerns the storage of energy by compressing air and storing it under pressure, either underground (e.g. in salt caverns) or above ground (e.g. in pressure vessels). Although the technology is proven, restricted availability of appropriate sites exists for new CAES facilities (World Energy Outlook 2016, 2016) (EASE/EERA, 2017) (Azure International, 2017). In general, CAES systems consist of compressors, expanders and air storage systems.

There are only two commercial scale facilities operating in Germany (Kraftwerk Huntorf) and in the USA (McIntosh CAES plant), storing energy coming from natural gas combustion plants for peak load shifting in grid operation (World Energy Outlook 2016, 2016) (EASE/EERA, 2017) (Azure International, 2017) (Laboratories, sd). Although the maturity level of conventional CAES is high, new technology developments are aimed at improving the round-trip efficiency[8], for example by applying Advanced Adiabatic CAES concepts in which heat generated during compression is stored and subsequently used during expansion. This development is still on a demonstration level (Azure International, 2017) (Laboratories, sd).

Hydrogen storage is the use of electricity to split water into hydrogen and oxygen, e.g. by electrolysis (EASE/EERA, 2017). Storage of hydrogen requires high pressure compression or liquefaction (EASE/EERA, 2017). The energy can be converted back into electricity via fuel cells or released as heat (IEA, Technology Roadmap Energy Storage, 2014). Hydrogen storage can be applied for seasonal storage, but this variant is addressed in a separate energy technology family. The maturity level of hydrogen storage for large-scale storage is

[8] The round-trip efficiency is the ratio between the energy put in a storage system to the energy retrieved from this storage system within one cycle under well-defined operating conditions (GL 2017).

still low and the costs are still high (IEA, Technology Roadmap Energy Storage, 2014) (World Energy Outlook 2016, 2016).

Battery technologies

Batteries store electricity via electrochemical charge/discharge reactions in a cell. From the various chemistries available, Li-ion batteries constitute the dominating battery technology in the market for grid support (World Energy Outlook 2016, 2016) (World Energy Resources E-Storage, 2016), due to their high energy density, efficiency, and relatively long life (Rethinking Energy 2017 - Accelerating the global energy transmission, 2017), (EASE/EERA, 2017). Moreover, they comply with the requirements for fast and daily response rates. It is interesting to note that Li-ion batteries are capable of providing most of the identified storage services (Ancillary Services, Distribution Support, Customer Services and Renewable Integration). Even though the current market share of battery storage systems for grid-connected services is still limited, it is predicted to grow due to the cost reduction forecasts to acceptable values, driven by Li-ion battery deployment in the automotive and consumer electronics industries (World Energy Outlook 2016, 2016). It is expected that Li-ion batteries will be included in up to 80% of all global electricity battery storage installations (Rethinking Energy 2017 - Accelerating the global energy transmission, 2017).

In the future, other chemistries such as metal-air, sodium-ion and lithium sulphur batteries are considered to be potential successors of Li-ion batteries because of their potential for higher energy densities. However, at present their maturity level is still low and they have to compete with the continuous improvement and learning rates of Li-ion batteries (EASE/EERA, 2017).

Other battery chemistries which are applied for grid support constitute:

- **Sodium Sulphur** (NaS), a commercially available molten-salt battery technology which requires high operating temperatures (300-350 ^{o}C (Azure International, 2017)). Although NaS has some market share in Japan and the USA, no significant market growth is predicted since few developments are reported today. The technology requires additional performance improvements and cost reductions to be able to compete with Li-ion (Irena Rethinking Energy 2017) (DNV GL expert);
- **Redox-Flow batteries** consist of an electrochemical stack and two separate electrolyte storage tanks. The tank volume and the nature and concentration of the chemical agents determines the energy storage capacity and the surface area of the membrane determines the power. Flow batteries have the advantage that the storage capacity and discharge duration can be expanded virtually without limitations (EASE/EERA, 2017). Vanadium redox flow batteries are the most common type. The market share for redox-flow batteries is still minor and the few companies developing redox flow batteries are located in Europe (EASE/EERA, 2017). Price reductions may cause an increasing interest in this technology (World Energy Resources E-Storage, 2016) (World Energy Outlook 2016, 2016);
- **Conventional lead acid batteries** consist of two lead plates and a sulfuric acid electrolyte. This low power/high energy technology is mature and the CAPEX costs are low, therefore it has been demonstrated in some small scale energy storage projects. Advanced lead acid technology combines lead acid batteries with high power devices into hybrid energy storage devices, with improved high-power performance and increased number of cycles. The market growth potential is however limited compared to predictions for Li-ion technology development (Azure International, 2017)(DNV GL expert).

Flywheels use electricity to drive an electric motor which accelerates a rotating mass. Electricity is retrieved from a flywheel when the rotating mass drives the electric motor, thus decelerating the rotating mass. Low speed flywheels (1.000 - 7.000 rpm) use heavy steel rotors for applications matching power and energy capacity (EASE/EERA, 2017). High-speed flywheels (25.000 – 3.6000 rpm) use light-weight composites for high power applications (e.g. frequency regulation). Low-speed flywheels are widely applied in the industrial sector in the USA. In Europe, the market for flywheels for grid support is still low. Market growth for standalone applications is not foreseen. Use in hybrid systems, e.g. in combination with batteries, is under exploration (World Energy Resources E-Storage, 2016) (DNV GL expert) (EASE/EERA, 2017).

Supercapacitors (also referred to as ultracapacitors) store electricity as electrostatic energy in an electric double layer at a porous carbon electrode with high efficiency and short discharge times (EASE/EERA, 2017). They are a relatively emerging technology for grid support, either as stand alone or in combination with batteries (EASE/EERA 2017). The market share is still marginal (World Energy Resources E-Storage, 2016) (Rethinking Energy 2017 - Accelerating the global energy transmission, 2017).

Thermal Energy Storage (TES) is applied to store heat or (excess) electricity. TES is divided into sensible heat storage (in solids or liquids), latent heat storage (in phase change materials) and thermo-chemical heat storage (in chemical reactions) (IRENA, Thermal Energy Storage Technology Brief, 2013) (World Energy Resources E-Storage, 2016). Low temperature sensible heat storage is most mature, especially storage in water, either contained in hot water tanks for residential applications or as large-scale Underground Thermal Energy Storage (UTES) in underground systems such as boreholes, pits, aquifers, or caverns (EASE/EERA 2017). High-temperature sensible heat storage in molten salts (mostly sodium nitrate and potassium nitrate) is commercially applied in Concentrated Solar Power (CSP), which is addressed in the summary paper about the solar family.

Figure 35 shows energy storage variants plotted according to their system power range and discharge time at rated power. It shows that no single storage technology can meet the full range of power and discharge times.

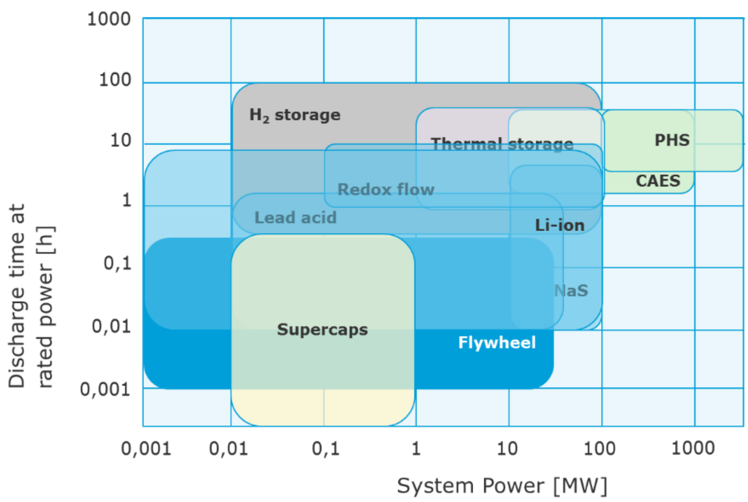


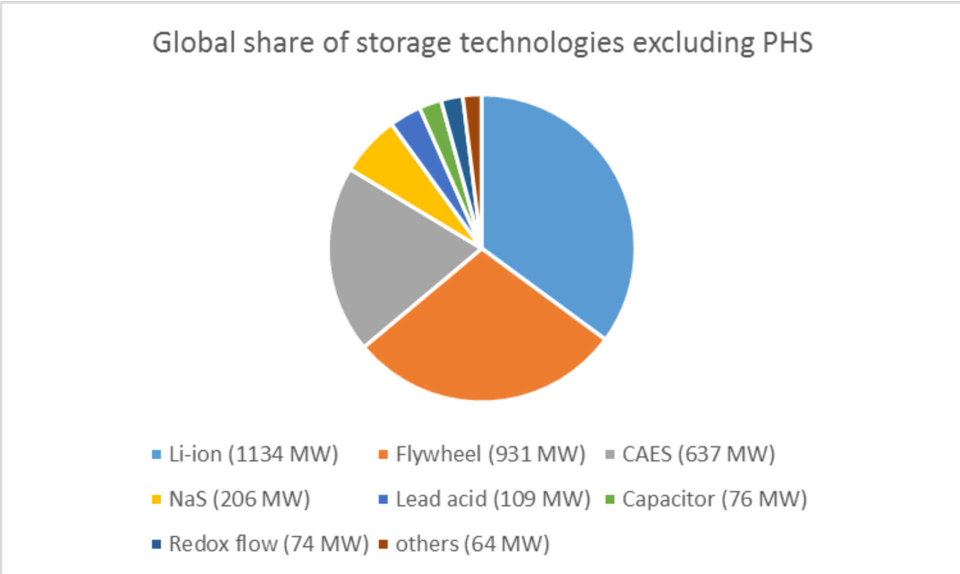
Figure 35: Variants of the energy storage family according to their system power and discharge time at rated power (GL, 2017).

Table 20 ranks the maturity of the energy storage variants described above.

Table 20 Ranking of maturity level of the energy storage variants, based on (World Energy Resources E-Storage, 2016) (Azure International, 2017) (EASE/EERA, 2017)

	Research and development	Demonstration and deployment	Commercial application
PHS			x
CAES[9]		x	x
Flywheels[10]		x	x
Li-ion batteries[11]		x	x
Redox flow batteries		x	
NaS batteries			x
Lead acid[12]		x	x
Super caps	x		
Hydrogen storage	x		
Thermal Energy Storage[13]	x	x	x

Figure 36 shows the market share of installed capacity worldwide for grid-connected storage systems (EASE/EERA, 2017) (Rethinking Energy 2017 - Accelerating the global energy transmission, 2017). Note that PHS is actually the dominating storage technology, with a current market share of 145 GW. For transparency, the market share of PHS is omitted from this figure.



9 Conventional CAES-technology is mature; AA-CAES-technology is at an early demonstration phase.
10 Low-speed flywheel technology is mature; high-speed flywheels are in an early demonstration phase.
11 Li-ion battery technology is commercially available for EV applications and widely applied in grid-connected demonstrations.
12 Conventional lead acid technology is mature; advanced lead acid is at an early demonstration phase.
13 Low-temperature sensible heat storage is mature (in water tanks for home storage and in underground (UTES)); high temperature sensible heat storage in molten salts is commercially used in combination with Concentrated Solar Plants; for other applications high temperature sensible heat storage is in demonstration phase; latent and thermochemical heat storage are at Research and Demonstration phase.

Figure 36 Global market share of energy storage technologies excluding PHS (EASE/EERA, 2017) (Rethinking Energy 2017 - Accelerating the global energy transmission, 2017).

It can be observed that CAES, flywheels (mainly in the USA), and Li-ion have comparable market shares in installed capacity (with Li-ion batteries ranking first among these technologies). However, growth predictions for Li-ion technology in grid-connected storage exceed those of CAES and flywheels (EASE/EERA, 2017) due to their more favourable performance characteristics rendering them applicable for the provision of a broad range of services. Most importantly, Li-ion batteries are also used in electric vehicles, a market which is expected to grow exponentially over the next few years, driving drastic and rapid cost reductions for Li-ion batteries to acceptable values (BNEF, 2017) (Figure 37). Favourable characteristics and strongly decreasing costs make this technology an increasingly attractive choice for many applications compared to alternative technologies.

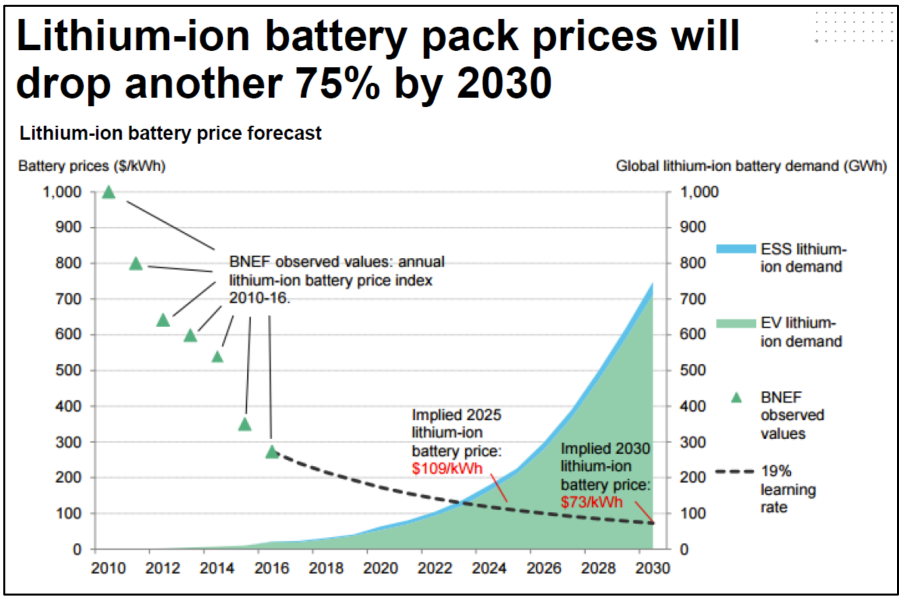


Figure 37 : Li-ion battery price and demand predictions (BNEF, 2017) (DNV GL expert).

This paper will focus on the dependence issues for Li-ion technology only.

5.1.2 *Description of Li-ion batteries*

Li-ion batteries constitute a rechargeable battery where the Li-ions move from the positive to the negative electrode during charging periods and from the negative to the positive electrode during discharging periods. The electrolyte that enables the movement of ions together with the two electrodes form the Li-ion battery cell (EASE/EERA, 2017) (Azure International, 2017).

There are several types of Li-ion chemistries available, such as:

- Lithium Cobalt Oxide (LCO);
- Lithium Nickel Manganese Cobalt Oxide (NMC or NCM);
- Lithium Manganese Oxide (LMO);
- Lithium Iron Phosphate (LFP);
- Lithium Nickel Cobalt Aluminum Oxide (NCA);
- Lithium Titanate (LTO).

These Li-ion chemistries differ mainly by energy density, power density, cycle life, and resistance to abuse. Among the various chemistries available for Li-ion batteries, the one expected to show significant growth in production and use is NMC; this is largely due to its suitability (e.g. high energy density, efficiency and safety) for the rapidly growing Electrical Vehicles market (Azure International, 2017).

Core Li-ion battery System Components

The core components of a Li-ion Electrical Energy Storage (EES) System are summarized in the following (GL, 2017)**:**

- Battery cell: This constitutes the heart of the Electrical Energy Storage system and is responsible for the process of storing the chemical energy;
- Battery block: This constitutes a parallel connection of a few cells;
- Battery modules: This constitutes an aggregation of several cells or blocks. It is also known as a "pack" or "tray", and is normally the smallest interchangeable part of the battery system. A positive and a negative terminal are included, while a module Battery Management System (BMS) may be included as well. This is responsible for checking the voltages, currents, and temperature (using appropriate sensors) as well for balancing the State of Charge (SOC) of the aggregated cells. The module BMS delivers information on internal states to a superior BMS, while it may also receive control signals;
- Battery rack: This constitutes an aggregation of several modules. A positive and a negative terminal are included. A superior BMS may be present, which controls the interaction of the separate modules. The rack BMS delivers information on the state of the rack to a superior control system;
- Battery system: This constitutes a parallel connection of several racks that form the battery. The battery system is part of the Electrical Energy Storage (EES) system and it contains disconnect devices and protective circuitry. The battery system BMS collects and aggregates all information from the connected racks and sends them to a superior control (i.e., the energy management system of the EES system);
- Power Electronic Converters: Multiple racks are connected to one conversion system which may comprise multiple converters. The converter has converter controls. Overall it is the system demand controller that communicates with the grid operator;
- Auxiliaries: Additionally, a tailored auxiliary system for heating, ventilation, and air conditioning (HVAC) is present, together with enclosures, fire suppression systems, and site controllers.

All the above mentioned components together with the low and high level controls, as well as a transformer that may be present mainly for grid-connection purposes, formulate the Electrical Energy Storage system. The storage system with all its core components and the exchange of power and data among them is depicted in Figure 38.

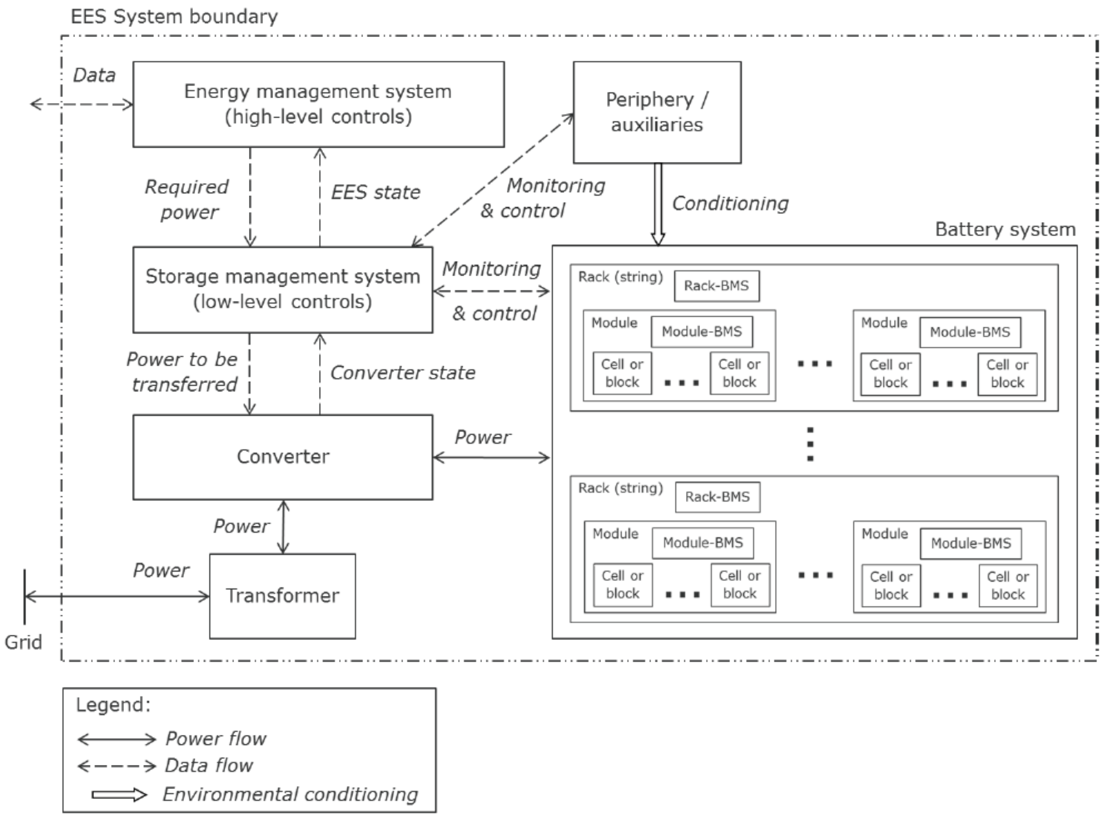


Figure 38 : General schematic and components of a cell-based battery EES system (GL, 2017).

From the above mentioned core components of an EES system, the most important ones to be further considered for dependency issues constitute the battery cell, the battery system, the power converter, as well as the storage system as a whole (Figure 39).

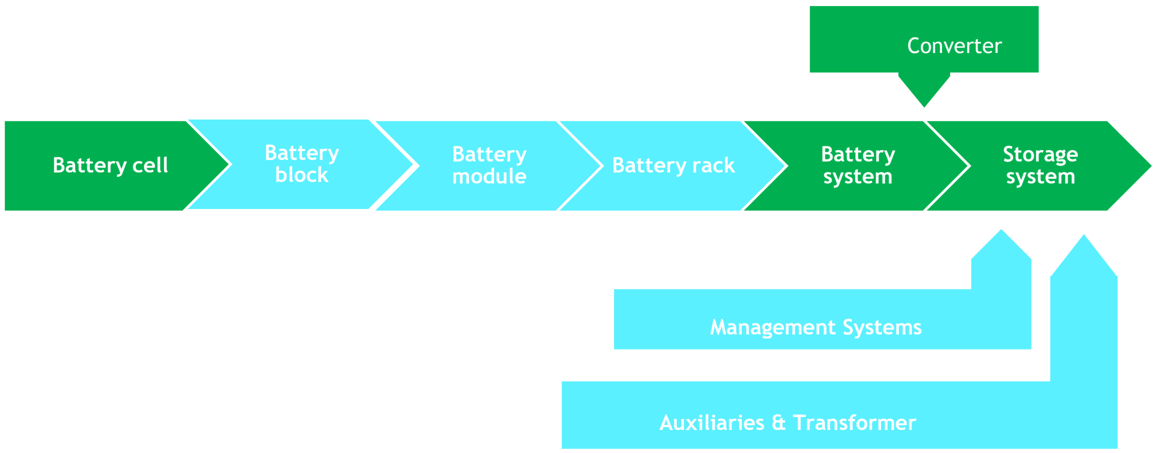


Figure 39 : Value chain of Electrical Energy Storage system.

5.1.3 Issues of dependency – Li-ion batteries

Market Concentration & Cost

Reliance on import per Li-ion battery core component

Battery cells: Major Li-ion battery cell manufacturers are Panasonic (Japan), Samsung (South Korea), LG Chem (Korea), Toshiba (Japan), BYD (China), CATL (China), and Kokam (South Korea). Small manufacturers in Europe are Fiamm (Italy), and SAFT (France). Thus, it can be concluded that the Li-ion battery cell business is mainly controlled by the manufacturers located in Asia. As such, a commercial risk is identified regarding reliance on the import of Li-ion battery cells. The impact of this reliance may be compounded by the expected increase in demand for Li-ion batteries. However, EV suppliers are already responding to this fact by securing their own battery supply capacity. For example, Tesla has announced several Gigafactories in the USA, Europe, and China (Electricity Storage and Renewables: Costs and Markets to 2030, 2017). Other large-scale factories are planned in Germany (TerraE), Sweden (Northvolt), Hungary, and Poland_(Greentech Media, sd). The growing production capacity of Li-ion cells in Gigafactories is an interesting mitigating measure against the reliance on import. Stationary energy storage will benefit from this economy of scale.

Battery systems: The most important battery system manufacturers constitute BYD (China), LG Chem (Korea), Samsung SDI (South Korea), Toshiba (Japan), NEC Energy Solutions (USA), Kokam (South Korea), Panasonic (Japan), Mitsubishi Electric (Japan), Younicos (Germany), Nidec (France/Italy), Leclanché (Swiss), and Tesla (USA). Although battery system manufacturers are mainly concentrated in Asia and the USA, there are some key European players. Therefore, no critical dependence is identified regarding battery systems.

Converters: Key converter suppliers constitute SMA (Germany), Dynapower (US), S&C Electric (USA), and Parker (USA). The converter manufacturers are spread worldwide and thus the production of converters is considered an international market. Note that converters are used in several applications other than energy storage systems. Therefore, no critical dependence is identified regarding the supply of converters.

Storage systems: Key manufacturers of storage systems constitute AES (USA), Younicos (Germany), Stem (USA), Nidec (Japan), Siemens (Germany), and Leclanché (Swiss). Thus, important storage system manufacturers also exist within Europe. As a result, no critical reliance on the import of storage system is identified.

Critical raw materials: One of the important issues of dependency that may arise is the dependence on raw materials. Possible issues that Europe may face in the future regarding the raw materials required are a lack of available resources worldwide, difficulty with the mining of a certain resource, the high concentration of a resource in one country outside Europe, the political situation of a supplying country that may jeopardize the supply of a certain resource, as well as adverse political relationships between Europe and supplying countries. Thus, it is important to identify which are the important raw materials that are used in Li-ion batteries and conclude to whether critical dependencies arise for each one of them.

Important raw materials used in Li-ion cells constitute lithium, cobalt, and phosphate rock.
The supply of lithium is not considered critical (Commission, 2017). Lithium is mainly mined in Chile, China, Argentina, and Australia, as depicted in Figure 40 (Study on the review of the list of Critical Raw Materials, 2017). These four countries are the most important suppliers, while smaller suppliers also exist. The fact that lithium is supplied in big quantities from more than one major supplier constitutes that the supply of lithium is non-critical. Moreover, lithium reserves are considered sufficient to cover the expected increased needs (Electricity Storage and Renewables: Costs and Markets to 2030, 2017).

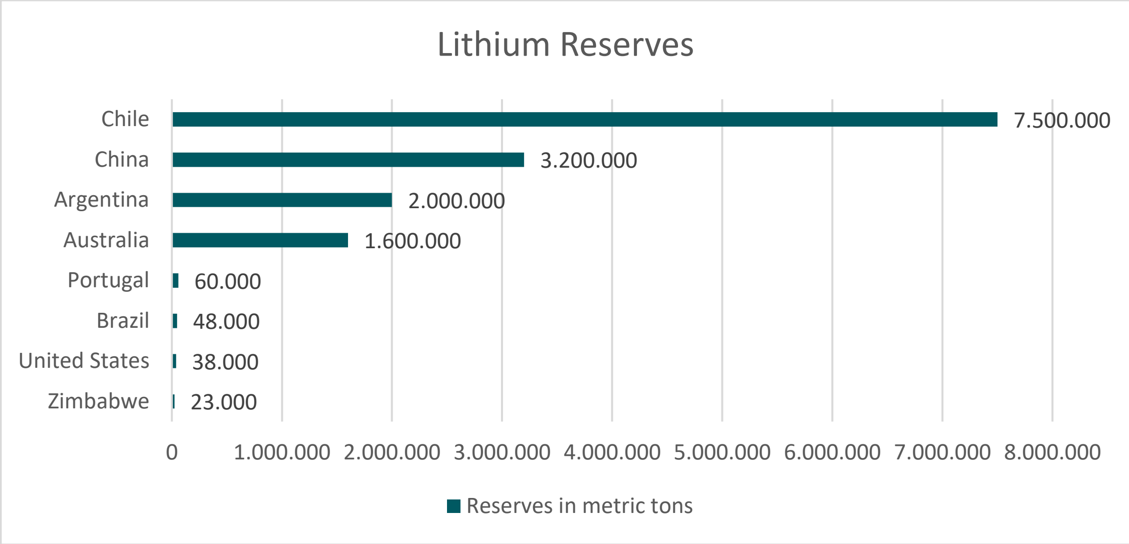


Figure 40 : Global Lithium resources (Statista, sd).

Regarding Cobalt, the import reliance rate is 32% and is thus considered medium. The most important portion of reserves is located in the Congo (64%) (Commission, 2017) (see Figure 41) (Study on the review of the list of Critical Raw Materials, 2017)). The most important importers of Cobalt for Europe are Russia (91%), and the Congo (7%), while the sources of European supply being Finland and Russia (Commission, 2017). The portion of cobalt used within Li-ion batteries is small, while alternative chemistries requiring less cobalt can be used instead (DNV GL expert).

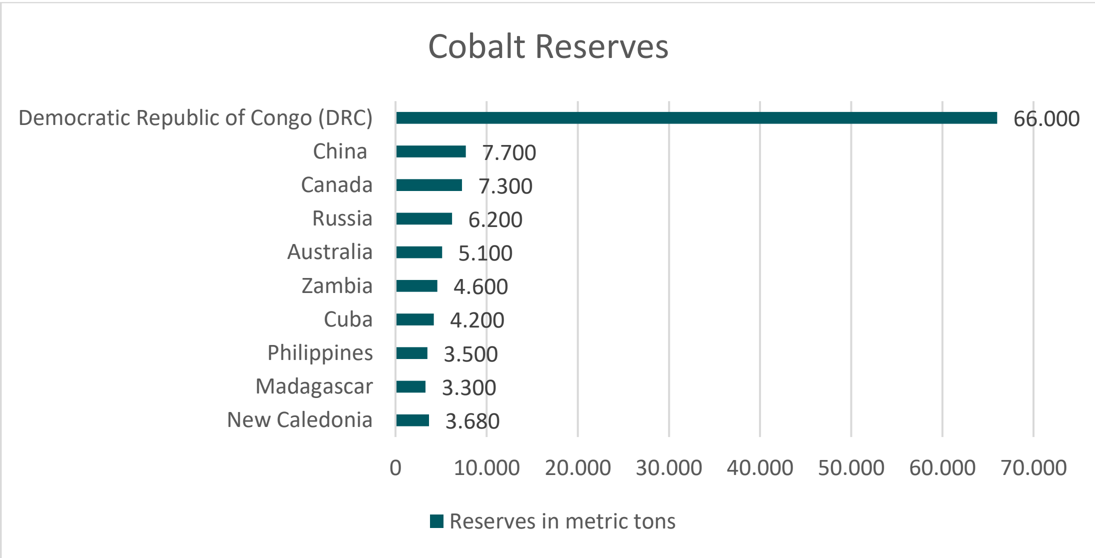


Figure 41 : Global cobalt resources (Investing News, sd).

Finally, the import reliance rate for phosphate rock is 88% and is thus considered high (Commission, 2017). The most important producers of phosphate rock constitute China (44%), Morocco (13%), and the USA (13%) (Commission, 2017), while more information about the rest of the important phosphate rock producers are provided in Figure 42 (Investing News, sd). The most important importers of phosphate rock to the EU constitute Morocco (31%), Russia (18%), Syria (12%), and Algeria (12%), while the sources of the European supply are Morocco, Russia, Syria, Algeria, and Finland (Commission, 2017). The portion of phosphate rock used within Li-ion batteries is small, while alternative chemistries requiring less phosphate rock can be used instead (DNV GL expert).

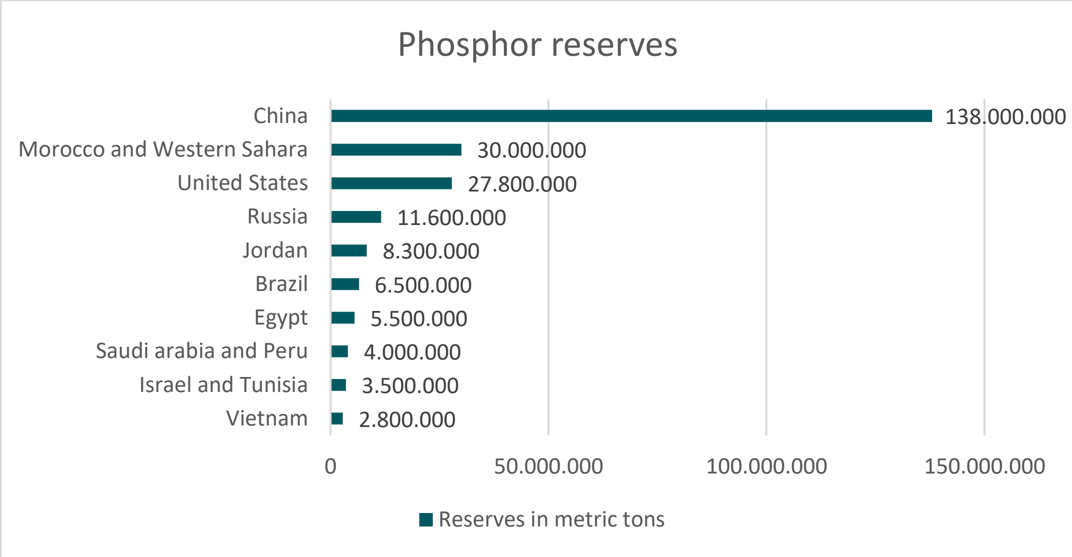


Figure 42 : Global phosphate rock resources (Investing News, sd).

Regarding the raw materials used within power electronics, the most important ones constitute silicon, copper, and gallium. From these, silicon is the most critical, with its import reliance rate reaching 64% and thus considered medium. The most important producers of Silicon metal constitute China (61%), Brazil (9%), Norway (7%), the USA (6%), and France (5%). The most important importers of Silicon to the EU are Norway (35%), Brazil (18%), and China (18%), while the sources of the European supply are Norway, France, Brazil, China, Spain and Germany (Commission, 2017).

Regarding Gallium, the import reliance rate reaches 34% and the reliance on import is thus considered medium, with the most important producers being China (85%), Germany (7%) and Kazakhstan (5%). The main importers of Gallium to the EU are China (53%), the USA (11%), Ukraine (9%), and South Korea (8%), while the main sources of European supply are China, Germany, the USA, Ukraine, South Korea, and Hungary (Commission, Communication from the Commission to the European Parliament, the Council, the European economic and Social Committee and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU., 2017). The supply of copper is not considered critical.

5.2 Conclusions

5.2.1 Critical dependencies for Li-ion batteries

To conclude, from the available storage technologies, the most relevant in terms of market share, cost, maturity and performance characteristics, is Li-ion batteries. The deployment of this technology is expected to grow rapidly in the future, resulting in a high market share of Li-ion batteries. The main reason is the fact that they are widely applied in the growing Electrical Vehicle industry leading to significant learning rates, in combination with the fact that they are also well suited for provision of various storage services such as ancillary services, renewable integration, customer services and distribution support (GL, 2017) (DNV GL expert). These services become more and more important, due to the increasing renewable penetration levels and the need to ensure grid stability and reliability. Finally, the increasingly attractive total cost of ownership of Li-ion battery systems makes this technology a top choice for many applications.

The reliance on import for Li-ion battery cells is considered high, since many cell manufacturers are concentrated in Asia. Thus, a commercial risk has been identified for this stage of the storage system value chain. Nevertheless, the fact that large scale factories are planned in Europe and other parts of the world will reduce the risk and will improve Europe's position within the Li-ion battery cell industry.

Finally, regarding reliance on import for raw materials, the critical raw materials that have been identified are cobalt and phosphate rock (for battery cells) and silicon and gallium (for converters). A medium reliance on import has been identified for Cobalt, a high reliance on import for Phosphate rock and a medium reliance on import for Silicon and Gallium (Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions on the 2017 list of Critical Raw Materials for the EU, 2017). The fact that the supply of cobalt and phosphor is critical may drive the developments of the alternative Li-ion chemistries, such as LMO cathodes with LTO anodes, which are characterized by lower proportions of cobalt and phosphor. On the other hand, the reliance on import for the supply of lithium is not considered critical, while the available resources are estimated to be sufficient to meet the increasing demand for Li-ion batteries.

5.2.2 Consideration of variants

Li-ion batteries are selected as the only variant for analysis because of its many advantages such as performance characteristics, maturity level, current market share, and predicted market growth potential. A further rationale for covering Li-ion technology and excluding other energy storage variants is provided below:

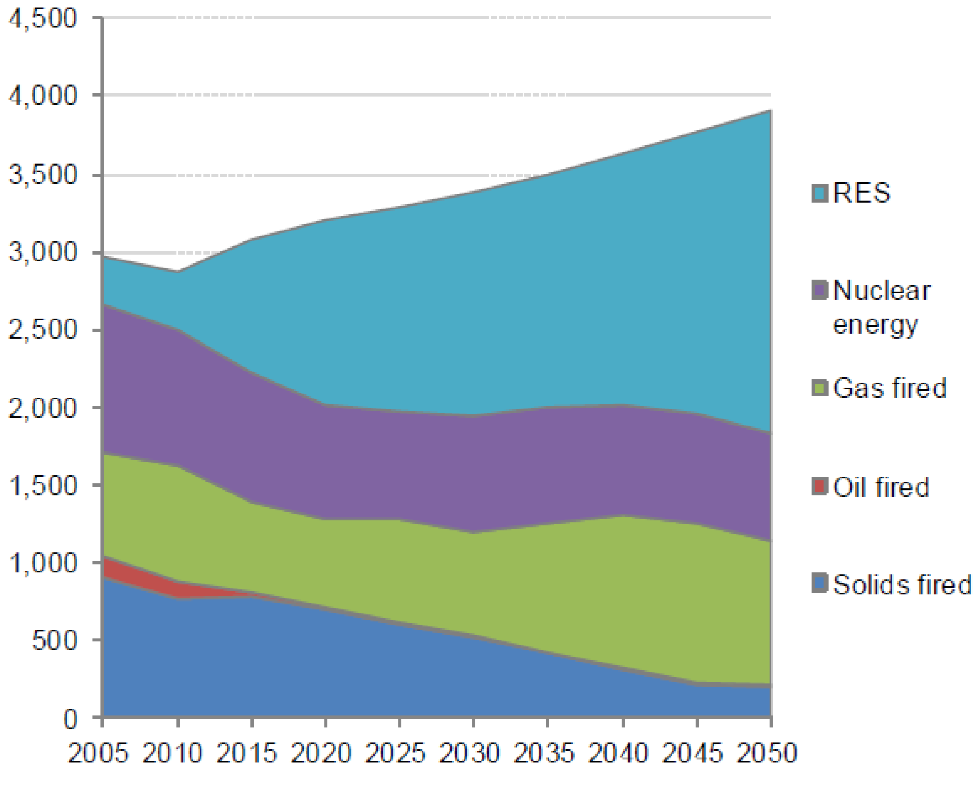
- Based upon current installed capacity, PHS is the most widespread applied and mature technology. However, the specifications of PHS limit the applicability of this technology to bulk storage and storage for renewable integration. Future market developments expect expanding markets for other services, which are less compliant with PHS. In addition, market growth is restricted by the specific geographical requirement for PHS. However, PHS is covered in the hydro summary paper;
- Battery technologies can provide all available storage services as is shown in Table 19. Among the numerous battery technologies available, Li-ion batteries are rapidly gaining importance and are expected to dominate the market for most grid connected applications over the coming decades. An important driver is the fact that, due to their performance characteristics, Li-ion batteries are the technology of preference for the growing Electric Vehicle industry. The realized learning rates contribute to significant cost reductions, performance improvements, and increased maturity levels for Li-ion batteries. These continuous developments also support the deployment of Li-ion batteries in grid-connected applications, at the expense of alternative battery technologies with similar characteristics and maturity levels which do not benefit from similar learning rates. Thus, Li-ion batteries constitute a very important variant to be further considered for dependency issues;
- Other storage technologies, such as CAES, flywheels, super capacitors, and hydrogen storage are not considered within this summary paper since at present their market growth potential is limited. None of these technologies can be applied for all storage services described in Table 19. For CAES there are limited numbers of appropriate sites and developments are required to improve the efficiency. Flywheels are not

considered since the market share in Europe is marginal and the maturity for grid supporting services is medium. Super capacitors are not considered since they are still an emerging technology for grid support. Finally, hydrogen storage and high temperature sensible heat storage are considered in other summary papers.

6 Flexible conventional thermal power plants

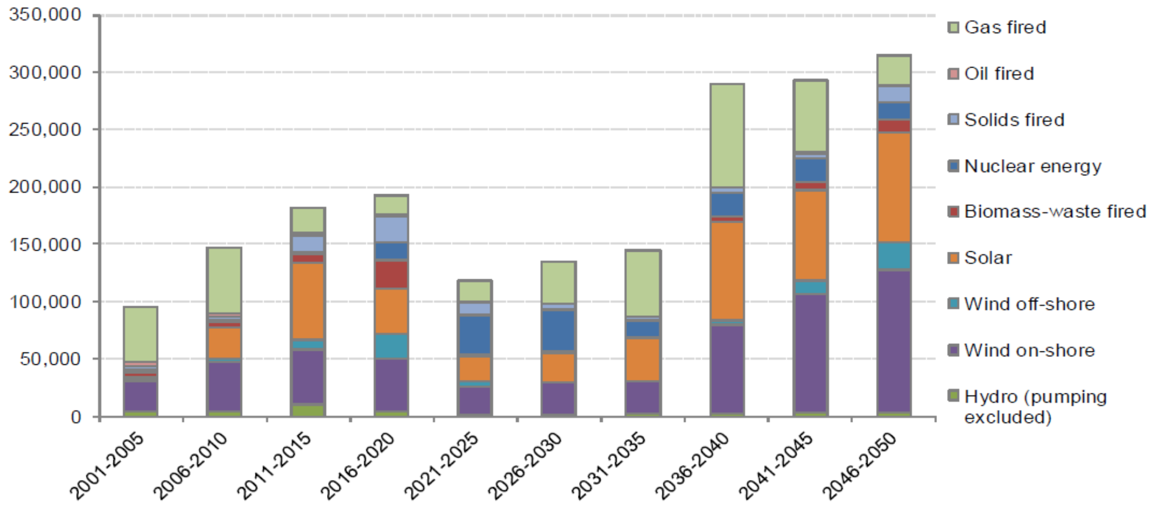
This summary paper focuses on conventional thermal plants that provide a high level of flexibility to the grid: gas engine-based, gas turbine-based, and pulverized coal plants. Note that nuclear power plants are not regarded as flexible power generation.

Pulverized coal plants are currently under great political pressure to close, to reduce CO_2 emissions. Various countries (e.g. Germany, Netherlands) are already phasing out some of their coal fired assets. New capacity in Europe is expected to be none to limited. The share of solids/coal in power generation significantly declines, but not before 2020, to 15% in 2030 (EC, EU Reference Scenario 2016 - Main results, 2016). Also the share of energy production from solids (coal) continues to decline (see Figure 43). Finally, new power investment capacities for solid (coal) fired assets are expected to be no more than a few percent after 2025 (see Figure 44). Therefore, pulverized coal plants are excluded from the summary paper.



Source: PRIMES

Figure 43 EU energy production (Mtoe) (EC, EU Reference Scenario 2016 - Main results, 2016)



Source: PRIMES

Figure 44 Net power capacity investments by plant type (MWh – for five year period) (EC, EU Reference Scenario 2016 - Main results, 2016)

On the contrary, gas fired generation will remain to play a substantial role both in terms of production (see Figure 43) and new capacity (see Figure 44) over the next decades. Flexible generation becomes of strategic importance for the EU energy system, balancing the grid when an increasing share of electricity is generated by intermittent sources. Natural gas will then be the predominant fuel source for flexible conventional power generation. Consequently, the variants considered will all be flexible gas-fired based. We consider that flexible generation plants shall be able to provide electricity quickly to the grid (within a few minutes) and shall be able to provide full load power within 30 minutes.

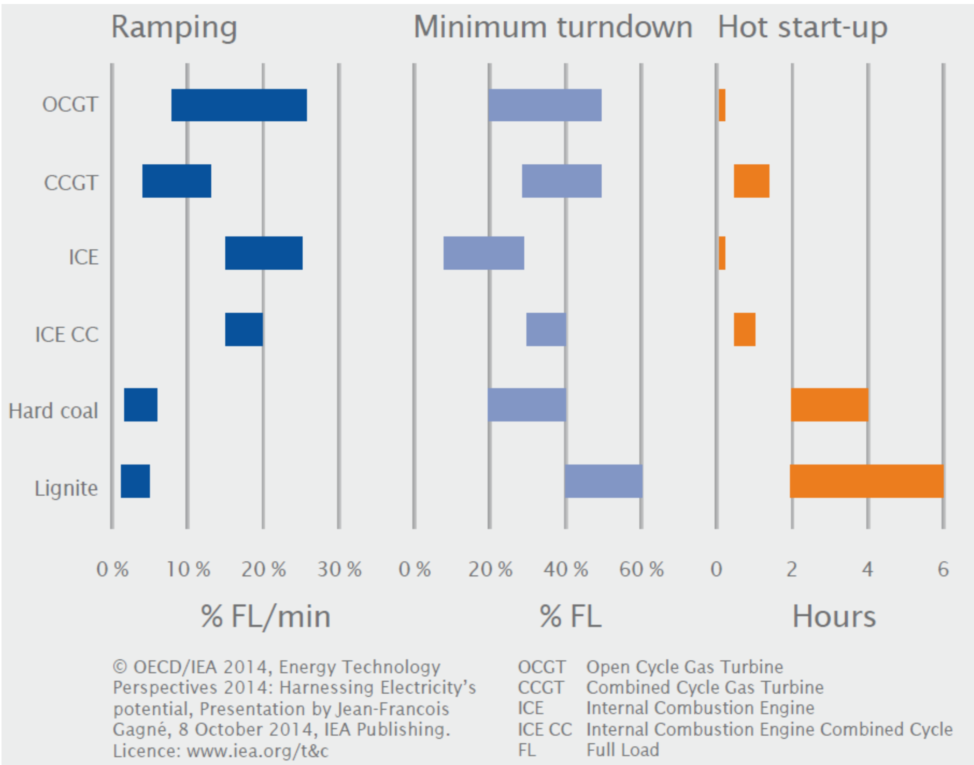


Figure 45 Ramp rates, minimum turndown percentage and hot start up times of different power sources (source OECD/IEA 2014) (EUGINE, 2015)

Figure 45 provides an overview of ramp rates of different gas-fired generation plants. Based on the previously stated definition of flexibility, flexible conventional power is generated by open cycle gas turbines (OCGT) or internal combustion engines (ICE). Heat recovery steam generators (included in combined cycle units) are then not considered as flexible, and are excluded from our analysis.

These two variants will be studied in the following chapter.

Both variants are proven and mature technologies. Thus, the following two variants will be studied further in this summary paper:

1) Gas engines (ICE) based power plants. Gas engines are reciprocating engines that convert the energy in the fuel to mechanical energy, and by a generator to electricity. The installed capacity in Europe is more than 30 GW;
2) Gas turbine based (open cycle) power plants. Gas turbines also convert the energy in the fuel to mechanical energy, and by a generator to electricity.

Not considered here are building materials.

Gas fired generation in the EU28 is expected to almost double (from 566 TWh in 2015 to 945 TWh in 2045 after which it is expected to decline) (EC, EU Reference Scenario 2016 - Main results, 2016). Gas fired capacity is expected to increase from 220 GWe in 2015, to 259 GWe in 2045, and to 269 GWe in 2050 (EC, EU Reference Scenario 2016 - Main results, 2016). This excludes electricity derived from gas-fired cogeneration units.

This summary paper provides an overview regarding the following dependency issues for both the variants:

Non-EU28 original equipment manufacturers (OEMs);

- Materials and components;
- Operations and maintenance capacity.

6.1 Gas engine based energy plants

6.1.1 Description of gas engines

Medium to large stationary gas engine based power plants provide flexible load to the grid. They are available in size ranges typically between 100 kW and 10 MW each (GE Jenbacher), or 19 MW (Wärtsilä) The single engines can provide electrical power up to 21 MW per unit and are normally four-stroke engines (Wideskog, 2017). Large gas engines will play a significant role in distributed power generation for the energy supply of the future (al., 2017).

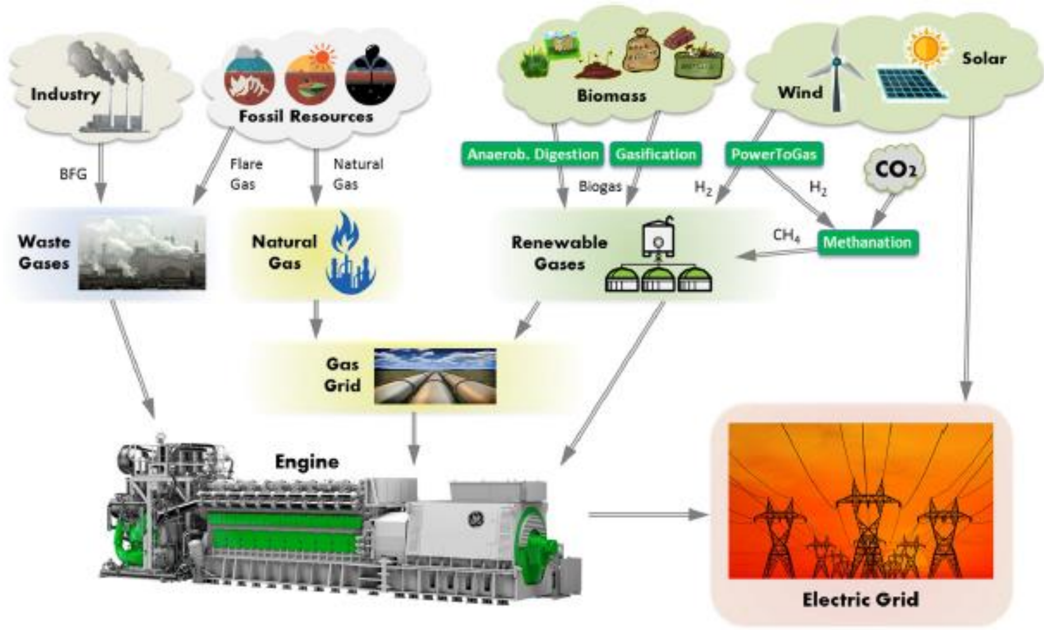


Figure 46 **Power generation routes via a gas engine (al., 2017)**

Gas engines are a core technology for power plants in several markets:

- Baseload plants, where they provide steady continuous power in e.g. remote locations (islands) or in extreme climates (deserts, mountains);
- Emergency reserve power plants, where they provide electricity in case of, for example, power failure for hospitals, datacenters, banks etc.;
- Combined heat and power plants, where they provide both heat and power to e.g. hospitals, swimming pools, shopping centers and greenhouses;
- Peak load power plants, where they ensure that instantaneous power demand is fulfilled;
- Biogas plants for e.g. farms or waste-water treatment facilities, where they convert green gas into green power.

These gas engines have similar manufacturers and components. They vary in design (internal geometries) but not much in materials or components.

Currently, around 30 GW of gas-engine based power is installed in the EU.

6.1.2 Issues of dependency – gas engines

The scope of the assessment consists of the import of engines from non-EU28 manufacturers, of components from non-EU28 manufacturers (subcontractors), and of materials.

A number of major original equipment manufacturers (OEMs) have manufacturing locations in Europe or North America (e.g. GE Jenbacher is located in Austria, GE Waukesha is present in the USA and Canada (gmtoday, sd)). A competitor for General Electric gas engine brands is Wärtsilä. Wärtsilä is located in Finland (please refer to Table 21 below). Another gas engine manufacturer is Caterpillar/MWM with its headquarters in Mannheim, Germany. Spare parts can be obtained from the original equipment manufacturers via servicing companies like Clarke Energy (UK) or from non-original component engineers/manufacturers such as ECI (Austria), or ACEnergy (Indonesia).

Table 21 List of original equipment manufacturers, their main locations, fuel type and engine sizes

OEM	Manufacturing locations	Fuel type	Engine size in kWe
GE Jenbacher/ Waukesha	Austria/Canada	Natural Gas, bio/landfill/sewage gas, industrial gas, propane	100 – 10,000
Deutz	USA	Natural Gas	24 – 240
Wärtsilä	Finland, Denmark, UK, Italy, China	Natural Gas, LPG, Biogases	10,000 – 19,000
Hyundai Heavy Industries (HiMSEN)	Korea	Natural Gas	2,779 – 9,624
Rolls Royce (Bergen Engines A.S.)/ MTU	Norway	Natural Gas	1,400 – 9,400
Caterpillar Inc.	USA	"a wide variety of gaseous fuels"	71 – 1,286
Perkins Engines (subsidiary of Caterpillar)	UK	Landfill gas, Digester gas, Biogas, Coal-bed mine gas	322 – 1,000
MWM (subsidiary of Caterpillar)	Germany	Natural gas, Shale gas, Mine gas, Biogas, Landfill gas, Sewage gas, Syngas	400 – 4,500
Kawasaki Heavy Industries	Japan	Green gas with methane number above 65	5,000 – 7,800
Liebherr	Switzerland	Biogas, Natural gas, Special gas	60 – 1,070
Siemens/ Dresser-rand/ Guascor	Germany, USA, India, France, Spain, Brazil	Natural gas, Lean gases from biomass gasification, Well gas, Waste gases from oil and gas industry	252 - 2,000
Doosan	U.K., Germany, Poland, Spain, Italy, U.S, Canada	Natural gas	128 - 451

Figure 47 **Engine power plants manufacturing (EUGINE, sd)**

Trade flows and imports of engines from outside the EU28 to the EU28 are not exactly known to the authors. Therefore, it is not possible to quantify the share of imports. However, Figure 47 shows that engine manufacturing sites are located across the European continent and in the UK. Table 21 shows also several (3-5) European equipment manufacturers, that supply gas engines or parts.

Essential to the design of a gas engine is the development of a profound understanding of wear mechanisms so that components can be optimized purposefully. With the design and manufacturing location of Jenbacher, the EU28 has a leadership position on this. Wärtsilä has joint ventures and manufacturing locations for parts globally, its main R&D centers are also located in the EU28. Other gas engine manufactures are Mitsubishi Heavy Industries (Japan), and Caterpillar (USA). With regard to R&D, the EU28 has a leadership position.

An engine is made up mainly of various metal alloys. The most important structural materials in 4-stroke engines are cast iron, alloy and structural steels, and aluminium alloys. The three main elements used in the metal alloys are iron 90.8% m/m, aluminium 2.7% m/m, and carbon 2.2% m/m (Wärtsilä, sd). All of these metals are not considered as critical for imports. In cast iron, a small amount of phosphorous is present.

Electric generators are key rotating equipment for producing electricity from the rotational energy provided by the engine. Electric generators use copper (Cu) as their main metal, but can alternatively also use alumina (Al). The supply risk of copper is considered low. Main European suppliers of generators and electrical equipment are Siemens (Germany), and Alstom (France).

Market concentration

If the EU28 would show significant imports of gas engines or components, then these can be contracted from e.g. GE Waukesha (USA/Canada), Caterpillar (USA), Kawasaki Heavy Industries (Japan), or Liebherr (Switzerland). Depending on the exact requirements of the client (size, fuel type) market concentration can be higher.

6.2 Stationary gas turbine based energy plants

6.2.1 *Description of gas turbines*

A gas turbine provides a great amount of power for its weight (Boyce, 2006). It converts gaseous or liquid fuel, mixed with compressed air, to power via a turbine. The hot gas drives a turbine, and the turbine drives a compressor and a generator, with the generator providing electricity. This is called an open cycle gas turbine. An open cycle gas turbine has a faster response and lower efficiency than a combined cycle gas turbine.

6.2.2 *Issues of dependency –gas turbines*

The scope of the assessment consists of the import of engines from non-EU28 manufacturers, of components from non-EU28 manufacturers (subcontractors) and of materials.

Major original equipment manufacturers with manufacturing locations in Europe for large gas turbines are Ansaldo (Italy), and Siemens (Germany). In addition, Mitsubishi Hitachi Power Systems Europe is situated in Germany, with Mitsubishi having offices and manufacturing locations across the globe. Finally, Switzerland (Baden) has the manufacturing location for the GE Alstom gas turbines.

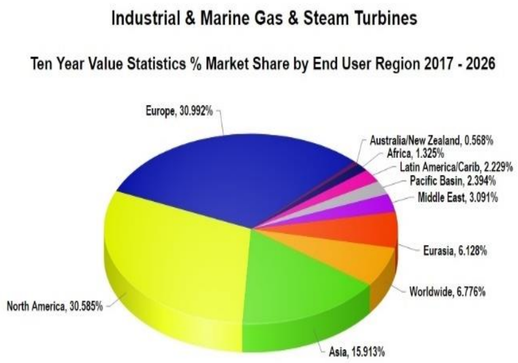
Table 22 Gas turbine OEM locations

Gas turbine OEM	Main locations	Fuel type	Gas turbine size in kWe
Kawasaki Gas Turbines	U.S, Japan, Malaysia, Germany	Gas/Liquid/Dual Fuel	1,200 – 20,000
Solar Turbines (Caterpillar)	U.S, worldwide coverage and service locations	Natural gas, Landfill gas, Digester gas, Synthetically produced gases incluiding diesel fuels	1,000 – 22,000
Siemens Power Generation	Germany, U.S	Natural gas, Liquid fuel, dual fuel, other fuel	4,000 – 564,000

Gas turbine OEM	Main locations	Fuel type	Gas turbine size in kWe
GE/Alstom	Switzerland, France, U.S.	More than 52 types of fuel	34,000 – 557,000
Ansaldo Energia	Italy	Wide selection of fuels, ranging from hydrogen enriched gas to liquid fuel	78,000 – 500,000
Mitsubishi Hitachi Power Systems	Japan, Brazil, India, China, Philippines, U.S.	Wide mixture of gases, including Blast furnace gas, Coal gas etc	30,000 – 490,000

The share (capacity) of the gas turbines from the original equipment manufacturers Siemens, Alstom, and Ansaldo compared to the total capacity installed is not exactly known to the authors. It is then unlikely that more than 70% of the gas turbines is imported. However, it is expected (and observed by the authors) that there are imports of gas turbines from General Electric and Mitsubishi. This can also be expected from Figure 48. In addition, Siemens announced that they will reduce worldwide production capacity. Siemens says it has the capacity to produce 400 large gas turbines a year. It expects demand will level out now around 110 turbines annually (Journals, 2017). It is thus possible that more than 30% of gas turbines will be from non-EU companies.

Electric generators are key rotating equipment for producing electricity from the rotational energy provided by the gas tubine. Electric generators use copper (Cu) as their main metal, but can alternatively also use alumina (Al). The supply risk of copper is considered low. Main European suppliers of generators and electrical equipment are Siemens (Germany), and Alstom (France).



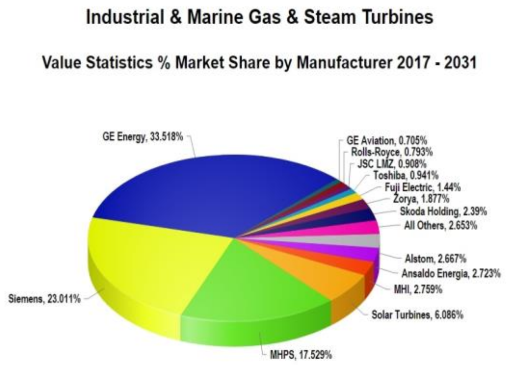


Figure 48 Value Shares by Region (left) and manufacturer (right) for industrial and Marine Gas Turbines 2017-2031 according to Forecast International (FI-Powerweb, sd)

To the extent of which they are imported, the number of companies that can supply a gas turbine is limited to a few large ones and a fair number of smaller ones (see Table 21 and Figure 48). Although there is a sheer difference in size between the top-3 companies and the rest, more than three suppliers can provide the EU28 with gas turbines. The market concentration is therefore considered as medium.

For the manufacturing of components and assembly of gas turbines, the most dominant manufacturer for gas and steam turbines is General Electric, followed by Siemens, and

Mitsubishi (FI-Powerweb, sd). These companies have factories around the globe (see Table 22). The main country for gas turbine manufacturing is the USA. GE for example has a main manufacturing plant in Greenville, South Carolina (Electric, 2017). Siemens has manufacturing locations in Berlin (Germany) but also opened a new manufacturing location in Charlotte (USA) in 2011 (Siemens, sd). Therefore, the production of components of original equipment manufacturers takes place primarily in the USA.

Gas turbines are made out of various steel alloys. A typical gas turbine contains over 1,000 precision cast parts, made from a range of different metal alloys, aluminium, titanium, and ferritic and austenitic steels (JRC Scientific and policy reports, 2013). Most demanding in terms of materials are the gas turbine blades. Gas turbines have turbine blades that must withstand very high temperatures at very high centrifugal forces. Ni-based super alloys are the predominant material for turbine blades of modern land-based gas turbines.

Table 23 Metal requirements for gas turbine blades (JRC Scientific and policy reports, 2013)

	kg/MW
Ni	0.617
Co	0.090
Cr	0.065
Mo	0.006
Ti	0.010
W	0.060
Ta	0.065
Re	0.030
Hf	0.001

Assuming that a 200MW turbine requires 200kg of weld alloy for the blades
Source: Alstom Thermal Power, 2012

Table 23 provides the specific requirements of metals for state-of-the-art gas turbine blades. Rhenium is applied in gas turbine blades. The European production capacity for Rhenium concentrates around Poland. Poland has a production capacity of 5 tonnes per year. This is equivalent to 166 GW of new gas turbine capacity, and hence a reliance on external imports is low if all this Rhenium would be available for gas turbines.

Gas turbines apply thermal barrier coatings at the first blades (first stages of the turbine). The ceramic topcoat is typically composed of yttria-stabilized zirconia (YSZ) (Thermal barrier coatings, sd). Zirconia is the common name for ZrO_2. The principal commercial source of zirconium is zircon (ZrSiO4), a silicate mineral (Zirconium, sd). Zirconium is a by-product of the mining and processing of the titanium minerals ilmenite and rutile, as well as tin mining. It is mainly used for ceramics, refractories, and foundries. The EU28 relies on the import of zircon. It is found primarily in Australia, Brazil, India, Russia, South Africa, and the USA, as well as in smaller deposits around the world. As of 2013, two-thirds of zircon mining occurs in Australia and South Africa. Zircon resources exceed 60 million tonnes worldwide and annual worldwide zirconium production is approximately 900,000 tonnes (Zirconium, sd). This exceeds the demands by far. Geographic market concentration is therefore considered as low.

Yttria is Y_2O_3. Yttrium is found in most rare-earth minerals, it is found in some uranium ores, but has never found in the Earth's crust as a free element. It is 400 times as abundant as silver. Like Rhenium, Tantallium is a byproduct from other mining activities, and the total production was estimated at 790 tonnes for 2011 (Zirconium, sd). EU28 relies on 100% import of Tantallium (Commission, 2017 list of Critical Raw Materials for the EU, 2017). However, the geographic market concentration is low, in particular when considering that the quantities needed for the gas/steam turbines compared to the production capacity of the mines is very low.

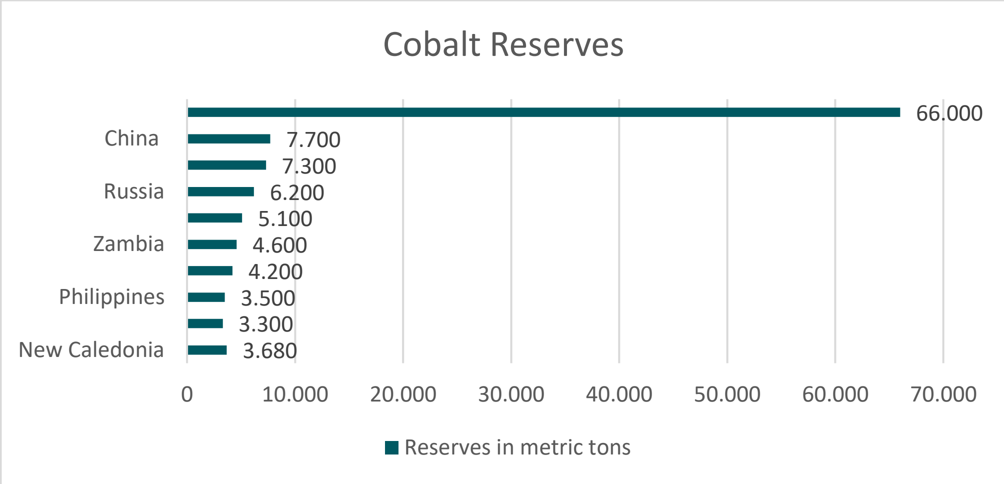


Figure 49 **Global Cobalt resources (News).**

An important component in cast steel is Cobalt. Cobalt is mainly produced as a by-product from both nickel and copper mining. Mining of cobalt takes place outside of EU28 whereas EU28 is one of the global leading market players for refining capacity (JRC Scientific and policy reports, 2013). Currently, the EU28 imports 32% of its Cobalt, solely from Russia. The remainder is sourced from Finland (Commission, 2017 list of Critical Raw Materials for the EU, 2017). Most Cobalt reserves are concentrated in Congo (see Figure 49), although reserves are available in many countries outside of EU28 (JRC Scientific and policy reports, 2013).

6.3 Conclusions

6.3.1 Critical dependencies

For gas turbines, the most critical dependency is the dominance of one market player. Although the EU28 has several market players (such as Siemens) that can supply gas turbines, there is still import of gas turbines from other manufacturers. The market concentration of large suppliers from outside the EU28 is medium (General Electric and Mitsubishi, to a lesser extend GE-Alstom, and several smaller ones).

An important component for cast steel and turbine blades is cobalt. The EU28 has refining capacity but relies for 32% on the import of raw cobalt material. Therefore, import reliance for cobalt is rated at medium. Although cobalt reserves are concentrated in the Congo (see Figure 8) there are many countries that can supply cobalt (for the amounts needed) and thus market concentration is considered high.

6.3.2 Consideration of variants

For both variants, one common dependency on gas imports can be identified. This is a common dependency for both variants.

For the variant gas turbines, two additional dependencies can be identified. Because of these extra dependencies we recommend that both variants will be treated separately in the next stages.

7 Geothermal energy

Geothermal energy provides a clean, renewable and constant form of energy, which can either be used as a base load power generator in energy systems, or to directly heat buildings or certain industrial processes. Geothermal projects involve drilling into the subsurface to access the thermal energy that is generated and stored there.

Geothermal energy sources are generally classified as low to medium enthalpy, indicating heat sources between about 40 and 150°C (water/steam), or high enthalpy, referring heat sources above 150 °C (steam). The enthalpy of the heat source generally determines the type of geothermal technology used to exploit the resource. High enthalpy geothermal wells are commonly drilled up to 2km in depth, where low enthalpy wells may be much shallower. In this broad brush assessment, three variants of geothermal energy technologies have been identified:

- Dry steam;
- Flash steam;
- Binary cycle.

Whereas low/medium enthalpy geothermal system are generally used for heating buildings, a high enthalpy surface installation uses steam to drive a turbine which generates electricity. Dry steam plants use steam piped directly from a geothermal reservoir to turn generator turbines. Flash steam plants take high-pressure hot water from deep inside the earth and convert it to steam to drive generator turbines. Such installations are common in Iceland and Italy, where the volcanically active geological environment means that geothermal heat sources reaching 200°C can be reached within a depth of 1000 m.

Most recently, medium enthalpy heat sources have also been exploited for power production, through the use of binary cycle power plants. Binary cycle power plants transfer the heat from hot water to another liquid, which has a lower boiling point. The heat causes the second liquid to turn to steam, which is then used to drive a generator turbine. This technology allows lower temperature geothermal resources to also be used for generating electricity. An overview of the different types and uses of geothermal resources is provided in Table 24.

Table 24 Types and use of geothermal resources

Types and uses of geothermal resources		
Resource type based on temperature	Geographical and geological location	Use/technology
High: 200°C	Globally around boundaries of tectonic plates, on hot spots and volcanic areas	Power generation with conventional steam, flash, double flash, or dry steam technology
Medium: 150-200°C	Globally mainly in sedimentary geology or adjacent to high-temperature resources	Power generation with binary power plants, e.g., ORC or Kalina technology
Low: <150°C	Exists in most countries (average temperature gradient of 30°C/km means that resources of about 150°C can be found at depths of about 5 km)	Direct uses (space and process heating, etc) and, depending on location and power tariff offered, power generation with a binary power plant.

Note on Enhanced Geothermal Systems

Enhanced geothermal systems (EGS) are engineered reservoirs created to produce energy from geothermal resources that are otherwise not economical due to a lack of water and/or permeability. For EGS systems, a set of two deep wells of between 3-5 kilometres deep are drilled and water is injected into the fractures of the rock, which captures the heat of the rock before being pumped out to the surface as very hot water and used in flash steam plants to generate electrical power. Important to note is that EGS is not a geothermal technology in itself, and the suite of techniques that could be considered as EGS systems must be combined with one of the power production methods mentioned above.

Given this justification, EGS is not considered as an individual technology variant, as the technology is focused primarily on the subsurface component of a geothermal project. The assessment of well drilling and construction covered in the assessment is relevant for EGS, as are all assessments related to the different power plants, all of which can be combined with EGS dependent on geology.

7.1 Description of variants

7.1.1 Description of dry steam geothermal

Dry steam geothermal is the most established form of geothermal energy, using direct steam liberated from rock pores and fractures in the earth's subsurface to drive a turbine, which in-turn produces electricity. The first dry-steam system was installed in Larderello, Italy, in 1904. Despite being one of cheapest forms of geothermal energy, the presence of major dry-stream fields are rare. According to Dipippo, only 5% of all hydrothermal (>200°C) reservoirs are capable of producing dry steam (DiPippo, 2012). Worldwide, there are only two major dry-steam fields in operation, Larderello in Italy, and The Geysers Geothermal Area in California.

The direct steam process begins with drilling a production well, where the dry stream is released from the subsurface and enters the system. The steam is then passed through a steam purifier that removes any large particles to prevent them damaging the system. Despite the steam being 'dry', there could be small amounts of moisture in it which must be removed by a demister. The steam then enters the powerhouse whereby the pressure of the steam turns the turbines, which are directly connected to a generator. The design of the turbines and generator of dry steam geothermal power plants are very similar to those of fossil-fuel power plants, with the exception of material selection and coatings of the turbine blades, given the corrosive geothermal steam. Once the steam has passed through the turbine, it enters the condenser where it cools and condenses into water which is then reinjected into the subsurface.

7.1.2 Description of flash steam geothermal

Flash steam geothermal power plants work by utilising the high temperature brine from geothermal reservoirs to create steam which drives turbines. 'Flashing' is the term used to describe the creation of steam from a saturated liquid, due to a decrease in pressure. Flash steam geothermal power plants are the most common form of geothermal energy worldwide, suitable for most liquid-dominated reservoirs. Flash steam plants use reservoirs with temperatures higher than 180°C. Flash steam plants are generally categorised as either a single-flash plant, or as a double-flash plant, depending on the number of flashing processes applied. For enhanced geothermal systems where temperatures can reach supercritical temperature (>350°C), triple-expansion power plants have been developed.

Similarly to the dry steam process, a well is drilled into a suitable geothermal resource. The hot brine then flows under its own pressure towards the surface installation where it is collected in a low-pressure tank. As the hot liquid elevates up the well-bore, the drop in pressure creates a two-phase flow of gas and liquid. In most modern plants, the two-phase flow is collected in a cyclone separator which is designed to separate the liquid and gas phases. In a cyclone separator, the process is carried out by generating centrifugal force on the mixture entering the separator by using a tangential or spiral inlet to the cyclone. As the fluid rotates, the liquid with higher density will move outward and downwards while the vapour which has lower density will move inward and upward (Zarrouka, 2015). The liquid collects at the bottom of the vessel and is removed, whereas the gas collects at the top. After the cyclone separator, the remaining process is akin to that of a dry steam power plant. The steam passes through a moisture remover, then the turbines, and is finally condensed and reinjected into the reservoir. Another minor difference over the dry steam system is the possible use of two re-injection wells/pumps, one for the separated brine mixture and one for the condensate.

7.1.3 Description of binary cycle geothermal plants

Binary cycle geothermal power plants vary greatly from the flash variants. Binary cycle power plants transfer the heat energy from the geothermal brine to another 'working fluid', which has a lower boiling point. The heat causes the working fluid to turn to a vapour, which is then used to drive a generator turbine. This technology allows lower temperature geothermal resources (120-190°C) to be used for generating electricity. Binary cycle plants use the working principle of the Organic Rankine Cycle (ORC).

Binary geothermal power plants have a greater deployment potential in the EU, given that they can operate using relatively lower temperature geothermal resources which have a higher prevalence than the higher temperature resources needed for flash systems. The prevalence of binary geothermal systems has increased in the EU in recent years, most notably in Germany (see Figure 50). Although outside the EU, Turkey represents another considerable growth market for binary geothermal systems (EGEC, 2017).

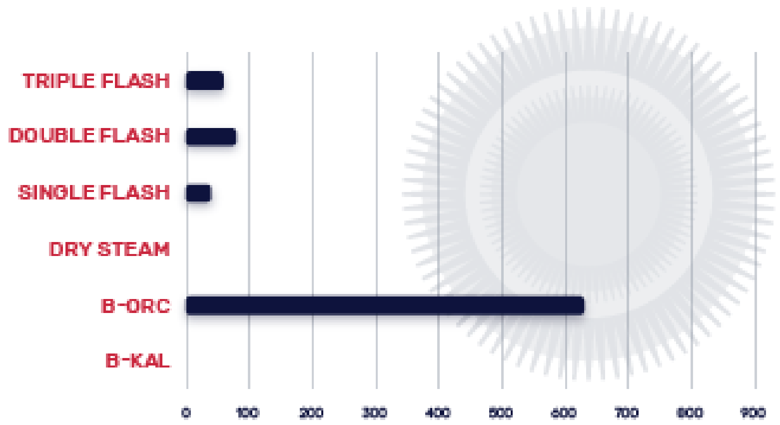


Figure 50 New installed capacity per technology between 2012-16 (MWe) (EGEC, 2017)

The binary cycle geothermal plant is a closed system, whereby the geothermal brine never comes into direct contact with the working fluid or the power plant's turbines. Once the brine is pumped from the geothermal reservoir it first passes through a sand remover, after which it enters the evaporator which facilitates the heat transfer between the brine and the working fluid. Key to the working fluid, is that it has a low triple-point temperature, a high enthalpy of vaporization, and high thermal conductivity. The vapour of the working fluid then drives the turbine to generate electricity, and is then passed through a condenser where it is cooled either by air or water. The working fluid is then recirculated back first to a preheater, where it is heated to its boiling point, and then back to the evaporator. Binary geothermal power plants can reach efficiencies of between 25% to 45% (JRC, 2014)

7.2 Issues of dependency with geothermal power plants

From the brief descriptions of the geothermal technology variants considered above, it can be deduced that there are a number of system components that are common across each of the systems studied. Table 25 provides an overview of the key components identified in geothermal power plants, and their use in the different types of geothermal power plants.

Table 25 Simplified list of key components for common geothermal power plant systems

Equipment	**Type of plant**		
	Dry-steam	Single/double flash	Binary cycle
Brine/steam extraction			
- Well construction			
- Downhole pumps (ESPs)			
- Wellhead valves and controls			
- Piping			
Steam/brine treatment and production			
- Steam purifier			
- Demister			
- Cyclone separator			
- Preheater			
- Evaporator			
- Working fluid			
Power plant			
- Turbine and generator			
Cooling			
- Condenser			
- Cooling tower			
Injection equipment			
- Condensate re-injection pump			
- Brine re-injection pump			

Based on the available project resources for the broad brush assessment, and the availability of reliable literature, a prioritisation of key components to investigate for the import share and market concentration has been made. The prioritisation of key components is based partly on:

- The occurrence of the component in multiple types of geothermal system type;
- The assumed contribution to the capital cost of a typical geothermal project, based on Figure 51 below (high capital cost components are given higher priority);
- The availability of reliable literature on import share and market concentration.

CATEGORY	SUB-CATEGORY	%
Drilling	Infrastructure for drilling site	4
	Electricity	1
	1st well	23
	2nd well	17
	Planning and Testing	6
	Reservoir engineering	4
		55
Production	Production and Injection pumps (LSP vs ESP)	3
	Heat exchanger	2
		5
Power plant (binary)	Turbine and generator	13
	Plant construction	5
	Coolers	2
		20
Infrastructure	Pipes and valves	2
	Grid connection	3
		5
Fees and Contingencies (contractor overhead costs, fees, profit, and construction)		15
		100

Figure 51 Share of capital expenditure on components required for a 5MWe geothermal power plant, with one production and one injection well, coupled with a binary power plant (EGEC, 2016 EGEC geothermal market report. Full report - Members Edition, 2017)

Based on the criteria for prioritisation, the following components of geothermal power plants have been selected for assessment:

- Well drilling and construction (all systems);
- Downhole pumps, specifically Electrical Submersible Pumps (binary systems);
- Heat exchangers (binary systems);
- Turbine/generators (all systems);
- Cooling towers (all systems) .

Well drilling and construction

Well drilling and construction can be considered both a service, and a component for a geothermal power plant project. A drilling rig is needed to gain access to the geothermal resource in the subsurface. Drilling rigs for geothermal projects are likely to be mobile drilling rigs. Once the well has been drilled and completed with well casing, cement, and production tubing, the rig will move away from the site. On the surface, the wellhead includes the necessary valves and equipment to monitor and control the flow of steam or brine from the well to the power plant. The well drilling and construction associated with a geothermal power plant can account for between 50% and 70% of the total capital costs of the project.

For the purposes of this study, the techniques and approach used for drilling and completing a geothermal well can be considered to be identical to that of drilling a well for the geological storage of CO_2. Given this, the reader is directed to the import share and market concentration assessment completed for the CO_2 storage technology.

One thing to note however from well drilling and construction, is that of rig availability. The European geothermal drilling industry cannot be considered as a robust, independent sector. Geothermal project developers are fully dependent on using drilling rigs from the oil and gas industry, and therefore the availability cannot always be guaranteed (EGEC, 2016 EGEC geothermal market report. Full report - Members Edition, 2017). Furthermore, there is understood to be a direct correlation between oil and gas prices, and the cost for drilling services in the geothermal sector. Higher oil and gas prices will generally indicate greater demand for rigs in the oil and gas industry, and often geothermal project developers cannot compete with this highly profitable sector.

Downhole pumps, specifically Electrical Submersible Pump

Downhole pumps are generally used in low temperature (i.e. binary) geothermal power plant projects. The pumps are used to lift the hot brine from the geothermal resource, up the well, and to the power production process. The traditional pumps used in the geothermal sector were line shaft pumps and hydraulic turbine pumps, but in recent years more low temperature projects are using electrical submersible pumps (ESPs) which can be operated in deeper wells (EGEC, 2016 EGEC geothermal market report. Full report - Members Edition, 2017). ESPs generally have a relatively short lifespan due to the highly corrosive and scaling environment in which they operate. ESPs operated in European geothermal wells have an average lifespan of between 4-5 years, and have to be replaced at a cost of between €180,000 and €300,000 (EGEC, 2016 EGEC geothermal market report. Full report - Members Edition, 2017).

Although the geothermal sector has specific needs in terms of its challenging operating environments, the market is insufficiently large enough to warrant pump manufacturer to develop ESP to the specific needs of the geothermal sector (EGEC, 2016 EGEC geothermal market report. Full report - Members Edition, 2017). The manufacturers of ESPs are all active in the oil and gas services sector. Table 26 provides an overview of current ESP manufacturers, and where possible, the location of their respective production facilities and the location of their headquarters. All data collected has been derived from public company web resources and documents.

Table 26 Location of production facilities and headquarters of ESP manufacturers

Large manufacturers of electrical submersible pumps				
Company	Total production facilities	Production facilities in the EU	Est. production in the EU	Location headquarters
Schlumberger	17	4	24%	Non-EU
Baker Hughes	>20	3	No data	Non-EU
GE Oil and Gas	No data	No data	No data	Non-EU
ITT/Goulds	12	1	8%	Non-EU
Canadian ESP	1	0	0%	Non-EU
Flowserve	10	5	50%	Non-EU
Halliburton	16	No data	No data	Non-EU
Weatherford International	50	No data	No data	Non-EU
Borets Company	7	1	14%	Non-EU

From this assessment it is clear that the EU is underrepresented with regards to the manufacture of ESPs, with all major manufacturers of ESPs headquartered outside the EU. Furthermore, few of the companies' production facilities appear to be located in the EU. Using COMTRADE, the import share of ESPs to the EU has been assessed under the category of 'centrifugal pumps' (see Table 27). This is a rather broad category, and the import/export of ESPs is likely a small portion of the total, but no other data is freely available.

Table 27 Import/export share to/from the EU of centrifugal pumps in 2014 and 2015

Import & export of centrifugal pumps (841370)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Export	World	3.9 bln	+
2014	EU-28	Import	World	644.8 m	
2015	EU-28	Export	World	3.4 bln	+
2015	EU-28	Import	World	602.2 m	

Conversely to the market share assessment, the CONTRADE data would indicate that the EU has a healthy trade balance when it comes to the balance of trade in centrifugal pumps, in conflict with the market concentration assessment. It is expected that although ESPs are categorically centrifugal pumps, this category is so broad that the market dynamics of specialised ESPs are masked by the trade in other types of centrifugal pumps.

Given this discrepancy between market concentration and import share, TNO has conducted additional internal work to gain insights from experts in the geothermal power industry. An electronic questionnaire was developed and sent to both project developers and associated experts in the geothermal sector. The questionnaire was completed by 11 participants, 9 of which had direct experience in the development of geothermal power plants. The questionnaire included a number of questions regarding the availability and perceived market share of the EU, with regards to ESPs. 74% of participants indicated that they believed that there were insufficient European manufacturers of ESPs for the geothermal sector, and 59% indicated that they perceived the global market position of European ESP manufacturers to be poor to average. These opinions seem to reflect those of the European Geothermal Energy Council, which states that the specific needs of the sector in terms of corrosion/scaling resistance are not addressed by ESP manufacturers, because the market potential of new ESP is limited compared to that of the oil and gas industry (EGEC, 2016 EGEC geothermal market report. Full report - Members Edition, 2017).

Heat exchangers

Heat exchanger are used in binary geothermal power plants to transfer the heat energy from the brine to create an organic vapour, which provides the mechanical energy to drive the turbine. There are different types of heat exchangers used on the market, namely: shell and tube, gasket plate, welded plate and shell, and plate heat exchangers. Heat exchanges are used widely across many industrial sectors, the power sector, heating and ventilation, and the food and beverage sectors. The primary material used in the construction of heat exchangers is carbon steel (EGEC, 2016 EGEC geothermal market report. Full report - Members Edition, 2017). Table 28 provides an overview of the current heat exchange manufacturers, and where possible, the location of their respective production facilities and the location of their headquarters.

Table 28 Location of production facilities and headquarters of heat exchanger manufacturers

Heat exchanger manufacturers for geothermal power plants				
Company	Total production facilities	Production facilities in the EU	Est. production in the EU	Location headquarters
Alfa Laval AB	42	22	52%	EU
Danfoss & Sondex Holdings A/S	69	36	52%	EU
Kelvion Holdings GmbH	49	32	65%	EU
SPX Corporation	28	<5	No data	Non-EU
Xylem Inc.	No data	No data	No data	Non-EU
Gunter AG & Co. KG	8	3	38%	EU
Haman & Cie International SA	3	1	33%	EU
Modine Manufacturing	No data	No data	No data	Non-EU
SWEP International	5	2	40%	EU

Based on this assessment, it can be concluded that the EU is well represented in the market of heat exchangers. According to (EGEC, 2016 EGEC geothermal market report. Full report - Members Edition, 2017), Europe has always been a strong market for heat exchangers, which can account for what appears to be a considerable production capacity in the region. Although India and Japan are newcomers to the European geothermal market, it is understood that specialist SMEs in Europe are able to provide project specific requirements on corrosion and scaling. The positive balance of trade in the output from COMTRADE in Table 29 below, would appear to support the market concentration assessment above.

Table 29 Import/export share to/from the EU of heat exchange units in 2014 and 2015

Import & export of heat exchange units, non-domestic, non-electric (841950)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Export	World	3.0 bln	+
2014	EU-28	Import	World	706.2 m	
2015	EU-28	Export	World	2.4 bln	+
2015	EU-28	Import	World	718.8 m	

Turbine/generators

The turbine/generator unit can be considered to be the heart of the geothermal power plant, and it is also the most expensive project component after the well drilling and construction. The turbine uses the heat energy from the steam to derive the mechanical energy necessary to generate electricity in a generator. Turbines are produced using stainless steel (13% Cr steel), however other grades of steel with Nickel and Copper may also be used to provide better corrosion resistance (Sakai, 2004). Steel, iron, copper, and aluminium are important materials for the generator.

Based on turbine installations at geothermal power plants in Europe between 2012 to 2016, the leading turbine manufacturers' active in the geothermal sector are Ormat (14 turbines installed), Exergy (11), Atlas Copco-Exergy (6) and Turboden (5). Table 30 below examines the location of the production facilities and headquarters of a number of key turbine manufacturers.

Table 30 Location of production facilities and headquarters of turbine manufacturers

Turbine manufacturer for geothermal power plants				
Company	Total production facilities	Production facilities in the EU	Est. production in the EU	Location headquarters
Ormat	>1	0	0%	Non-EU
Exergy	2	1	50%	EU
Atlas-Copco	5	1	20%	EU
Turboden	1	1	100%	EU
Fuji	2	0	0%	Non-EU
Mitsubishi	1	0	0%	Non-EU
Siemens	1	1	100%	EU
Cryostar	1	1	100%	EU
GE Power	3	1	33%	Non-EU
Franco Tosi Meccanica	1	1	100%	EU

According to EGEC (EGEC, 2016 EGEC geothermal market report. Full report - Members Edition, 2017), the global turbine market is dominated by conventional dry steam or flash systems, with Mitsubishi, Ormat and Fuji, all non-EU based companies, supplying 75% of installed capacity. Despite a considerable market share of turbine supply to the global market belonging to Japanese- and USA-based interests, there are numerous companies in the EU specialised in the development, manufacturing and installation of turbine/generators for geothermal projects. Particularly in Italy, with its considerable history in high temperature geothermal power production, several suppliers (Exergy, Atlas-Copco, Turboden[14], GE Power, Franco Tosi Meccanica) have manufacturing facilities located there. There appears to be considerable EU manufacturing capacity and expertise in turbine construction, and the market concentration ratio would appear to be low.

The COMTRADE database has been examined to acquire an insight into the EU's import share of steam and other vapour turbines. Both commodity codes for turbines with an output of less than 40MW and more than 40MW were assessed. Whereas some dry steam and flash geothermal systems may have larger electrical production capacities (greater than 40MW), binary systems will generally have capacities below 40MW. From the outputs of COMTRADE (Table 31 and Table 32) it is evident that the EU has a positive balance of trade, or trade surplus, in the manufacture of turbines.

Table 31 Import/export share to/from the EU of >40MW turbines in 2014 and 2015

Import & export of steam turbines & oth. vapour turbines (excl. for marine propulsion), of an output >40MW (840681)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Export	World	355.7 m	+
2014	EU-28	Import	World	10.7 m	
2015	EU-28	Export	World	337.6 m	+
2015	EU-28	Import	World	1 m	

[14] Now a subsidiary of Mitsubishi (as of 2013), however still headquartered in Italy.

Table 32 Import/export share to/from the EU of <40MW turbines in 2014 and 2015

Import & export of steam turbines & oth. vapour turbines (excl. for marine propulsion), of an output <40MW (840682)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Export	World	229.5 m	+
2014	EU-28	Import	World	45.4 m	
2015	EU-28	Export	World	163.9 m	+
2015	EU-28	Import	World	30.4 m	

Data from COMTRADE also indicates the EU has a trade surplus with regards to AC generators, which are used in geothermal power plants (Table 33).

Table 33 Import & export of AC generators to/from the EU in 2014 and 2015

Import & export of AC generators, of an output of > 750 kVA (850164)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Export	World	1.2 bln	+
2014	EU-28	Import	World	276.3 m	
2015	EU-28	Export	World	791.2 m	+
2015	EU-28	Import	World	267.2 m	

Cooling towers

The main function of the cooling system is to condense the steam or vapour and dissipate the removed heat to the environment. A closed cooling system of a geothermal power plant general consists of two parts, the condenser and the cooling towers. Key suppliers for cooling systems, both condensers and cooling towers, are generally headquartered outside of the EU (see Table 34). All of the manufacturers however can be considered to have a global presence, and also have production facilities of cooling systems for power production applications in the EU. Unlike turbine and heat exchanges for geothermal applications, EU companies appear to be underrepresented in the cooling system market.

Table 34 Location of production facilities and headquarters of cooling system manufacturers

Cooling system manufacturers for geothermal power plants				
Company	Total production facilities	Production facilities in the EU	Est. production in the EU	Location headquarters
Dow Chemical Company	11	1	9%	Non-EU
GE Power	42	14	33%	Non-EU
Babcock & Wilcox	9	3	33%	Non-EU
SPX	28	5	18%	Non-EU
Ecolab/Nalco	11	3	27%	Non-EU
Environmental Treatment Concepts Ltd	1	1	100%	EU

The closest category that could be used on COMTRADE was “Boilers; condensers, for steam or other vapour power units”. This data would suggest that the EU has a trade surplus with regards to condensers which could be used in the geothermal sector (Table 35).

Table 35 Import & export of condensors to/from the EU in 2014 and 2015

Import & export of condensors for steam or other vapour power units (840420)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Export	World	42.9 m	+
2014	EU-28	Import	World	0.9 m	
2015	EU-28	Export	World	22.5 m	+
2015	EU-28	Import	World	0.6 m	

7.3 Raw material assessment

Geothermal power plants require a range of raw material, but steel is the key material used in all components of geothermal power plants. Whereas iron ore, the precursor to steel, is an abundant material globally, the EU produces very little iron ore of its own. In 2015, the EU imported nearly 86 million tonnes of iron ore, at a cost of $4.7 billion, and exported just 315,000 tonnes (United Nations, 2017). On the other hand, the EU has considerable capacity for primary steel production, the product that is eventually used in the construction of geothermal power plants. Copper is another material that the EU has a trade deficit in, which is both needed in heat exchangers and power generators of geothermal power plants. However, the role of copper in geothermal power plants is not as critical to that of steel. The external dependency on iron ore and copper products from outside the EU is high, however the market concentration ratio of these globally traded commodities is low. It is not considered that the availability of materials will restrict the wider proliferation of geothermal power plants by 2030 or beyond.

7.4 Conclusions

7.4.1 Critical dependencies

EU energy technology dependence

Of all the key components of geothermal power plants assessed, the electrical submersible pumps (ESP) appear to be an area of concern in terms of dependency from suppliers outside of the EU. All of the key suppliers are headquartered outside of the EU, however a few do have manufacturing facilities within the EU. The results of the questionnaire would also suggest that a general consensus exists between the experts that were interviewed that there are insufficient EU manufacturers of ESPs.

Regarding the other key components that have been assessed (heat exchangers, turbines/generators, condensers), from the evidence gathered concerning market concentration, the presence of European manufacturers and import share, there appear to be no further issues of critical dependence.

Critical dependence

In light of the evidence presented above, the broad brush assessment concludes that the external dependence of the EU on ESPs for geothermal power plant projects is high.

Internationally, there are sufficient suppliers of ESPs (mainly in the oil and gas market), which reduces the immediate criticality for projects, however the limited number of European manufacturers could prove critical in the future.

Implications

ESPs are primarily used in low temperature geothermal projects, specifically binary-ORC projects. ESPs do not have such a relevance for dry steam or high temperature flash projects. Low temperature binary projects have accounted for the bulk of geothermal installations over the last 4 years, and this trend is expected to continue (EGEC, 2016 EGEC geothermal market report. Full report - Members Edition, 2017). A lack of an EU supplier network may mean that the specific needs of geothermal power plants being developed in the EU are being overlooked. Issues such as corrosion and scaling of ESPs in EU geothermal projects are the key cause of the high replacement rate of such components, which generally leads to a higher overall project cost (EGEC, 2017). A higher overall project cost for low temperature geothermal projects could limit, or delay, the broader proliferation of geothermal power plants in the EU towards 2030.

7.4.2 Consideration of variants

Table 25 provides an overview of which of the above components are relevant for each of the 3 variants covered above. As ESPs are only relevant for binary geothermal power plants, it is recommended that dry steam and flash variants are treated as 'high enthalpy' variants (therefore considered together as one variant), and binary (low temperature) geothermal power plants are considered as a 'low enthalpy' variant.

8 Heat pumps

A heat pump is an electrical device used to transfer heat from one place to another. Generally speaking, when used for heating, the heat pump transfers heat from the outside of a building to the inside. In cooling mode, air conditioners use heat pumps to transfer heat from inside a building to outside. Heat pumps can provide heating, cooling and sanitary hot water for residential, commercial, and industrial applications. Heat pumps transform energy from the air, ground, and water to useful heat. This transformation is done via the refrigerant cycle (EHPA, 2017a). The basic mechanism of a heat pump is the transfer of heat by circulating a substance called a refrigerant through a cycle of evaporation, compression and condensation.

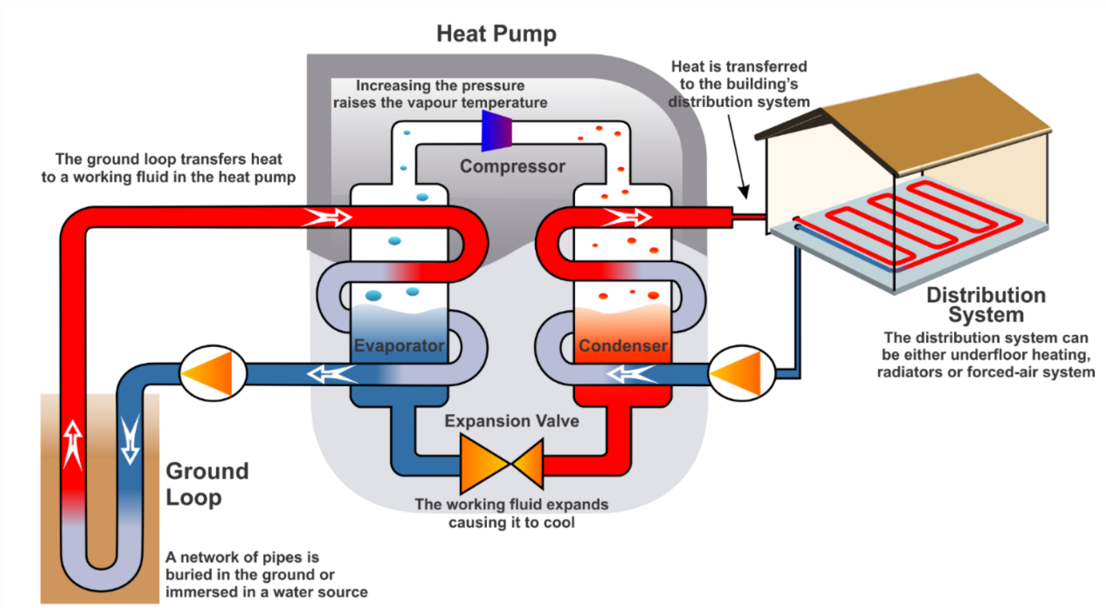


Figure 52 Simplified schematic of the workings of a ground source heat pump (Greenpowerco, 2017)

With reference to the simplified diagram above (Figure 52), a heat pump has an outdoor heat source and an indoor outlet. The heat can either be derived from ambient air, exhaust air (in the case of an industrial process), or as in the case above, ground rock or ground water. According to the European Heat Pump Association (EHPA), a heat pump can derive 75% of the energy used to operate from these sources. The energy from a number of these sources is infinite and therefore renewable. As the ground and air outside always contain some heat, a heat pump can supply heat to a house even on cold winter days (EHPA, 2017a).

The refrigerant is key to the function of a heat pump. It is a substance that has a low boiling point and can be easily pumped through the system. Within the heat pump system, a compressor pumps the refrigerant between two heat exchanger coils. In the coil located outside (the evaporator), at low temperature and pressure, the thermal energy is used to boil the refrigerant which is then evaporated. The refrigerant then passes through to a compressor which compresses the refrigerant, which is now in a gaseous state. As the gas is compressed to a higher pressure, the temperature of the gas also increases. Electricity is needed for the compressor to work, which provides the other 25% of the total energy needed for the heat pump to operate (EHPA, 2017a).

After the compressor, the hot and high pressure vapour passes through a second heat exchanger coil, also called the condenser, which in the case of a heating cycle, would be located inside the building. The heat will then flow from the heat exchanger into the inside environment. As the heat leaves the refrigerant, the vapour then condenses back into liquid form. Although the refrigerant is back in liquid form, it still has a high temperature and pressure. To return the refrigerant back to a low pressure and temperature state, it passes through an expansion valve which greatly reduces its temperature and pressure prior to recirculation through the outside heat exchanger (the evaporator).

As mentioned above, there are a range of heat sources that are used in heat pump systems, however the thermodynamic principle remains the same. From an operating efficiency perspective, the choice of the most suitable heat pump technology is dependent on many factors including: the required temperature of the transferred heat, the availability of a heat source (e.g. waste heat from a process, or mechanical ventilation system), geographical/geological factors (for water source for example), whether the system can also be used for cooling, and practical factors such as building condition (retrofit or new build). Other aspects that may play a role on the type of technology selected is the price of alternate energy sources for heating (gas/electricity), and if the system is to be used as a primary or auxiliary form of heating. Table 36 provides an overview of the different types of heat pumps and their typical regional distribution in Europe.

Table 36 Types of heat pumps, associated capacities, applications, and typical regional deployment (Forsén, Roots, & Bertenstam, 2008)

Type of heat pump	Most common capacity range	Application	Dominant region
Air-air	3 - 5 kW	Heating + cooling	Southern Europe*
Air-water	4 - 40 kW	Heating	Central Europe
Exhaust air	2 - 3 kW	Heating	Primarily Sweden
Ground rock	5 – 40 kW	Heating + cooling	Northern + central
Ground soil	5 – 25 kW	Heating	Northern + central
Lake water	15 – 40 kW	Heating	Limited deployment

* Main application in cooling

With reference to Figure 53, the European[15] market for heat pumps has grown significantly since 2005 at a relatively constant rate of 700,000 to 800,000 units sold per year since 2008. Reversible air-air heating, capable of both heating, and cooling buildings, has been the most common form of heat pumps sold in Europe since 2005. Although a similar trend can be seen throughout the years, recent growth in the sales of air/water heat pump systems, which also includes sanitary hot water systems, is noteworthy. Whereas sanitary hot water systems are combined with a hot water storage tank, air/water heat pump systems are generally used for heating purposes. The increased efficiency of air/water heat pumps appears to be having a dampening effect on the sales of ground/water heat pumps, which require more invasive installation procedures, have higher capital costs and geographical restrictions (EHPA, 2015).

[15] The EHPA collects data from 21 European countries as included in Figure 54

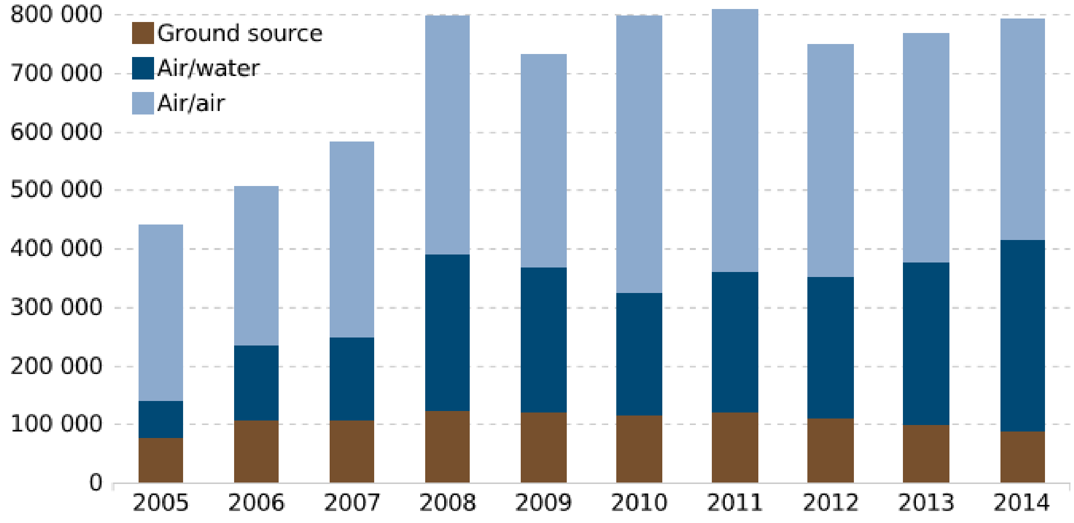


Figure 53 Development of heat pump sales in Europe 2005–2014, by category (EHPA, 2015)

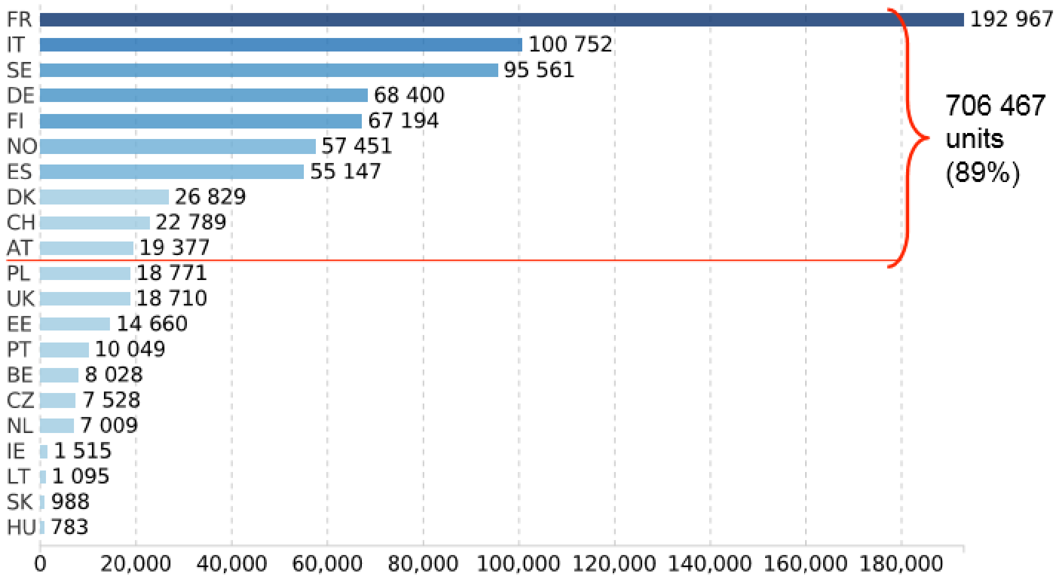


Figure 54 Heat pump sales per European country in 2014 (EHPA, 2015)

Figure 54 provides an overview of the size of the heat pump market in different European Member States in 2014. France, Italy, Germany, and a number of Scandinavian countries are the largest markets for heat pumps, a trend that has been quite consistent in recent years. Outside of these countries, Ireland, Estonia, Lithuania and Poland have recently experienced a +20% year-on-year growth in heat pumps sales (EHPA, 2017b).

Technology variants of heat pumps

Although heat pumps can vary both in heat source and capacity, all have the same basic components of a compressor, a condenser, an evaporator, and an expansion valve. Large heat pump manufacturers often provide products covering air, water and ground source applications (see Table 37). Based on the above, it has been decided that for the purposes of this broad brush summary paper, heat pumps shall be treated at the technology family level and not be broken down into separate variants.

8.1.1 *Heat pumps*

Description of a heat pump

The basic mechanism of a heat pump is the transfer of heat by circulating a substance called a refrigerant through a cycle of evaporation, compression and condensation. A heat pump consists of a number of key components (see also Figure 55):

- **An evaporator** – the evaporator is made up of many small, thin copper or aluminium tubes. The low pressure and low temperature refrigerant enters the evaporator coil, of which the temperature of the coil reduces to below the atmospheric temperature. Heat is then drawn from the surrounding air and transferred to the refrigerant;
- **A fan** - or blower, blows atmospheric air over the evaporator giving up the heat to the refrigerant and heating it. In an air-air heat pump, there will be one fan in the outside unit and one fan in the inside unit to distribute the heat from the condenser coil;
- **A compressor** – low pressure and medium temperature refrigerant in gas phase enters the compressor. In the compressor the refrigerant is compressed to a high pressure and high temperature gas. Modern heat pumps generally use rotary compressors, which have replaced less efficient reciprocating compressors;
- **A condenser** – the refrigerant leaving the compressor is at very high pressure and high temperature. This refrigerant enters the condenser, which is usually made of copper coil. The fan or blower behind the condenser coil, blows room air over the hot condenser coil transferring the heat to the desired area;
- **An expansion valve** – the role of the expansion valve is to control the flow of refrigerant back into the evaporator. The high pressure, medium temperature refrigerant is passed through an orifice in the valve which causes a reduction both in pressure and temperature. The types of expansion valve most commonly used in heat pumps are capillary tube, thermostatic, or electronic expansion valves;
- **Pipework/ducting** – provide the rest of the piping needed to connect the condenser and evaporator units
- **Metal casing** – Heat pump units are encased in a metal housing to protect the internal components from the outside and environment and for safety/aesthetic reasons;
- **Electronic control unit –** are used to control and monitor the operation of the heat pump. Heat pump manufacturers general use freely programmable controllers to aid compatibility with other HVAC components that may be combined with the heat pump
- **Refrigerants –** There are a range of refrigerants used by various manufacturers, including: R-134a, R-407c, R-410a, R-290, R-744. Recent attention has been focused on the use of natural refrigerants, R717 (ammonia), R744 (CO_2) and R718 (water);
- **Installation and service –** heat pumps in the residential and service sectors can be installed and maintained by trained heating, ventilation and air-conditioning (HVAC) technicians.

Figure 55 Cross-sectional diagram of a heat pump system for domestic hot water (DHW). This particular model is also intended to be combined with solar collectors (Viessmann, 2017)

8.1.2 Issues of dependency – Heat pumps

Note on individual heat pump components

Although heat pumps are comprised of a number of individual components as described above, from an initial European market assessment it is assumed with a high degree of confidence that most companies manufacture all necessary heat pump components for individual systems. This is expected to be particularly true for larger manufacturers operating in the EU. It cannot be ruled out however, that certain European heat pump manufacturers may assemble heat pumps using certain components from outside the EU. Particularly compressor units are of relevance here. It will be highly unlikely that manufacturers will share information of the acquisition of individual components of their heat pump products. Given these limitations, the dependency assessment will focus on the import reliance and market concentration of complete heat pump products/packages.

The EU has many established heat pumps manufacturers, and the market for heat pumps can be considered mature. Particularly for France and Scandinavian countries, heat pump systems were first installed more than 30 years ago (EurObserv'er, 2016). The vast majority of heat pump manufactures are also large suppliers of complete HVAC systems which can include heat pumps. In 2016, the total market value of heat pumps (including taxes and installation) was estimated at €5.2 billion (EHPA, 2017b). Given the considerable demand for heat pumps in the EU, it is unsurprising that there are a multitude of global and European based heat pumps manufacturers active in the sector.

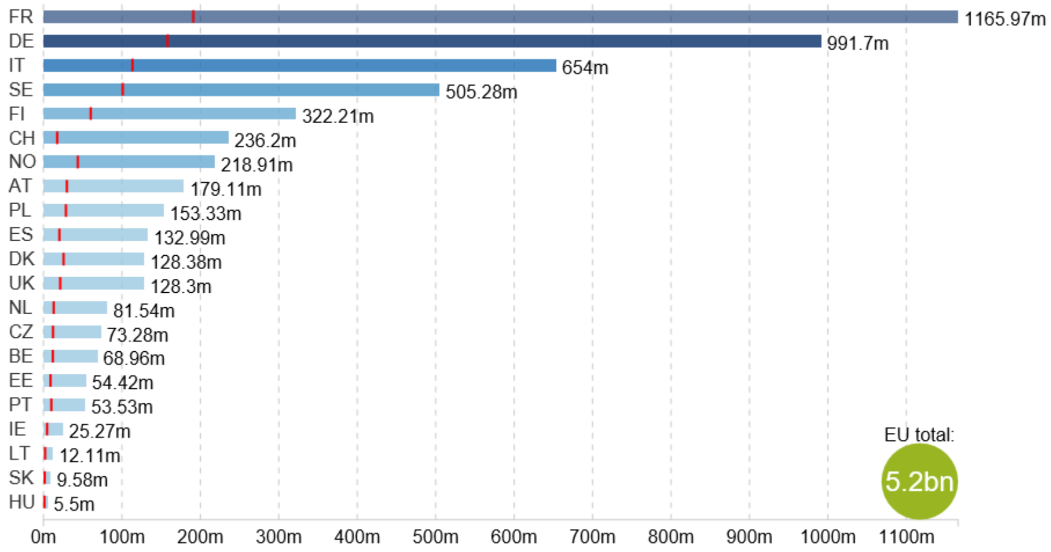


Figure 56 Turnover from heat pump sales per EU country in 2016. The red lines indicate the estimated taxable revenue (VAT) associated with the sales (EHPA, 2017b)

There is limited available data indicating the global market share of heat pump sales, however the leading heat pump manufactures with the greatest market share are identified as (Technavio, 2017):

- Carrier Corporation;
- Daikin;
- Danfoss;
- Mitsubishi Electric;
- NIBE;
- Carrier Corporation;
- Daikin;
- Danfoss;
- Mitsubishi Electric;
- NIBE;
- Carrier Corporation (HQ – US);
- Daiken (HQ – Japan);
- Danfoss (HQ – Denmark);
- Mitsubishi Electric (HQ – Japan);
- NIBE (HQ – Sweden).

A comprehensive assessment of heat pump manufacturers active in the EU market, and an overview of any associated subsidiaries and their products has been made by EuroObserv'ser (see Table 37). From this overview it can be deducted that there is a considerable number of EU-based suppliers for a range of heat pumps of various types and capacities.

Table 37 Overview of large European heat pump manufacturers, country origin and product types (EurObserv'er, 2016)

Company	Brand	Country	Type and capacity range in kW (in 2015)
BDR Thermea	De Dietrich	France	Brine/Water; Air/Water; Water/Water: 3,7 - 27,9 kW

Company	Brand	Country	Type and capacity range in kW (in 2015)
	Sofath	France	Brine/Brine: 2,8 - 14,2 kW Brine/Water: 6,0 - 29,5 kW Water/Water: 5,7 - 32,2 kW Air/Water: 3,7 - 24 kW
	Brötje	Germany	Air/Water: 7,4 - 11,5 kW Air/Water (Split): 6 - 15,7 kW Brine/Water: 5,9 - 21,2 kW
Bosch Thermotechnology	IVT Industrier (Bosch Thermotechnik)	Sweden	GSHP: 4,7 - 17,4 kW Air/water: 8,6 - 17,4 kW Air/Air: 0,6 - 6,5 kW Exhaust Air HP: 1,5 kW
Daikin Europe	Rotex	Germany	Air/Water + Brine/Water: 3,5 - 15 kW
Danfoss	Thermia Värme AB (Danfoss)	Sweden	Air/water: 6 - 36 kW Air/Air: 1,4 - 6 kW GSHP: 3 - 17 kW
	KH Nordtherm (Klimadan)	Denmark	GSHP: 20 - 336 kW (Cascade)
Nibe	Alpha Innotec	Germany	Air/Water: 5 - 31 kW Brine/Water: 3 - 160 kW Water/Water: 11 - 430 kW
	Nibe Energy Systems Division	Sweden	GSHP: 1,5 - 17 kW Air/Water: 5 - 22 kW Air/Air heat pumps: n.a.
	Technibel	France	Air/Water: 5 - 250 kW Brine/Water: 5 - 58 kW
	KNV	Austria	Brine/Water: 1,5 - 16 kW Air/Water: 5 - 15 kW Water/Water: 1,5 - 16 kW
Vaillant Group	Saunier Duval	France	Air/Water: 5 - 15 kW
	Vaillant	Germany	Brine/Water: 22 - 46 kW Water/Water: 3 - 19 kW Air/Water: 5 - 15 kW
	Bulex	Belgium	Air/Water: 5 - 15 kW
Viessmann Group (KWT, SATAG)		Germany	Brine/Water: 5,6 –42,8 kW Water/ Water: 7,5 - 58,8 kW Air/Water: 7 - 50 kW (250 kW in cascade) Air/Water (Split): 3 - 50 kW
Buderus		Germany	Brine/Water: 6 - 17 kW, 40,2 kW Air/Water: 6 - 41 kW (82 KW cascade)
Ochsner Wärmepumpen		Austria	HP from 2 - 1600 kW (all types) Air: 5 - 80 kW GSHP: 5 - 18 kW Water: 7 - 104 kW Brine: 5 - 72 kW
Stiebel Eltron		Germany	Air/Water: 4,2 - 30 kW Brine/Water: 4 - 56 kW Water/Water: 6 - 21 kW
Waterkotte		Germany	Air/Air: 4 -14 kW (Cascade 22 - 56 kW) GSHP: 15 - 26 kW Water/Water: 5 - 26 kW
Wolf Heiztechnik		Germany	Air/Water: 8 - 14 kW Brine/Water: 6 - 16 kW

Company	Brand	Country	Type and capacity range in kW (in 2015)
			Water/Water: 7 - 21 kW

* Non-exhaustive list.

With regards to import dependence of the EU on heat pumps, no evidence can be found. Data from the COMTRADE database (UN, 2017) indicates that the EU has a trade surplus with the rest of the World with regards to heat pumps. Given that the total market value of heat pumps in the EU is estimated at €5.2 billion by the European Heat Pump Association (EHPA, 2017b), the import trade values seen in Table 38 would suggest that the EU has little or no import reliance on heat pumps from countries outside the EU.

Table 38 Import/export share to/from the EU of heat pumps in 2014 and 2015 (UN, 2017)

Import & export of heat pumps; other than air conditioning machines (841861)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Export	World	456.9 m	+
2014	EU-28	Import	World	158.3 m	
2015	EU-28	Export	World	364.5 m	+
2015	EU-28	Import	World	173.8 m	

In light of the considerable presence of heat pump manufacturers, and the maturity of the market in Europe, it can also be deducted that the EU has a very good knowledge position for heat pump innovation and development. However, given that heat pumps are a mature technology, they have already been greatly optimised in recent years and further efficiency gains are expected to be minimal.

8.1.3 Raw material assessment

The most important raw materials used in heat pumps are iron castings, stainless steel components, copper and aluminium tubing. The iron castings which are used in compressor components, may also have small amounts of nickel, molybdenum and magnesium to improve the mechanical and corrosion-resisting characteristics of the castings. Dependent on the type of refrigerant used, the piping system may also require corrosion resistant stainless steel or aluminium. The refrigerants for heat pumps are widely available and generally do not need replacing during the lifetime of the heat pump unless a leakage occurs. The housing of the heat pump is made of mild steel (Madehow, 2017).

8.1.4 Conclusions

Critical dependence

From this assessment it is concluded that the critical dependency of the EU on heat pumps from external countries is very low. No evidence could be found of external dependence on heat pumps or individual components. There are a multitude of heat pump suppliers within Europe, and therefore the market can be considered as competitive rather than concentrated.

From a raw materials perspective, magnesium may be used in iron castings of compressors. The EU is fully dependent on imports of magnesium (European Commission, 2017). However, for this to be considered a critical dependency, further research would be needed specifically to assess the amounts needed and substitutability of magnesium in heat pump compressors.

Consideration of variants

Heat pumps should be considered at the technology family level.

Implications

Not applicable, as no critical dependence has been identified.

9 Hydro Power

9.1 Hydro power

9.1.1 Description of Hydro Power

A hydroelectric power plant converts energy from different water levels (upstream and downstream of the hydroelectric plant) to power (eurelectric, 2011). It converts the potential energy that is available in the water source into kinetic energy. This kinetic energy drives a turbine and generator to produce power (IEA-ETSAP, 2015).

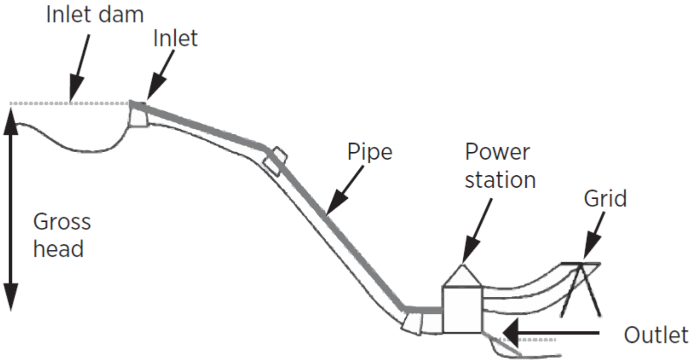


Figure 57 Generic scheme of a Hydro Power Plant based on a dam (IEA-ETSAP, 2015).

The hydropower technology is considered a mature technology. The technology is widely used for producing renewable electricity (IEA-ETSAP, 2015). Significant installed capacities of hydropower within the EU28 can be found in countries that have abundant water resources, in combination with height differences (e.g. Italy, Austria, United Kingdom). Examples of hydroelectric power plant sites within Europe are depicted in Figure 59 and Figure 58.

Figure 59 Dolgarrag hydro site, United Kingdom, Innogy SE [3].

Figure 58 Lake Schluchsee pump storage hydropower plant, Germany, Schluchseewerke AG [3].

Current State

The share of hydropower in the European renewable electricity generation is significant (POWERTECH). Hydropower accounts for 42% of the European renewable electricity generation and 72% of the global generation (see Figure 60 and Figure 61.)

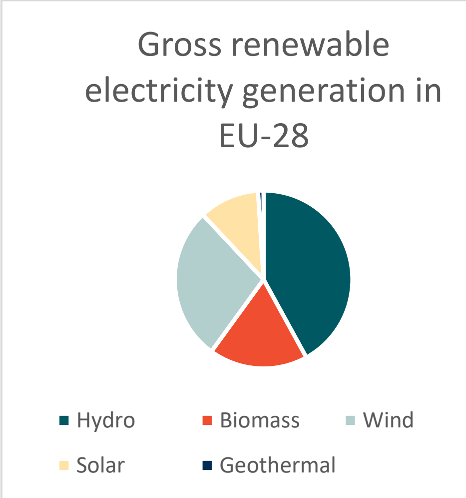


Figure 60 Gross renewable electricity generation in EU-28.

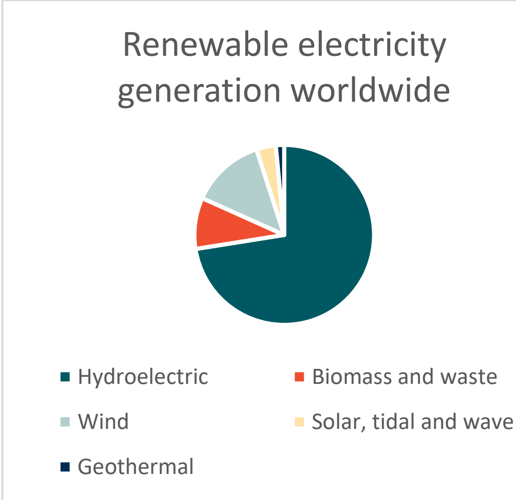


Figure 61 Renewable electricity generation worldwide.

Potential

Hydropower is considered to play a vital role within the European power system and has already a significant penetration level (Figure 60 and Table 39). Higher renewable penetration levels can still be achieved (Table 39) (EEA, 2017).

Table 39 Hydropower generation in Europe and the undeveloped potential (POWERTECH)

Key figures on hydropower in Europe		
	EU-28	EURELECTRIC members
Generation	403 TWh	553 TWh
Capacity	150 GW	198 GW
Further generation potential	298 TWh	650 TWh

Variants

Hydropower can be categorized into three variants:

- <u>Run-of river hydropower plants</u> utilise the kinetic energy from river flow. Run of river plants capacity vary from a few kilowatts to 100 megawatts. The number of operating hours of a run of river plant relies on seasonal resources, i.e. rainfall and melt water;
- <u>Reservoir hydropower plants</u> utilise the potential energy of water stored in a water basin. The energy driver is the height difference. Reservoir hydropower plants capacity vary from 10 MW to over 1 GW. Reservoir hydropower plants are less dependent on seasonal influences than run of river plants because of the large reservoir directly upstream of the hydropower plant. Thus, reservoir power plants can be dispatched for grid balancing and even function as black start units (POWERTECH);
- <u>Pumped storage plants</u> convert electrical energy into potential energy for later use. Water is pumped from a lower reservoir towards a higher reservoir using electricity from the grid. The stored energy can then be re-converted to electricity.

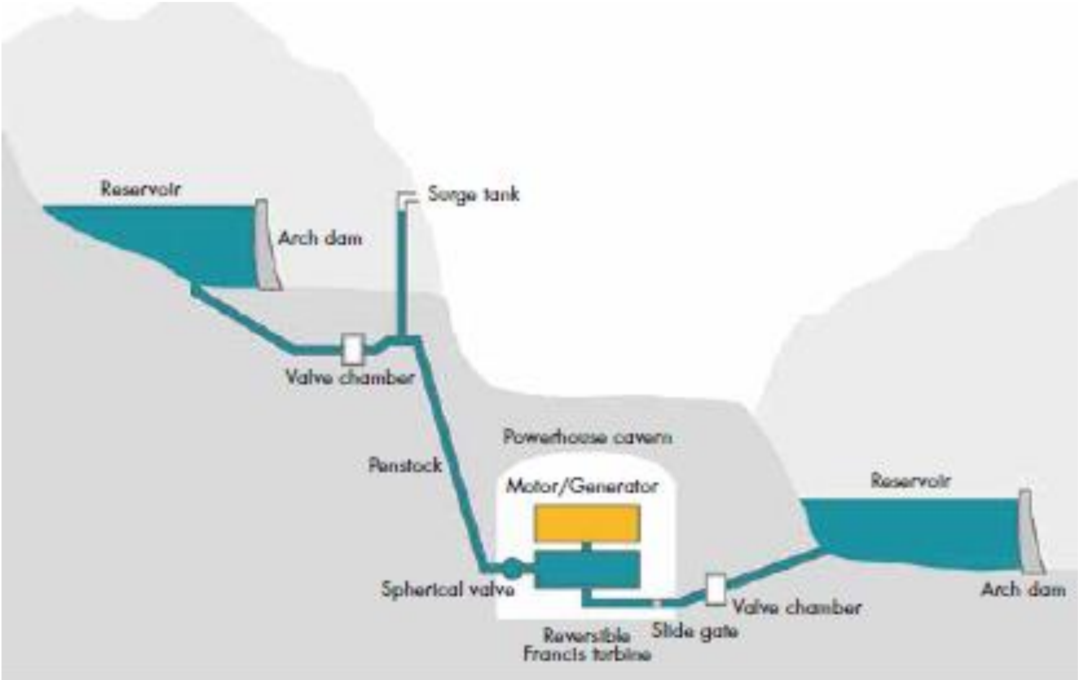


Figure 62 Schematic illustration of a pumped storage hydropower plant (POWERTECH).

Figure 62 shows an illustration of a pumped storage hydroelectric plant with all major components.

Table 40 Value chain items. Dependency issues are found to be similar across each of the variants

Variant	Scale	Operations	Energy resource	Main components
Run-of-river	Small to medium	Base load / seasonal	River / melt water	Penstock, (dam), turbine, generator, valves
Reservoir	Medium to large	Flexible load / peak load	River / Melt water	Penstock, dam, turbine, generator, valves
Pumped storage	Medium to large	Flexible load / storage	River / Melt water	Penstock, dam (2x), reversible turbine, motor, generator, valves

Reservoir and pumped storage plants represent 99% of the worldwide installed power storage capacity (POWERTECH). Table 40 shows in addition that the pumped storage variant is the most exhaustive solution in terms of equipment. This variant entails the equipment of the other two variants, except for non-reversible turbines. Therefore, we combine the reservoir and pumped storage variant into a single large scale hydroelectric power variant.

9.1.2 Issues of dependency – Large scale Hydroelectric power

The following **main components** have been considered (IFC):

- Civil works;
- Penstock;
- Turbine;
- Generator.

Civil works

Civil works can be divided into the following structures:

- Headworks: a concrete structure that allows the water level to rise sufficiently, and a concrete water intake structure that allows for safe diversion of water from the river to the waterway;
- Waterway: concrete and steel components (e.g., pipes, pressure galleries, etc.) required to convey water from the intake and to the power house;
- Powerhouse: stone, concrete, wood or steel structure that hosts the generator, turbine and auxiliary equipment;
- Tailrace: concrete alley that evacuates the water from the powerhouse and turbine and feeds it back into the river.

For civil structures import is considered for the elements (1) imports of concrete, and (2) imports of construction companies.

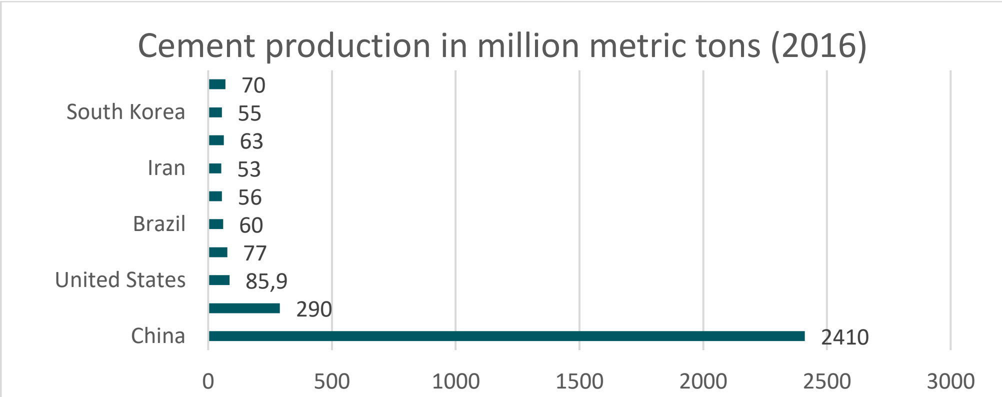


Figure 63 Cement production of top 10 countries (2016) (Statista, sd).

Hydro power plants dams are made from concrete. The main raw component for concrete is cement. Cement is mined or a by-product from steel making industries (present in e.g. Germany, the Netherlands and Poland). As of 2014/2015, there was a net export of cement from EU28 to non-EU28 countries. The production was around 170 million tons whereas the consumption was around 150 million tons (Statista, sd), (CEMBUREAU, sd). Therefore, no critical reliance on import has been identified for concrete.

Construction companies include major European companies like Bauer, Vincy and Hoghtief. They all provide construction of dams for hydroelectric power plants. Therefore, no import dependence for construction companies has been identified.

Penstock

Penstock are constructed from concrete and/or steel. Concrete has been discussed in the previous section.

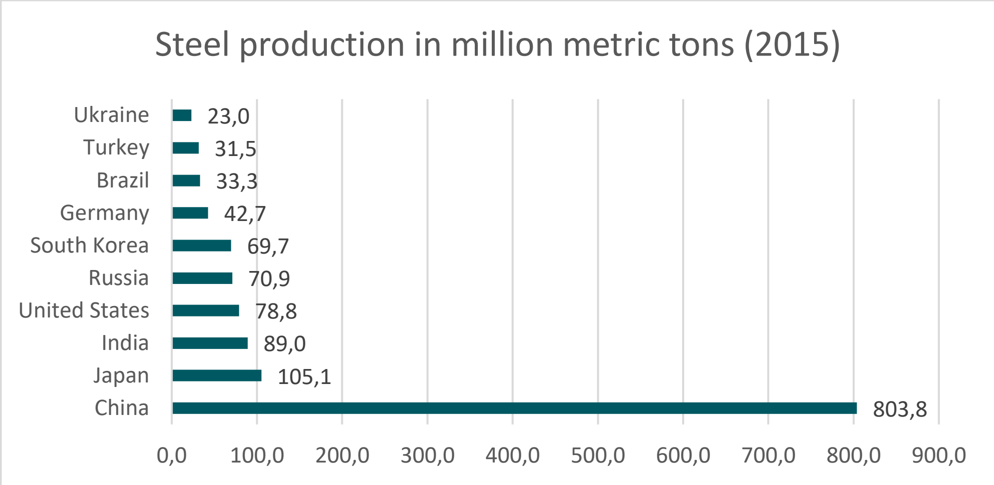


Figure 64 Steel production and consumption data in million metric tons in 2015 (Business Insider, sd).

The top 10 biggest steel producing countries worldwide are depicted in Figure 64.

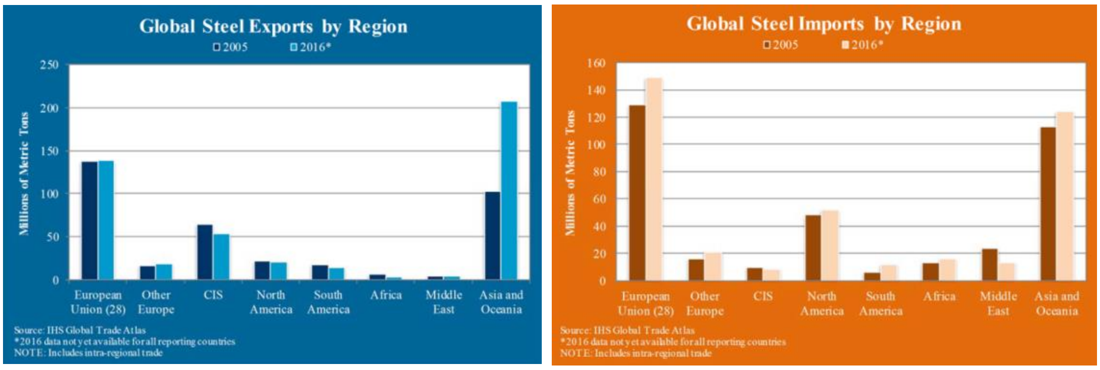


Figure 65 International steel exports (left) and imports (right) (ITA, 2017)

The EU28 used to be a net exporter of steel, but declined over the last decade. In 2016 EU28 exports of steel were in balance with imports, both around 150 million of metric tons (see Figure 65). The EU28 steelmaking capacity utilization rate dropped from around 80% in 2005 to around 70% in 2016. This capacity utilization rate provides ample room for increasing production capacity when needed. Therefore, the reliance on import regarding steel is not considered critical.

Turbine

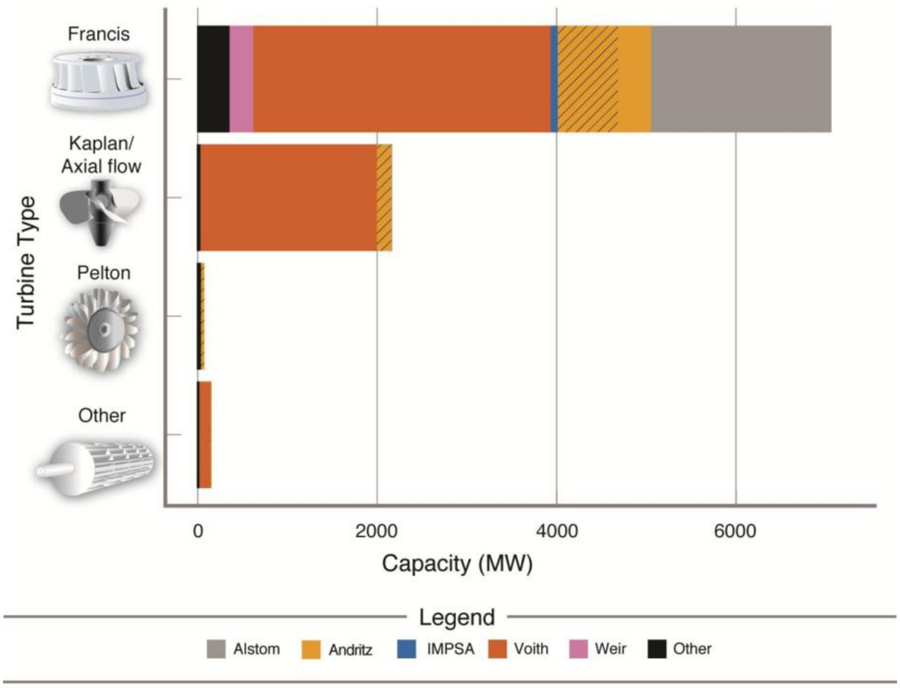
There are two main types of hydro turbines: impulse and reaction. An impulse turbine uses the velocity of water to move the runner and is generally suitable for high head, low flow applications. A reaction turbine depends on higher flows of water and lower heads.

Table 41 summarises the various types and names of turbines and the materials they require.

Table 41 Types of hydropower turbines, names and materials

<table>
<tr><th>Main type</th><th>Name</th><th>Main characteristics</th><th>Materials used</th></tr>
<tr><td rowspan="2">Impulse turbine</td><td>Pelton</td><td>One or more jets discharging water onto a wheel with spoon-shaped buckets</td><td rowspan="5">Runners are made of stainless steel alloys with chromium. They also have small amounts of nickel and molybdenum to improve pitting resistance
Casing is generally made of cast iron (iron with small amounts of carbon, silicon manganese, phosphorus and sulphur)</td></tr>
<tr><td>Cross-flow</td><td>Inlet guide van directs flow to turbine. Water flows across the turbine.</td></tr>
<tr><td rowspan="3">Reaction turbine</td><td>Propeller (bulb)</td><td>Operating the same way as a ship propeller but in opposite direction</td></tr>
<tr><td>Kaplan</td><td>A propeller turbine variant with variable blades</td></tr>
<tr><td>Francis</td><td>An inward flow turbine that combines radial and axial flow concepts</td></tr>
</table>

Turbines for hydroelectric power plants are manufactured in Europe. Major suppliers of hydro turbines are Voith (Austria), Andritz (Austria), Alstom (France). These are all European companies. Important non-EU players are GE (USA), Impsa (Argentina/Brasil) and Rainpower (Norway). However, Alstom has a 50/50 Joint Venture with GE for hydropower.



Note: The hashed portions of the bars correspond to turbines installed by companies that were acquired during the 1996-2011 period by the manufacturer Andritz.

Source: NHAAP

Figure 66 Installed hydropower turbines in the United States between 1996 and 2011 (DOE, 2014)

Although trade flows of turbines from non-EU28 companies to EU28 are not exactly known to the authors, data on turbines from EU suppliers to the U.S. are known. Figure 66 shows that most of the turbines that have been installed in the U.S. over the last two decades or so are manufactured by European companies, although the actual manufacturing locations of individual components may be outside of the EU28.

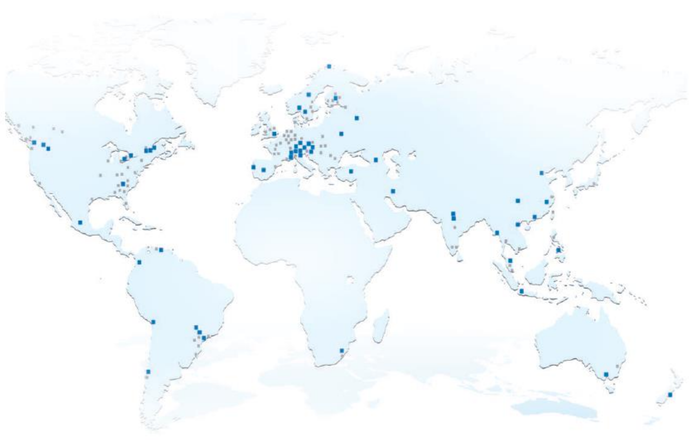


Figure 67 **Andritz hydro presence (Andritz, Andritz hydro, large hydro, 2017)**

Manufacturing of Alstom turbines is in Grenoble. Andritz manufactures its turbines across the globe (see Figure 67). Table 42 summarises the three manufacturers by main locations, services and R&D activities.

Table 42 The three main hydro power manufacturers in Europe with further details

Manufacturer	Market share	Main manufacturing locations	Services	R&D activities
GE Renewable Energy / Alstom	GE claims that its hydro turbines and generators represent more than 25% of the total capacity worldwide	France, Switzerland, Spain, India, China, Canada, Brazil	Hydro solutions and services from water to wire, from individual equipment to complete turnkey solutions, for new plants and the installed base. Both large and small hydropower.	Research on high strength steel, head loss reduction and fatigue and corrosion phenomena. (GE, sd)
Andritz Hydro	Andritz claims to be a leading supplier in the service and rehabilitation market and a world market leader.	Austria, Germany Finland, Brazil, U.S., Canada, China, Mexico	global supplier of electromechanical systems and services ("from water to wire") for hydropower plants	flexible and speed-adjustable solutions, in particular for electrical and hydraulic equipment and the control systems (Andritz, Research and development, sd)
Voith Hydropower	Voith claims to be one of the world's leading companies	Germany, Sweden, India, Shanghai, Brazil. U.S.	hydropower equipment and services for both new and modernization projects. Full-service in the field of hydropower. ("water to wire")	Research and development on generators, fish friendly turbines, expansion of weirs, shut-off valve and control and regulation systems (Hydropower, sd)

The conclusion is that there are few major turbine suppliers, and most of these are European. Consequently, there is hardly any import of turbines from non-EU28 suppliers, although these European suppliers have manufacturing locations for components or production processes (e.g. coating) across the globe.

Hydro turbines require certain materials (see right column of Table 41). The EU relies on the import of phosphorus for producing cast iron (Commision, 2017). Although the amounts are small, the material is hard to replace. The import reliance rate for phosphorus is 100% and is thus considered very high (Commision, 2017). The most important producers constitute China (58%), Vietnam (19%), Kazakhstan (13%) and the USA (11%). The main importers and sources of supply of phosphorus to the EU constitute Kazakhstan (77%), China (14%) and Vietnam (8%) (Commision, 2017).

Generator

Generators for hydroelectric plants (in combination with Francis, Kaplan and Pelton turbines) are also manufactured by e.g. Andritz, Alstom/GE, Voith and IMPSA. A generator mainly consists of copper (Cu) and iron (Fe) as main metals but can alternatively also use aluminium (Al). The supply risk of copper and iron are considered low (Commision, 2017).

Overall metal use of a hydropower plant

Overall metal requirements for a hydropower plant is shown in Table 43. In comparison to expected world supply, these metal requirements are very modest (Ray Moss and Evangelos Tzimas (Institute for Energy and Transport, 2013).

Table 43 Hydropower metals requirements (Ray Moss and Evangelos Tzimas (Institute for Energy and Transport, 2013)

Technology	Elements	Materials demand (kg/MW)	Annual EU Demand (tonnes)		Annual EU Demand / World Supply	
			2020	2030	2020	2030
Hydropower	Ni	31.0	23.72	15.87	<0.1%	<0.1%
	Mo	2.9	2.22	1.48	<0.1%	<0.1%
	Cu	67	51.26	34.30	<0.1%	<0.1%
	Mg	1.92	1.47	0.98	<0.1%	<0.1%
	Cr	12.5	9.56	6.40	<0.1%	<0.1%
	Pb	5.36	4.10	2.74	<0.1%	<0.1%
	Zn	5	3.83	2.56	<0.1%	<0.1%
	Mn	1.7	1.30	0.87	<0.1%	<0.1%
	Ti	0.24	0.18	0.12	<0.1%	<0.1%
	Sn	0.00308	0.00	0.00	<0.1%	<0.1%
	Zr	0.000013	0.00	0.00	<0.1%	<0.1%

Leading position of the European hydropower industry

Being a leader in the fields of production and innovation of the hydropower technology, Europe hosts three of the large companies that produce hydro equipment as well as many smaller ones, covering two thirds of the global hydropower market with their water to wire services (POWERTECH). Water to wire means that the complete power plant is manufactured by one manufacturer. This includes turbine, generator, civil construction, control and protection systems, and electricity grid connection. Thus, a strong technology sector is established for hydropower technology within Europe.

Technology maturity and need for R&D

Hydropower is considered a proven and mature technology (EEA, 2017). Two rather important scientific fields that deserve further attention have been identified. These are the environmental and the technical improvement of the technology. Both areas are considered by the European hydropower industry, which invests on enhancing the production capabilities of the turbines as well as on improving the flexibility capabilities offered. Finally, focus is placed also on the environmental impact of this technology (POWERTECH).

9.2 Conclusions

9.2.1 Critical dependencies,

Reliance on non-EU countries/firms

No reliance on suppliers, for any parts of the hydroelectric plant, have been identified. Europe has a leading position on the hydropower industry, hosting three of the larger hydro equipment manufacturers, delivering water to wire solutions. These companies have manufacturing locations worldwide. Various metals are used in hydroelectric plants. These are all non-scare metals, and the metals requirements are very modest. Also no import dependence for concrete or steel has been identified. The EU28 has a high reliance on the import for phosphorous. Phosphorous is an ingredient for cast iron. However, the portion of phosphorous used within cast iron is small.

Market concentration

The concentration of phosphor resources within China is considered high compared to the amount of reserves provided by the rest of the suppliers. Globally, phosphorus is supplied by China (58%), Vietnam (18%), Kazakhstan (13%) and the USA (11%).

9.2.2 Consideration of variants

We combined the variants, because they have the same components and materials involved. Therefore, we propose to consider hydroelectric power as a technology family as a whole.

10 Hydrogen & Fuel Cells

Abbreviations

AFC	Alkaline fuel cell
DMFC	Direct methanol fuel cell
FC	Fuel cell (often used after the type of fuel cell)
LSM	Lanthanum strontium manganite
MCFC	Molten carbonate fuel cell
MEA	Membrane electrode assembly
PAFC	Phosphoric acid fuel cell
PEM	Proton exchange membrane or polymer electrolyte membrane
SOFC	Solid oxide fuel cell
YSZ	Yttria-stabilized zirconia

Fuel cells are a clean and efficient technology that, at the most basic level, convert chemical energy directly into electrical energy. Efficiency of fuel cells can reach 60%, and the cost in 2009 was at about $61/kW (Wang, Chen, Mishler, Cho, & Adroher, 2011). Components of fuel cells include an anode, a cathode, an electrolyte, a constant source of fuel, and an oxidizing agent[16].

The hydrogen fuel cell is a type of fuel cell, where the fuel is hydrogen gas (H_2) and the only products are water, heat, and electricity. The six main types of fuel cells are as follows: 1) polymer electrolyte membrane fuel cell (PEMFC), also known as proton exchange membrane fuel cells; 2) solid oxide fuel cell (SOFC); 3) alkaline fuel cell (AFC); 4) phosphoric acid fuel cell (PAFC); 5) molten carbonate fuel cell (MCFC); and 6) direct methanol fuel cell (DMFC) (Larminie & Dicks, 2003). Solid electrolytes have been preferred in recent years, thus the fuel cell focus has been more toward PEMFCs and SOFCs, with the main difference being that SOFCs require temperatures of around 550°C to 900°C to operate (Adler, 2005).

The EU has supported hydrogen and fuel cell research over the past 30 years, now primarily providing support through the participation of the Fuel Cells and Hydrogen Joint Undertaking. This is a public private partnership, which tries to promote the development of fuel cell technology in Europe (Fuel Cells and Hydrogen Joint Undertaking, 2016).

[16] The anode separates the electron from the fuel, from where the electron passes through a circuit to generate electricity, and continues on to the cathode. The fuel ions pass through the electrolyte to the cathode, where it combines with the oxidising agent and the electrons to form the by-product.

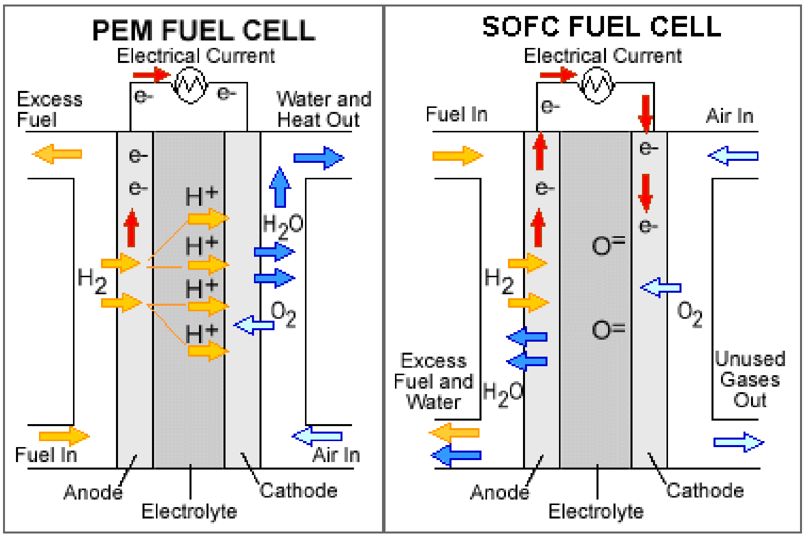


Figure 68. Depiction of two main fuel cell types: the PEMFC (left) and SOFC (right). Images from U.S. DOE (Office of Energy Efficiency & Renewable Energy, 2016).

The fuel cell industry grew from $1.3 billion to $2.2 billion between 2013 and 2014 primarily from stationary fuel cells in the USA and from residential fuel cells in Japan. Fuel cell technology has been pushed by Japan and South Korea, while energy storage and power-to-gas regarding fuel cells have been a focus of Europe. Of the 9 power-to-gas[17] and hydrogen energy storage projects announced in 2014, 5 take place in Europe, while 4 of the 6 manufacturers come from Europe (Curtin & Gangi, Fuel Cell Technologies Market Report 2014, 2014). Though when compared to other regions in fuel cell shipping, Europe plays a small role (see Figure 69).

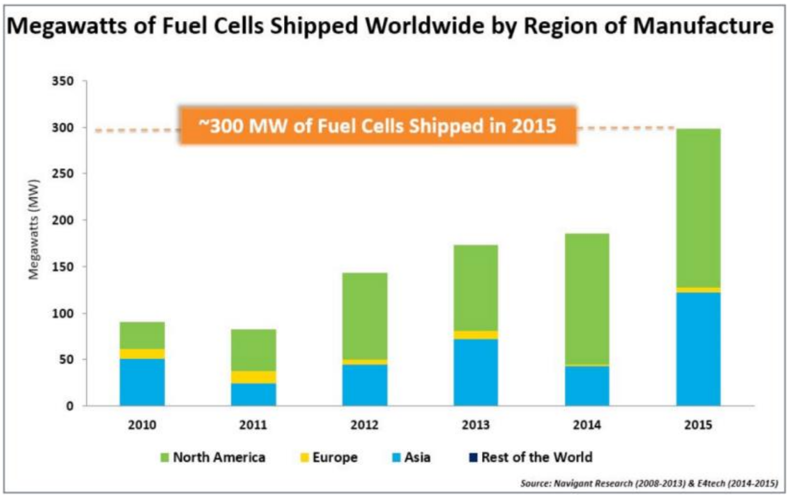


Figure 69. Megawatts of fuel cells shipped worldwide by geographical region. Image from (Curtin & Gangi, Fuel Cell Technologies Market Report 2015, 2015).

One third of the cost of a fuel cell comes from the membrane, catalyst, membrane electrode assemblies, gas diffusion layers, and bipolar plates, which are the components that are most likely to cause an issue in supply (Milburn and Adamson, 2012). Europe and Asia Pacific have the largest number of manufacturers for these components, as can be seen in Figure 70.

[17] Power-to-gas is a technology that uses electrolysis to split water into hydrogen and oxygen, producing either hydrogen fuel or methane. The majority of hydrogen is produced via natural gas reformation, which produces emissions, while this method is a way to generate "green hydrogen" when coupled with excess renewable energy, such as wind or solar.

Specific areas where Europe is participating in hydrogen and fuel cell development is shown in Table 44, while a summary of important components of the supply chain are provided in Table 45.

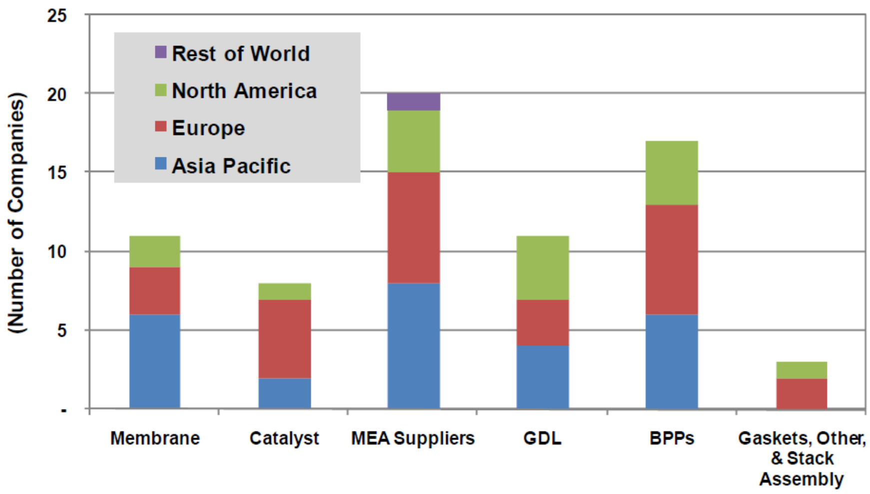


Figure 70. Commercial suppliers for the components of fuel cells per region. MEA: membrane electrode assemblies, GDL: gas diffusion layer, BPP: bipolar plates. Plot from (Milburn & Adamson, 2012).

Table 44. Briefing of the European presence in different aspects of the fuel cell industry as detailed by (Curtin & Gangi, Fuel Cell Technologies Market Report 2014, 2014). This information is summarized in the supply chain table that follows.

Fuel cell **R&D** - £13 million U.K. expenditures in R&D in 2012, shrunk to about £7 million in 2013 and 2014 - Fairly constant in Germany, with about €4.5 million expenditures in 2012, 2013, and 2014 for R&D - Contrarily, the USA R&D expenditures have grown from \$14 million in 2012 to \$18 million in 2014 with one company, and then from \$5.4 million in 2012 to \$6.5 million in 2014 in another fuel cell company.
Commercially present in **fuel cells** in - Light duty vehicles (Germany, France) - Buses (Germany, Belgium, Netherlands, Poland) - Material handling (Denmark, U.K., Germany, France) - Other transport e.g. trains, utility vehicles, aircrafts (U.K., France) - Stationary power (Germany) – most commercially available from the USA and Japan. - Prime power (Finland, Germany) – USA companies have several international projects, EU project Biogas2 PEM-FC, power plant pilot in Finland - Micro combined heat and power (France, U.K.) – majority in Japan - Backup and remote power (Italy, Spain, France, Denmark, Sweden, Germany) - Micro fuel cells (U.K.) – small sector - Military (U.K.) – small sector
Commercially present in **hydrogen infrastructure** in - Refuelling stations (Germany, U.K., France, Finland) – 17 new in 2014, 12 in Europe - Supply (Italy, Netherlands, U.K., France)
Commercially present in **hydrogen storage** in - Power-to-Gas/Hydrogen energy storage (Spain, France, U.K.)

Table 45. Supply chain components for the hydrogen and fuel cell industry.

Supply Chain Points	Strengths	Dependencies
Fuel cell R&D		Universities, have a slight presence in fuel cell research (Switzerland and the U.K.). Fuel cell technology investment in Asia Pacific.
Fuel cell production - Components - Commercialization - Shipping	Well represented in both fuel cell component supply and in most fields of commercialization.	Minimally represented in fuel cell applications of stationary power, prime power, and micro-combined heat and power. Shadowed by Asia Pacific and N. America in shipping of fuel cells.
Hydrogen infrastructure - Supply - Refuelling stations - Transportation	Plans for infrastructure development, as well as capabilities for hydrogen generation and producing refuelling stations.	Not much discussion over transportation (e.g. via pipeline)
Hydrogen storage	Growing energy storage and Power-to-Gas projects in Spain, France, and the U.K.	

This document will go through the market dependencies of renewable hydrogen, as well as two types of promising fuel cells: Proton-Exchange Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cell (SOFC). Due to the fact that developments and improvements (e.g. in cost, applications and efficiency) are still being made for fuel cell technologies, not all markets could be established, but were estimated where possible. As the technology for fuel cells is the reverse process for electrolysis, dependencies in the renewable hydrogen section for PEM technology are not described, but rather described later in the following section on PEMFC.

10.1 Renewable Hydrogen

10.1.1 Description of renewable hydrogen

Hydrogen is one of the primary fuels that can be utilized by a fuel cell and has a high energy density per mass. When consumed, it only emits water, being a clean fuel to utilize. Currently, hydrogen is mainly produced through the use of fossil fuels; it can also be produced by electrolysis using electricity from renewable sources such as wind, solar, and geothermal (see Figure 71). Electrolysis is the reverse process of a fuel cell, using an electrolyser (made from a cathode, an anode and an electrolyte) to split water into hydrogen and oxygen. The production and storage of hydrogen is an approach for offsetting the variable electricity production of renewable resources - during times of low demand and high supply excess electricity could be used to produce hydrogen (Office of Energy Efficiency & Renewable Energy, 2013) (European Commission, n.d.). Hydrogen is primarily used for industrial purposes (such as for the chemical industry or refineries) and mobility (as fuel for fuel cell vehicles). Over 90% of hydrogen consumption occurs in the industry sector, with the numbers of vehicles requiring hydrogen expected to grow a possible 9% – 13% by 2030 (Fraile, Lanoix, Maio, Rangel, & Torres, 2015).

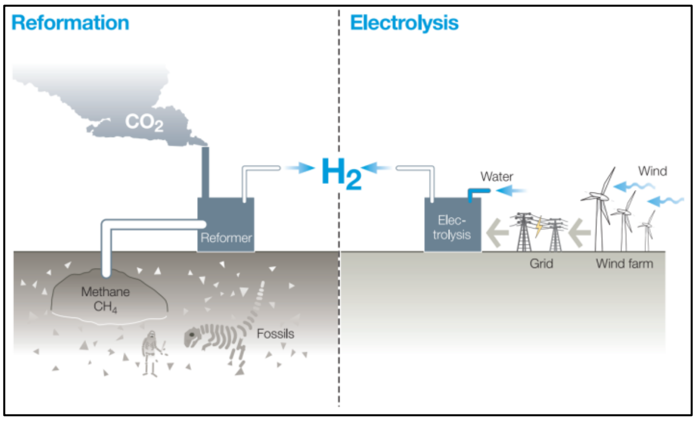


Figure 71. Production of hydrogen from hydrocarbons and electrolysis. Source: (Maclaurin & Slater, 2007).

Analysis of potential dependence issues is limited to hydrogen produced by electrolysis from renewable electricity. As the future of fossil fuels is not within the scope of this project, hydrogen fuel made from hydrocarbons (i.e. steam reformation) is not addressed further.

10.1.2 Issues of dependency – renewable hydrogen

The technology used to produce hydrogen that is considered in this project is electrolysis. Two common electrolysers are the alkaline (popular because of their commercial availability) and polymer electrolyte membrane (popular because of their hydrogen purity, simplicity, and robustness with variable power) (Gahleitner, 2013). Within Europe, there are several major producers of these variants of electrolysers, including Siemens (DE), Areva (FR), Nel (NO), McPhy (FR), and Acta (IT) (Alkaline Electrolyzer Segment to Record Higher Market Value Whereas PEM Segment to Exhibit Promising Growth, 2017). Currently, Europe is in the lead regarding the global market for electrolysers, with Asia Pacific excluding Japan following them, thus dependency on electrolysers is not a severe threat to Europe (Hydrogen Electrolyzer Market: Alkaline Electrolyzer Product Type Segment Projected to Account for over Half the Global Market Value During the Forecast Period: Global Industry Analysis 2012-2016..., 2017).

More recent data submitted by the EU members show the produced merchant hydrogen to be closer to 18 billion m^3/year in 2010 and approaching 19 billion m^3/year in 2014 (see Table 46) (Eurostat). Overall, there is a trade surplus of hydrogen with the EU28 and the rest of the world, as can be seen from the UN's Comtrade Database (Table 47). From the period of 2011 until 2015, the EU28 did not import more than 100,000 m^3 of hydrogen in a single year, while hydrogen exports for each year were more than double the amount imported (United Nations Trade Statistics).

Table 46. Total hydrogen production in the EU-28. Source: (Eurostat)

Year	Billion Nm^3
2010	17.799
2011	17.961
2012	18.345
2013	18.367
2014	18.848

Table 47. Import/export share to and from the EU of hydrogen in 2014 and 2015. Source: (United Nations Trade Statistics)

Import & export of hydrogen (281511 and 281512)					
Event	**Region**	**Trade flow**	**Partner country**	**Trade value**	**Balance of trade**
2014	EU28	Export	World	$5.311 mln	+
2014	EU28	Import	World	$0.693 mln	
2015	EU28	Export	World	$2.338 mln	+
2015	EU28	Import	World	$0.606 mln	

One of the methods of producing hydrogen is with an alkaline electrolyser, which often uses sodium hydroxide (NaOH) or potassium hydroxide (KOH) as the electrolyte, and nickel-coated steel for the electrode (Fuel Cell Today, 2013). Table 48 and Table 49 show the exports and imports for the two common electrolytes in electrolysers, showing a slight trade surplus for the potassium hydroxide for 2014 and 2015 and a trade surplus and deficit for sodium hydroxide for 2014 and 2015, respectively (United Nations Trade Statistics). Regarding the sodium hydroxide market, the Asia Pacific region without Japan dominates, with North America following. Eastern Europe and Japan have a rather small role in this market, showing a possible dependency for this chemical (Nikam, 2017). Europe does have several of the major potassium hydroxide manufacturers, with about 25% of the share of production capacity (Major Potassium Hydroxide Facilities are Located in APAC, Americas and Europe, 2015).

Table 48. Import/export share to and from the EU of sodium hydroxide in 2014 and 2015. Source: (United Nations Trade Statistics)

Import & export of sodium hydroxide, solid and aqueous solution (281511 and 281512)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU28	Export	World	$180.7 mln	+
2014	EU28	Import	World	$163.2 mln	
2015	EU28	Export	World	$156.2 mln	-
2015	EU28	Import	World	$179.7 mln	

Table 49. Import/export share to and from the EU of potassium hydroxide in 2014 and 2015. Source: (United Nations Trade Statistics)

Import & export of potassium hydroxide (281520)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU28	Export	World	$23.6 mln	+
2014	EU28	Import	World	$21.0 mln	
2015	EU28	Export	World	$21.5 mln	+
2015	EU28	Import	World	$20.4 mln	

For the nickel-coated steel that is used as the electrode for alkaline electrolysers, there is a major manufacturer in Europe (Tata Steel, though based in India) (Tata Steel, 2017). Nickel and iron (for steel) can be found in Europe, with Nickel being mined in Finland, Norway, the UK, Greece, and Macedonia, while major nickel mines exist also in the Philippines, Russia, Canada, and Australia (see Table 50). Iron is also produced in the EU, primarily in Sweden, but also to a lesser extent in Austria and Germany, while Australia and Brazil produce the most iron worldwide (see Table 51) (EuroGeoSurveys Mineral Resources Expert Group, 2014) (Statista, n.d.).

Table 50. Import/export share to and from the EU of nickel ores in 2014 and 2015. Source: (United Nations Trade Statistics)

Import & export of nickel ores (2604)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Export	World	$246.6 mln	-
2014	EU-28	Import	World	$511.4 mln	
2015	EU-28	Export	World	$210.4 mln	-
2015	EU-28	Import	World	$296.8 mln	

Table 51. Import/export share to and from the EU of iron ores in 2014 and 2015. Source: (United Nations Trade Statistics)

Import & export of iron ores (2601)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Export	World	$1.1 bln	-
2014	EU-28	Import	World	$11.9 bln	
2015	EU-28	Export	World	$0.6 bln	-
2015	EU-28	Import	World	$7.2 bln	

As the technologies for PEM and solid oxide electrolysers are similar for those technologies of the fuel cells, these dependencies are discussed below in the sections about PEM fuel cells and solid oxide fuel cells.

In summary, the primary dependencies for hydrogen and alkaline electrolysers seem to be more on the raw materials level, including the sodium hydroxide, nickel, and iron while the production of hydrogen and the market for electrolysers themselves is largely influenced by Europe.

10.2 Proton-Exchange Membrane Fuel Cells (PEMFC)

10.2.1 Description of PEMFCs

The proton-exchange membrane, or polymer electrolyte membrane, fuel cell (Figure 72) is one of the main types of fuel cells, which creates electrical current from hydrogen fuel. This type of fuel cell operates around 50-80 °C (lower than other types of fuel cells) and has the highest power density out of other fuel cell technologies (Peighambardoust, Rowshanzamir, & Amjadi, 2010). These cells operate on pure hydrogen, with a short start-up time, and are the main fuel cell type used in light duty vehicles and material handling vehicles - though they are not widely applied to stationary fuel cells (Fuel Cell Today, n.d.). Drawbacks of this fuel cell type are that it is very costly, despite major progress since the early 2000s, as well as degradation of the membrane electrode assembly after long-term operation. This variant was chosen because of its potential for wide-scale application, especially because of its power density and success in passenger vehicles.

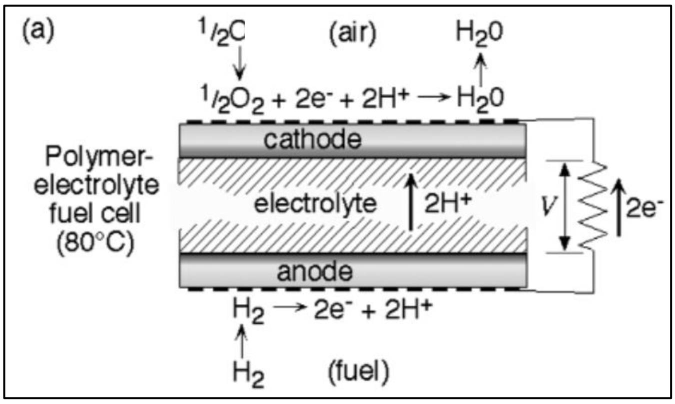


Figure 72. Depiction of a PEM fuel cell, where hydrogen fuel is delivered to the MEA, which then splits into protons and electrons. The protons then permeate through the membrane toward the other side where the cathode is located, combining with oxygen to form the waste product of water. Source from (Adler, 2005).

10.2.2 Issues of dependency – PEMFCs

Europe has several manufacturers of the entire PEMFC: two prominent ones being Nedstack (NL) and PowerCell (SE). The primary component for the PEMFC is the membrane electrode assembly (MEA), which is the combined electrode (which contains the catalyst) and the solid polymer electrolyte, which is the membrane. Within the MEA, a main component is the membrane itself. This is commercially produced by many players - one is in the US (a major one which produces Nafion®) and one is in Germany (which produces fumapem®) (Carmo, Fritz, Mergel, & Stolten, 2013). Other producers of polymer electrolyte membranes are located in Japan and Belgium (Jones, 2017). Thus, there is not a great dependency, but there potentially could be if expansion within Europe is limited. The entire MEA, which again is the combined product of electrode, catalyst, and membrane, is also produced by several manufacturers in Europe, for example Johnson Matthey (UK), gGmbH (DE), and EWII Fuel Cells A/S (DK), which does not show a limitation in European production.

Often used for the catalyst in PEM technology is platinum, which is imported by all EU member states, exposing another possible dependency, despite this element being present in Germany and Poland (Carmo, Fritz, Mergel, & Stolten, 2013) (EuroGeoSurveys Mineral Resources Expert Group, 2014). Trade of platinum is still a surplus for the EU, as can be seen by Table 52, but for the raw material, the top five producers are not located in Europe[18] (Sousa, 2017). Often the gas diffusion layer in a PEMFC is a layer of carbon paper or carbon cloth (Park & Popov, 2011). There are producers of the carbon cloth which are used for the electrodes in Europe (i.e. SGL Group and Freudenberg), while also produced in Japan and North America (Fuel Cells Etc, 2013). As for carbon paper, the exports of this product greatly outweigh the imports (see Table 53).

[18] This occurrence is possible because certain countries import and utilize much more platinum than European countries. The US, China (including Hong Kong), and Japan import large amounts of platinum, and these trades are all surpluses for Europe (United Nations Trade Statistics).

Table 52. Import/export share to and from the EU of platinum in 2014 and 2015. Source: (United Nations Trade Statistics)

Import & export of platinum (7110)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Export	World	$5.871 bln	+
2014	EU-28	Import	World	$5.612 bln	
2015	EU-28	Export	World	$5.016 bln	+
2015	EU-28	Import	World	$4.422 bln	

Table 53. Import/export share to and from the EU of carbon paper in 2014 and 2015. Source: (United Nations Trade Statistics)

Import & export of carbon paper (4809)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Export	World	$146.1 mln	+
2014	EU-28	Import	World	$25.4 mln	
2015	EU-28	Export	World	$137.7 mln	+
2015	EU-28	Import	World	$18.1 mln	

10.3 Solid Oxide Fuel Cell (SOFC)

10.3.1 Description of SOFCs

The second type of fuel cells discussed is the solid oxide fuel cell (SOFC, see Figure 73), which is primarily applied to baseload power generation. In existing systems, steam is required to warm up several of the components of the SOFC (and fuel), which lowers the overall efficiency of the system. Looking at the SOFC without these preheating requirements, efficiency is quite high (around 81%) partly due to the high operating temperatures of around 800-1000 °C (Peighambardoust, Rowshanzamir, & Amjadi, 2010) (de Kler, 2017). A combined heat and power system can be used with the waste heat, which can contribute to higher overall efficiencies. Drawbacks are that it is slow to start up and the heat temperatures create a hazard potential for people, meaning limitations in the transportation industry (Office of Energy Efficiency & Renewable Energy, 2016). The efficiency of this type of fuel cell makes the technology very promising, thus is it discussed here.

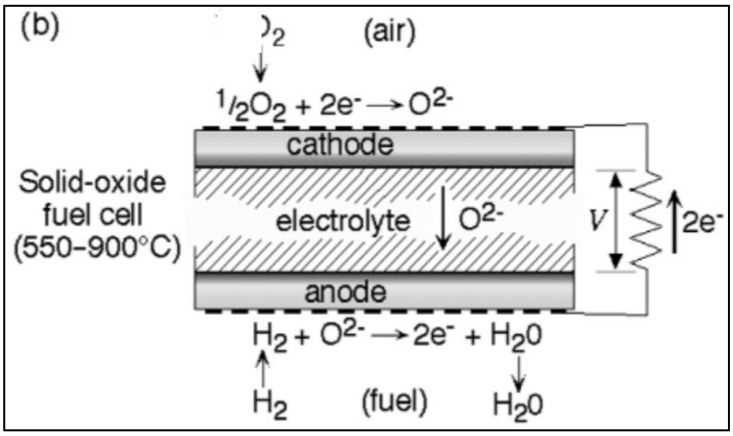


Figure 73. Depiction of a solid oxide fuel cell (SOFC). In this fuel cell, oxygen moves across the cathode, where then the oxygen ions move across the electrolyte toward the anode, which then combines with the hydrogen fuel to for the waste product of water. Source from (Adler, 2005).

10.3.2 Issues of dependency – SOFCs

There are several companies within Europe that produce solid oxide fuel cells, thus they are well represented in the market. These include Convion (FI), Elcogen (EE), and Sunfire (DE) (VentureRadar, n.d.). There is a large presence of companies also in the USA producing SOFCs, but this does not seem to be a dependency threat.

The SOFC is a solid fuel cell, where the components are largely made from ceramic materials. Often, the electrolyte used is the yttria-stabilized zirconia (YSZ) electrolyte (Zuo, Liu, & Liu, 2012). The primary producers of this ceramic are in Asia and North America, while there are a few producers in Europe (i.e. Treibacher Industrie AG in Austria and Zircomet in the UK). It is expected that Asia and Europe will consume much of this product, so it is possible that a dependence on the main producers will be present (Transparency Market Research, n.d.).

The common anode for a SOFC is a porous nickel-YSZ cermet, which is a ceramic metal, also serving as the catalyst in the system (Zuo, Liu, & Liu, 2012). The market for this is not well established, thus it could serve as a potential European dependency in the future, if SOFCs become a wide-spread technology. As for cermets in general, Europe performs well in exports regarding this material, as shown in Table 54. The cathode used in SOFCs is usually a combination of YSZ and the ceramic material lanthanum strontium magnetite (LSM) (Zuo, Liu, & Liu, 2012). Again, this is not a common product on the market, thus not much literature is available on the manufacturing of this material. Obvious producers are in the USA, showing again, a potential dependency for Europe.

Table 54. Import/export share to and from the EU of cermets in 2014 and 2015. Source: (United Nations Trade Statistics)

Import & export of cermets (811300)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Export	World	$231.5 mln	+
2014	EU-28	Import	World	$172.2 mln	
2015	EU-28	Export	World	$199.4 mln	+
2015	EU-28	Import	World	$151.5 mln	

The electrolyte and the electrodes of SOFCs contain the elements yttrium and zirconium, which could prove further dependencies on countries outside Europe. Table 55 and Table 56 below show the export and import trade, as well as the balance. Nickel has been previously described in the hydrogen section so will not be repeated here. As can be seen, Europe has a trade deficit with these base elements that are needed to produce solid oxide fuel cells. This is something to be aware of when considering Europe's dependency on other countries for this particular type of fuel cell.

Table 55. Import/export share to and from the EU of yttrium in 2014 and 2015. Source: (United Nations Trade Statistics)

Import & export of yttrium (261510)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Export	World	$1.4 mln	-
2014	EU-28	Import	World	$13.4 mln	
2015	EU-28	Export	World	$2.3 mln	-
2015	EU-28	Import	World	$12.7 mln	

Table 56. Import/export share to and from the EU of zirconium in 2014 and 2015. Source: (United Nations Trade Statistics)

Import & export of zirconium (261510)					
Event	Region	Trade flow	Partner country	Trade value	Balance of trade
2014	EU-28	Export	World	$16.9 mln	-
2014	EU-28	Import	World	$268.9 mln	
2015	EU-28	Export	World	$15.0 mln	-
2015	EU-28	Import	World	$297.5 mln	

10.4 Conclusions

10.4.1 Critical dependencies

Viewing the three broad topics discussed (i.e. renewable hydrogen, proton-exchange membrane fuel cells, and solid oxide fuel cells), there were three primary technologies that were discussed specifically: alkaline, proton-exchange membrane, and solid oxide. These three technologies are applied to both electrolysers (where hydrogen is made) and fuel cells (where hydrogen fuel is utilized to create electricity), so the materials necessary for electrolysis are often similar to the materials necessary for fuel cells.

At the top level, Europe has a foothold in the market for hydrogen and fuel cells, with constant production, a trade surplus, as well as incentives from the legislative perspective. Overall, the market for these fields is not extremely developed, so it’s likely to change in the coming years; though European companies already exist in each of these fields. Looking into the alkaline technology, the dependencies seem to lie among the intermediary materials, namely sodium hydroxide and potassium hydroxide, and base elements, namely nickel and iron. For the proton-exchange membrane technology, Europe has no severe dependencies, due to the fact that there are several manufacturers of the membrane electrode assembly, and there is a trade surplus of the platinum and carbon paper necessary for the electrocatalyst. Lastly, for the solid oxide technology, there are several producers of this type of fuel cell, but zooming into the elements shows a possible dependency on yttrium and zirconium, used for the electrodes and the electrolyte. Throughout these different technologies, countries that have quite some progress in the field are the USA, China, and Japan.

For the production side of hydrogen and fuel cell technologies, Europe has an advantageous position. There are several companies who both produce the equipment and provide services for hydrogen and fuel cells. Market opportunities where Europe is slightly behind other regions is with fuel cell forklifts and large fuel cell combined heat and power and primary power. These figures are shown in Table 57, which also show Europe overall excelling in electrolysers, fuel cell buses, hydrogen storage, and hydrogen refuelling stations (Fuel Cells and Hydrogen Joint Undertaking, 2017).

Table 57. Assessment of the position of the EU in hydrogen and fuel cell technologies, based on over 150 companies. The strength and growth scores are out of 15, meaning an overall max score of 30 is possible. A value of 9 signifies that Europe is as advanced as other regions, while a score of 10 or above means that Europe is ahead of other regions. Source: (Fuel Cells and Hydrogen Joint Undertaking, 2017)

	Fuel cell cars (FCEV)	Fuel cell buses	Fuel cell forklifts	Micro CHP	Large fuel cell CHP and Primary Power	Fuel cell APUs for trucks	Electrolysers	Hydrogen storage	Hydrogen Refuelling Stations
Strength	9	10	7	9	8	8	13	9	11
Growth	10	12	8	9	7	11	11	11	9
Overall	19	22	15	18	15	19	24	20	20

10.4.2 Consideration of variants

The dependencies previously discussed are common in that it is primarily the base minerals which are the cause of dependence. In some of the cases, Europe has the materials present, but still require much more imports than what can be exported. There is much literature around for hydrogen generation and fuel cell development within Europe, thus the knowledge base is present, as well as several companies producing electrolysers and fuel cells.

The three variants, i.e. renewable hydrogen, proton-exchange membrane fuel cells, and solid oxide fuel cells, are quite different in their technology requirements, processes, and dependencies. For this reason, they should be treated separately when examining the field of hydrogen and fuel cells.

11 Ocean Energy

The Ocean energy sector is relatively young and is still emerging. Figure 74 gives an overview of the most important types of Ocean Energy, and its timeline for their development phase. This chapter describes the dependencies for ocean energy, and describes two variants:

- Wave energy (chapter 11.1), wave energy converters generate electricity from ocean waves;
- Tidal energy (chapter 11.2), Tidal energy converters capture the energy contained in the difference between high and low tide, and convert it to electricity.

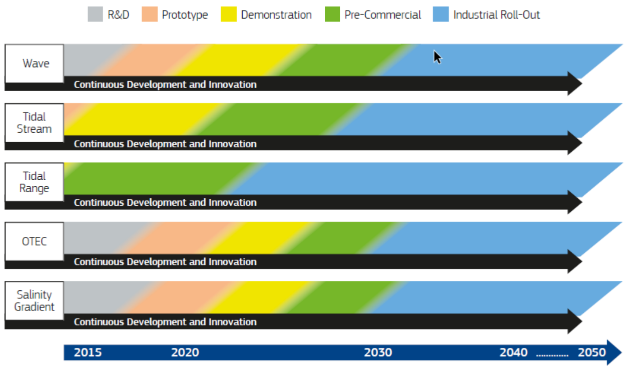


Figure 74 Timeline for the development phase of ocean energy technologies (Ocean_Energy_Forum, 2016).

The two variants wave and tidal energy are described in greater detail in chapter 11.1 and 11.2. OTEC and Salient Gradient are considered to still be in R&D phase (Figure 74). Therefore these variants are not described in detail, but a short summary on their dependency is given below.

The dependency for OTEC and Salient Gradient technologies is mainly on R&D sites and facilities. For the OTEC technology there is a lack of available locations in Europe, for OTEC plants to be constructed. The dependency for OTEC for Europe therefore is considered to be low. For salinity gradient power technologies, the dependency on the R&D on membranes seems to be a critical dependency for this technology. For building commercial plants, large quantities of membranes are needed. A 2 MW plant would at least need 2 million m2 of membrane surface. This membrane needs replacement over time, e.g. 5 years. Membrane efficiency increased the last years, however more efficient membranes are only available on small scale. Up scaled power plants require much larger quantities, and these are worldwide not available yet. A growing number of companies are actively pursuing the development of more efficient and economic membranes. (IRENA, Salinity gradient energy 2014).

The Ocean Energy sector remains promising, especially when niche markets (e.g. islands, remote locations) and export potential of ocean energy should be considered. Figure 75 gives an overview of the potential of Wave and Tidal energy, and Figure 76 shows the installed capacity in Europe. The potential for wave energy resources is the biggest. Although several wave energy prototypes are already deployed, some of which are grid-connected, the maturity level of wave energy is less than that of tidal energy technologies (European_Commission, DG_R&I, & DG_E, 2017).

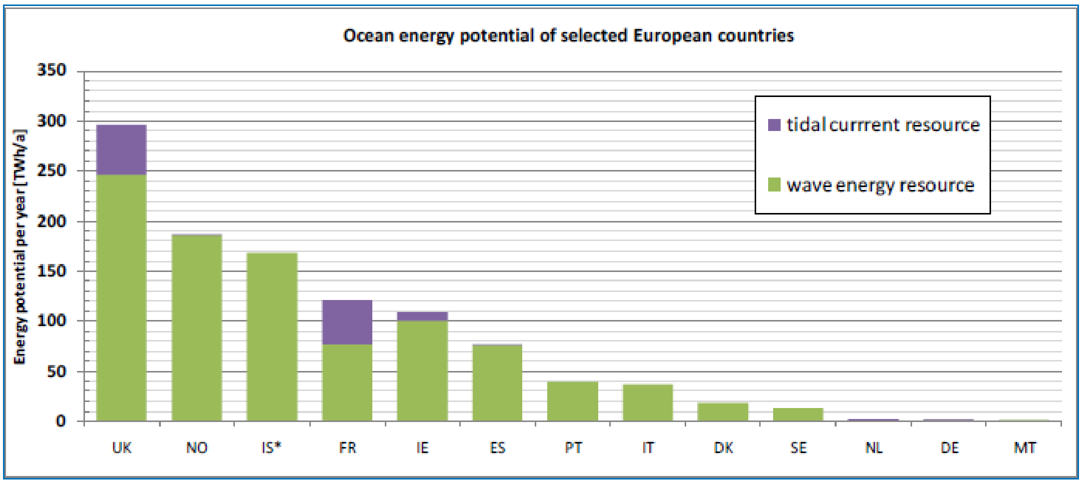


Figure 75 **Potential of Ocean Energy in Europe (European_Commission, DG_R&I, & DG_E, 2017)**

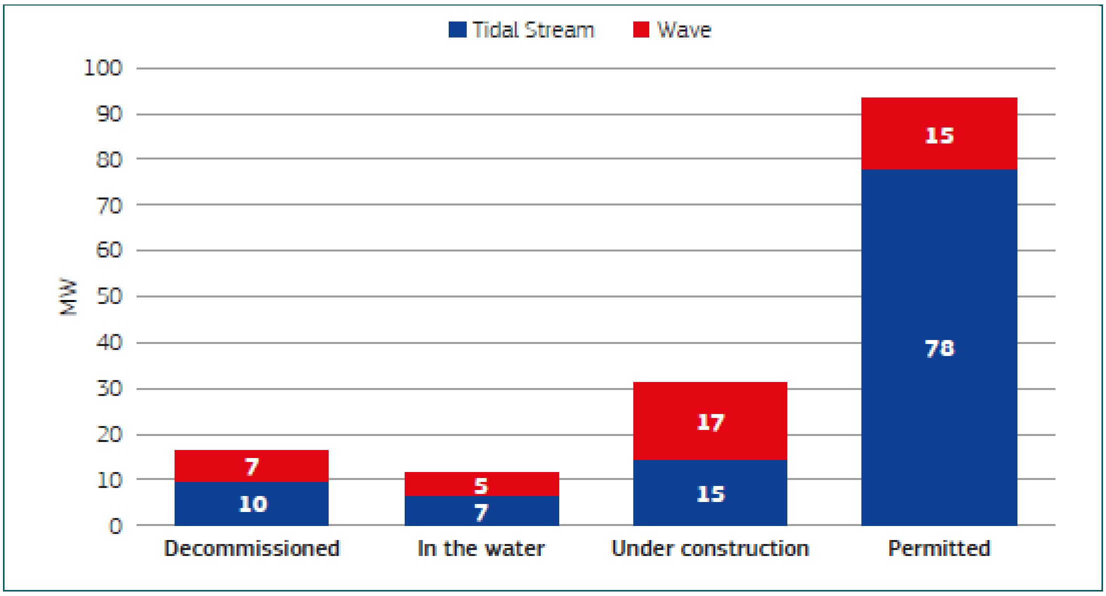


Figure 76 **Europe – deployed tidal stream and wave capacity, capacity under construction and permitted capacity (MW) – situation at June 2016 (Ocean_Energy_Forum, 2016)**

11.1 Wave energy

11.1.1 Description of Wave energy

Wave energy converters generate electricity from ocean waves (generated by wind passing over the surface). There are several technologies available, differing in location specification and energy conversion technology.

The most common types of wave energy technology are (IRENA, Wave Energy, 2014) described below and are shown in Figure 77:

- Oscillating Water Columns (OWC) with a trapped air pocket above a water column. The oscillating water columns are conversion devices. The waves act as a piston, moving up and down in a semi-submerged chamber with a trapped air pocket above the column of water. By this movement a high velocity air stream is generated, driving a turbine generator to produce electricity (Figure 77(a));

- Overtopping converters with water reservoirs that collect water from overtopping waves. This technology consists of a floating or bottom fixed water reservoir structure. Reflecting arms guide the waves into the device, where the waves spill over the top of a ramp structure and are restrained in a reservoir of the device. The potential energy of the height difference is being converted to electrical energy by low head turbines (Figure 77(b));
- Oscillating Body Converters with floating or submerged systems that can operate in deep water with more powerful wave regimes (over 40 meters' depth). In general, these systems are more complex than OWCs. There are various types of different concepts of Oscillating Body Converters which resulted in various conversion technologies, to convert wave energy to electricity, e.g., linear electric generators, hydraulic generators with linear hydraulic actuators, piston based pumps, etc. (Figure 77(c)).

(a) 

;

(b) 
;

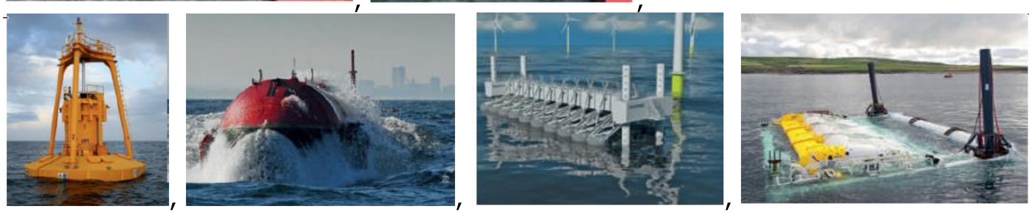
(c) 

Figure 77 Wave energy (IRENA, Wave Energy, 2014);
(a) Oscillating water columns
(b) Overtopping converters
(c) Oscillating body converters

Shoreline wave technologies (breakwater based technologies) are based on civil engineering constructions and are dependent on the availability of shoreline locations, while offshore wave technologies are based on mechanical engineering (constructions) and are depended on the availability of offshore resources locations, see also Figure 78 (European_Commission, DG_R&I, & DG_E, 2017).

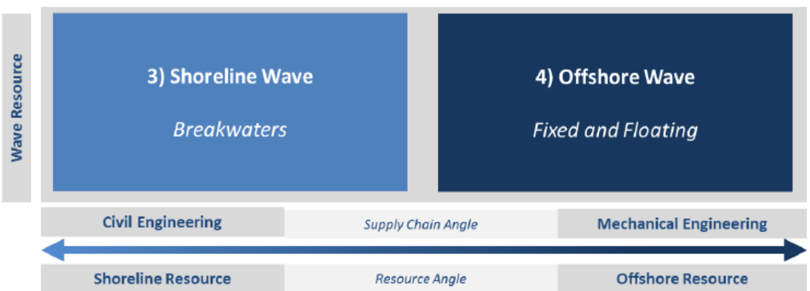


Figure 78 Resources and engineering needed for shoreline wave and offshore wave technologies. (European_Commission, DG_R&I, & DG_E, 2017)

11.1.2 Issues of dependency – Wave energy

Most of the wave energy technologies are still at prototype or demonstration phase. For wave energy technologies, no critical materials (EC, EC Critical Raw Materials, 2017) have been identified. Materials for wave energy are materials used for civil engineering (e.g. creating dams or local concrete structures to capture the energy of the waves). Wave energy converter technologies also use steel-alloys in their structures and constructions to resist corrosion, erosion, and other harsh environmental influences applicable within the deployment of wave energy. Besides the commonly used materials for producing generators (such as Cu, Al), steel alloys, and eg. Concrete structures for civil engineering constructions are being used for constructive parts. The wave energy technology includes various components for harvesting electricity from ocean waves, such as hydrodynamic converters ("prime mover"), power-take-off (mechanical/electrical), moorings and foundations, control system, offshore substation, and grid ("balance of plant") (European_Commission, DG_R&I, & DG_E, 2017). Since the components used are made of commonly used materials, and normally available in EU, less dependency on these materials is expected.

Because these technologies are still in at the prototype or demonstration phase, the technological innovation are one of the main barriers and so dependencies for this technology. A lot of the technology innovations for wave energy (and for tidal energy) have a generic nature (World Energy Resources, 2016). These technology innovations, which currently are taking place, are horizontally carried out over the variants of the ocean energy technologies, and therefore show overlap with developments in other variants of Ocean Energy technologies, as also described under chapter 11.2. For these technologies, new materials are being developed, in combination with new ways of production, installation, operation and maintenance.

Current, innovations and technology improvements can be found in the field of system efficiencies, but also in the development and utilisation of material developments since conversion devices are emitted to harsh environments (e.g. storms, salt seawater (corrosion), cyclic movements etc.). Here materials other than steel for the structure and prime mover are being researched. In this field one could think of steel reinforced concrete, rubbers, or Fibre Reinforced Polymers (FRP-composite materials, e.g. for weight savings). Innovative device coatings will also help in protecting materials against corrosion, water absorption, cavitation etc. but also against biofouling and turbulence. These topics of research go beyond the ocean energy sector, and are being researched in other sectors as well, for example in cases where 'offshore' or 'nearshore' structures are being developed, such as in the oil and gas industry, the maritime and shipping industry, or the offshore wind industry. For this reason, it is justifiable that the variant Wave Energy has no dependency on non-European countries for these research topics and innovations.

In the field of installation and operational developments further research is conducted in the field of cable installation and operation (dynamic cables to manage device movement) and in control systems and electricity infrastructure. Innovative methods for installation (e.g. pin-piling techniques for foundations and remote operations) and other O&M cost reductions (e.g. via ROVs, site sensors (cameras, positioning sensors etc.) will be used in ocean energy technologies. In the field of resource characterisation, a lot of research and testing is being performed on creating an accurate picture of existing and future ocean energy resource conditions (wind, atmospheric temperature, wave height, tidal flow etc.).

For wave energy technologies Europe is still the leading market, other countries and regions are progressing fast (IRENA, Wave Energy, 2014). Components used are depending on the specific technology used, as specified in greater detail in Figure 77, and can vary from e.g. pistons, (low head) turbines, floating structures, underwater turbines, hydraulic generators, etc. These various components can be considered to be based on existing technologies already developed and applied within Europe in different sectors. Europe is therefore not depending on companies from outside Europe. This is also given by the fact that many European initiatives on wave energy generation already can be given.
In 2004 the first Wave Energy Converters (WECs) were deployed; Pelamis prototype (750 kW; UK), and the Archimedes Wave Swing2 prototype (2 MW ; Portugal). In Portugal, one of the first wave energy farms (2.25 MW) was tested in 2008. This farm was based on three Pelamis prototypes. In the Orkney Islands, Aquamarine Power installed its 315 kW Oyster in 2009, and an 800 kW Oyster in 2011. There are projects being run in Denmark and Malta, by the Danish company Dexawave. EVE (the Basque Energy Board) has opened a first commercially-operated wave power plant in 2011, in Mutriku's breakwater. This wave powerplant was equipped with 16 OWC wave turbines of 18.5 kW and a total installed capacity of 296 kW. AW-Energy Ltd. (from Finland) has deployed three WaveRollers in Portugal (of 100 kW each), and plans a 1.5 MW farm in France. Another company from Finland, Wello Ltd., is testing its Penguin design (based on a rotating mass) in the UK. Langlee Wave power (from Norway) started with pilot projects in 2014 on the Canary Islands. Seatricity has their Oceanus 2 (160 kW) at the Wave Hub Facility in the UK, and planned a 10 MW wave energy farm to be operational by 2015. (IRENA, Wave Energy, 2014)

In total the dependency and reliance on import of materials from outside of the EU is not considered critical at the component or the material level. Therefore it can be concluded that the European reliance on imports for wave energy is relatively limited, since no critical raw materials are used and EU R&D facilities are available. For Europe, it is estimated that there are no critical dependencies on the facilitating companies and organisations to work on these innovations for the sector.

11.2 Tidal energy

11.2.1 Description of Tidal Energy

Tidal energy converters capture the energy contained in the difference between high and low tide, and convert it to electricity. One of the major advantages of tidal energy is its predictability, since low and high tides occur twice every day making long-term generation forecasting possible.

Figure 74 gives the development level for tidal energy technology. Two main technologies can be distinguished, tidal range and tidal stream.

- Tidal range (also called tidal barrage) technologies use a dam or other barrier to harvest potential energy from the height difference between tides. The power is generated via tidal turbines. There are several full-scale, grid-connected tidal range farms existing worldwide;
- Tidal stream: Tidal current or tidal stream technologies convert kinetic energy of tidal currents or tidal streams into electricity. Tidal energy systems generate power for some 14 -20 hours per day and for tidal stream generation drops when the tide turns. Tidal energy technologies need to cope in hostile environments with corrosion and currents. Three main categories can be distinguished (IRENA, Tidal Energy, 2014), see also Figure 79:

- Horizontal-axis axial and vertical-axis cross flow turbines use blades that are positioned either in parallel (horizontal) or perpendicular (vertical) to the direction flow direction of the water. Turbine-designs are like wind turbines, but due to higher density of the water, blades are smaller and turn more slowly;
- Reciprocating devices; have blades called hydrofoils (shaped like airplane wings) that move up and down as the tidal stream flows. Up and down movement is converted in electrical energy, by a converting the upward/downwards movement to drive a rotating shaft, or to drive pistons to support a hydraulic system for power generation.
- Other designs: A number of other designs are in a research and development stage. This category includes rotating screw-like devices and tidal kites.

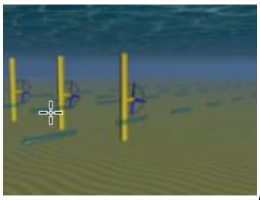
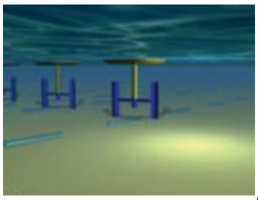
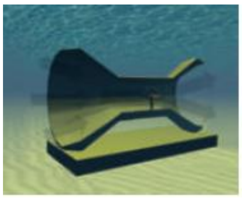
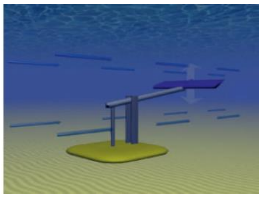
(a) , , , 

Figure 79 Tidal Energy (IRENA, Tidal Energy, 2014):

(a) Horizontal (left) and vertical (middle) axis turbines, and enclosed turbines (right)

(b) Reciprocating devices: hydrofoil shaped design concept

Figure 80 shows that tidal range technologies (barrage, lagoon based technologies) are based on civil engineering constructions and it shows that these technologies are dependent on the availability of shoreline locations. Tidal stream technologies on the other hand are based on mechanical engineering for their constructions and depend on the availability of offshore resource locations (European_Commission, DG_R&I, & DG_E, 2017).

Figure 80 Resources and engineering needed for tidal range and tidal stream technologies (European_Commission, DG_R&I, & DG_E, 2017).

11.2.2 Issues of dependency – Tidal energy

The most important barrier for tidal range technologies constitute the relative high upfront costs related to the developments of the dykes or embankments as well as the ecological impact of tidal energy projects. Other barriers/dependencies can be found in the field of deploying more R&D for improving turbine efficiency (e.g. by innovative reversible turbines for high and low tide generation), since the load factor of a tidal barrage is around 25%, leading to a higher cost of energy.

Dependencies for tidal stream technologies are identified in the need for continuous support for demonstration and availability of demonstration sites. Improvements of materials used and reductions of operation and maintenance cost can be based on the outcome of these demonstrations. However, simultaneous research and development of new infrastructures for flood defences, coastal restructuring, bridge and road construction can also offer opportunities to advance tidal energy technologies (IRENA, Tidal Energy, 2014). On a world scale, developments of this technology are taking place in (IRENA, Tidal Energy, 2014); Europe (France, Ireland, Spain, and the UK; with new test sites planned in Portugal and Spain) and Non-Europe (Canada, China, Japan, South Korea, and the USA; with new test sites planned in Chile, China, New Zealand and the USA).

Most of these countries have at least one open sea test site. In particular, the European Marine Energy Centre (EMEC), based in Scotland, is one of the longest running sites where tidal current turbines have been tested since 2005 (IRENA, Tidal Energy, 2014). Other major developers from Europe that delivered successful demonstration projects in the 2000s included Italy's University of Naples Federico II (2000), Norway's Hammerfest Strom (now Andritz Hydro Hammerfest) (2003), Ireland's OpenHydro (2006), Australia's Atlantis Resources (2006), and the Netherlands' Tocardo (2008) (World Energy Resources, 2016).

Table 58 shows the metal dependencies for Tidal energy.

Table 58 Tidal energy, metal requirements (Moss & Tzimas, 2013)

Technology	Elements	Materials demand (kg/MW)	Expected EU demand (tonnes)		Annual EU Demand / World Supply	
			2020	2030	2020	2030
Tidal	Cu	5.00	250	350	<0.1%	<0.1%
	Mo	0.05	2	3	<0.1%	<0.1%
	Ni	0.22	11	15	<0.1%	<0.1%
	Cr	0.31	15	21	<0.1%	<0.1%
	Ti	0.01	1	1	<0.1%	<0.1%

For tidal energy technologies, no critical materials (EC, EC Critical Raw Materials, 2017) have been identified. Besides the commonly used materials for producing generators (such as Cu, Al), steel alloys are being used for constructive parts. Power electronics are needed for the grid connections. Innovations in new materials, e.g. in composite materials are also not considered to create a critical dependency. In total the dependency is not considered critical at the component or the material level.

Leading countries in the world in the field of tidal energy generation are regions with good tidal resources, for example: South Korea, which has tidal range differences of 9m to 14m; or Canada, with various locations along the Lawrence River.

Together with Atlantis Resources, RusHydro is exploring tidal range projects in Western Australia. Furthermore, current tidal range projects appear to have great benefits in cases where existing dams or compounds are used, and where the objective of energy production is combined with the objective to improve water quality. A good example within Europe is the Netherlands, which is developing a project in the Grevelingen Lake. (IRENA, Tidal Energy, 2014).

Most of the developments in tidal energy are taking place in several countries within Europe, in countries like France, Ireland, Spain and the UK, and outside of Europe in countries like Canada, China, Japan, South Korea, and USA. In most of these countries there is at least one open sea test site. Based on these activities, Europe is not depending on companies outside of Europe.
The European Marine Centre (EMEC), which is based in Scotland, is one of the longest running sites where tidal current turbines are being tested since 2005. Within Europe there are several countries who are planning new test sites, such as Portugal and Spain. Also countries outside the EU are planning to build test sites, such as Chile, China, New Zealand, and USA.

New industrial companies have entered the market, such as Andritz Hydro, which took over Hammerfest Strøm and Alstom acquired the company Tidal Generation Ltd (TGL); MCT is now part of Siemens and ABB invested in Scotrenewables Tidal Power. DCNS took over Open Hydro, and has projects deployed in France and the UK (Scotland), but also outside of Europe, in Canada. Within Europe GDF Suez is supporting the development of Sabella, an enclosed turbine, in France. Hyundai Heavy Industries has finalised site trials with a 500 kW tidal system, and Kawasaki Heavy Industries has been testing full-scale technologies at European Marine Energy Centre (EMEC) (but also in Japan). Various European companies already deploy horizontal axis turbines of more than 1 MW demonstration units in the sea, such as Alstom TGL, Andritz Hydro Hammerfest, Scotrenewables Tidal Power, DCNS Open Hydro, Voith Hydro all deploy, and MCT/Siemens. Atlantis is working together with Lockheed Martin to optimise its new 1.5 MW tidal turbines. Of these technologies, turbines from Andritz Hydro Hammerfest, MCT/Siemens, and possibly Alstom TGL have been selected in three European funded demonstration projects for tidal arrays to be operational in the 2014 – 2016 time frame. In April 2014 DCNS OpenHydro and Alderney Renewable announced plans for a 300 MW tidal array. Most work on arrays still have a focus on model development. Several smaller technologies are being developed, aside from advances in applications close to the coast. These technologies could also be used for inland applications or as river current generators. A good example can be that Tocardo Turbines are in operation in the Netherlands in the North Afsluitdijk and soon also in the Eastern Scheld barrage (IRENA, Tidal Energy, 2014).

11.3 Conclusions

11.3.1 Critical dependencies

This paragraph describes the critical dependencies for ocean energy.

Dependencies in wave energy

For wave energy technologies, no critical materials (EC, EC Critical Raw Materials, 2017) have been identified. Besides the commonly used materials for producing generators (such as Cu, Al), steel alloys are being used for constructive parts. Power electronics are needed for the grid connections. Innovations in new materials, e.g. in composite materials are also not considered to create a critical dependency. In total, the dependency and reliance on import of materials from outside of the EU is not considered critical at the component or material level. It therefore can be concluded that the European reliance on import for tidal energy is relatively limited, since no critical raw materials are used and EU R&D facilities are available.

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11.3.2 Consideration of variants

The ocean energy variants are distinct technologies with different supply chains. Hence, they should be treated separately.

12 Solar Energy

Sunlight is used in various manners. The most obvious is photosynthesis, where plants convert sunlight to grow. Humanity has found uses of solar energy in generating heat and in converting solar energy into electricity. The sun is an abundant source of energy providing around 1000 W/m^2 of irradiance on earth, accumulating to 23,000 TWh annually. This exceeds the global demand for energy (16 TWh in 2016) (Perez, 2009).

Three variants of the conversion of solar energy to usable energy are discussed in this paper. All three are relevant for the discussion on dependency since they all represent a significant installed capacity in the EU. Photovoltaic conversion, in which light is directly converted into electricity, is discussed in the section on photovoltaics (see section 12.1). Concentrated solar power (CSP) (see section 12.2) uses optical elements to concentrate sunlight to harvest solar energy in the form of heat, which can then be converted from heat to electricity (by steam conversion or a Stirling engine). Solar heating and cooling is the most direct method of using sunlight, where a gas or a liquid is heated without conversion of the heat into electricity or kinetic energy. This is discussed in the section on solar heating (see section 12.3). Often CSP and solar heating are both referred to as solar thermal energy. To avoid confusion solar heating and cooling consists of flat plate collectors or evacuated heat-pipe tubes and CSP contains all concentrating solar thermal technologies.

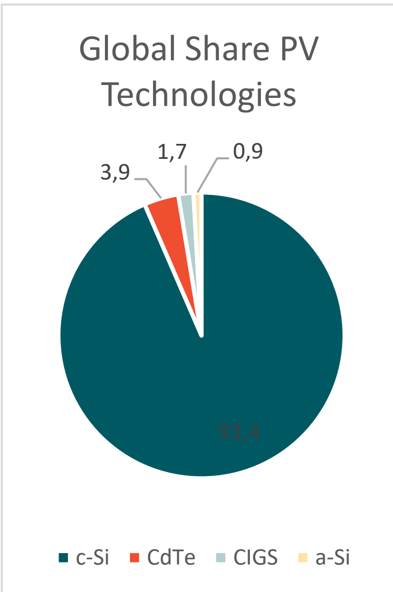
The total installed capacity of CSP was 4.8 GW in 2016 (REN21, 2017), solar heating and cooling amounted to 456 GW_{th} in 2014 (REN21, 2017), and solar PV amounted to 306.5 GW in 2016 (Solar Power Europe, 2017).

12.1 **Photovoltaics**

12.1.1 Description of Photovoltaics

Photovoltaics (PV) is a technology in which sunlight is directly converted into electrical energy via the photovoltaic effect. Photons (light) from the sun are absorbed and converted into electrons by a semi-conducting material (or a material possessing semi-conducting properties). As shown in Figure 81 the most commonly applied type of PV is the crystalline silicon (c-Si) flat plate PV module. Other PV types are made from other materials as for example: Cadmium telluride (CdTe), Copper Indium Gallium Selenium (CIGS), amorphous silicon (a-Si), organic materials (polymers or perovskites) and third generation technologies (III-V materials). All the latter are often called thin-film PV due to their thinner layer of active material. (Fraunhofer ISE & NREL, 2015).

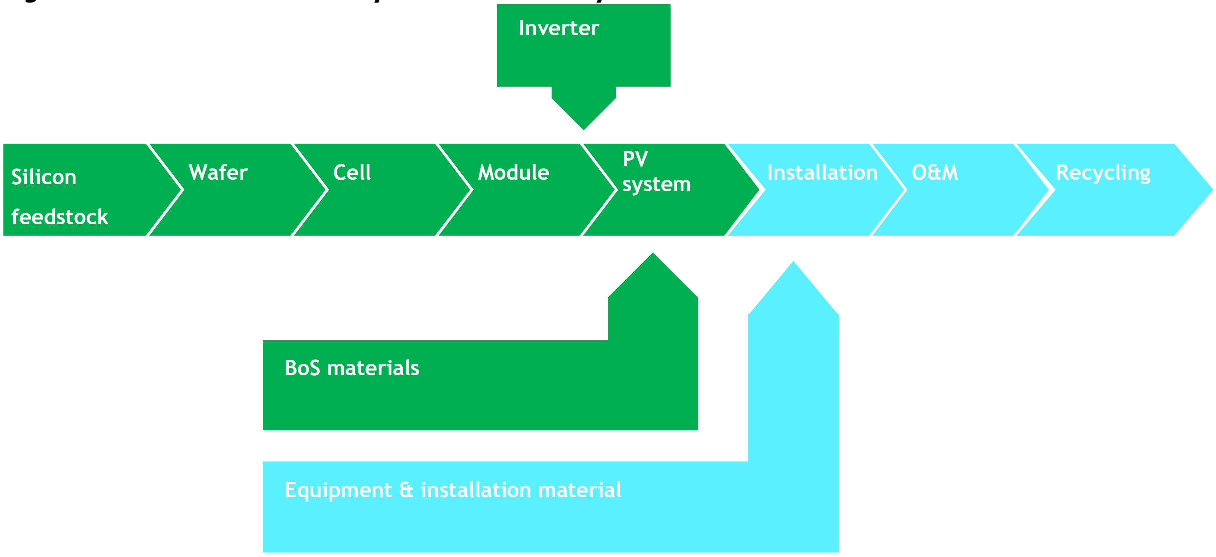
Figure 81 - Global share of PV technologies (Fraunhofer ISE, 2017)



There is a broad dependency of the above-mentioned technologies on their various supply chain components (wafers, cells, etc.), equipment (for manufacturing) and materials (metals, silicon, etc.). Since c-Si dominates the PV market with a market share of 93%

(Fraunhofer ISE, 2017), the dependency analysis will be limited to c-Si PV technology. The value chain and system lifecycle for c-Si PV systems is shown in Figure 82. It starts with purification of silicon into silicon ingots and continues with slicing (sawing) the ingots into wafers, producing PV cells, forming PV modules from individual cells, assembling a PV system including the PV modules, inverters and other components (Balance of System). The lifecycle is completed by the Operation and Maintenance of the installation until recycling at end-of-life. From Figure 82 the green indicated items are further discussed in the context of technology dependence as the items from installation onwards typically depend on local resources. It should be noted that the EU PV industry is largely dominated by equipment manufacturing (63% of PV industry in 2015) followed by inverter manufacturing (Trinomics, 2017).

Figure 82 Value chain and lifecycle of silicon PV systems

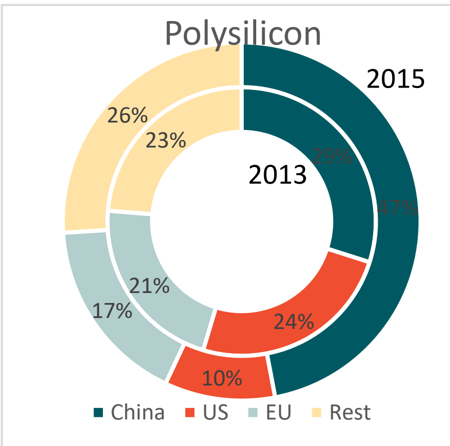


12.1.2 Issues of dependency – Solar PV

Silicon

The first step in the production of silicon PV modules (or cells) is the production of polysilicon feedstock (polysilicon ingot) either via the Siemens process (80% in 2009) or the Fluidised-bed process (20%) (Jäger-Waldau, PV status report 2016, 2016).

Figure 83 Production of Polysilicon for PV purposes per region in 2013 inner (Fu et al., 2015) and in 2015 (outer) (PVPS, 2016).



The global demand of polysilicon is dominated by the PV industry which accumulates to 90% of the annual polysilicon supply. In 2015, China produced 50% of global polysilicon production for PV (165 000 tonnes of total 310 000 tonnes) and imported 9 500 tonnes (PVPS, 2016). Figure 83 shows that the production has shifted largely from the US to China due to anti-dumping duties issued by the US government. The EU production remained nearly the same between 2013 and 2015 (PVPS, 2016). The import reliance rate for Silicon metal is medium (64%), while the most important producers constitute China (61%), Brazil (9%), Norway (7%), the USA (6%) and France (5%) (Commission, Communication from the Commission to the European Parliament, the Council, the European economic and Social

Committee and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU., 2017). The main importers to the EU are Norway (35%), Brazil (18%), and China (18%), while the main sources of European supply are Norway, France, Brazil, China, Spain and Germany (Commission, Communication from the Commission to the European Parliament, the Council, the European economic and Social Committee and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU., 2017). In terms of market concentration, it can be concluded that there is a tendency for polysilicon to be supplied from China. However, since export from the EU exceeded import of polysilicon in the EU, there is no critical dependency on polysilicon for the EU on non-EU countries. Export totalled 54,785 tonnes (predominantly to China, 67%) and import totalled 4,029 tonnes (predominantly from the USA, 58%; followed by Asia, >30%) (European Commission, 2017)[19].

Wafers

From the silicon ingot (purified silicon) wafers are cut using a sawing mechanism. There are two types of ingots, the single-crystalline (mono-crystalline) and multi-crystalline, which respectively account for 26% and 74% of the total silicon ingot (for PV) production (in 2016) (Fraunhofer ISE, 2017). In 2015, 60 GW of silicon wafer (for PV) were produced of which 48 GW was produced in China resulting in a market concentration in China of 80%.

Modules & Cells

The total production of PV modules (calculated from companies producing the cell and modules) is 77 GW in 2016 (Jäger-Waldau, Snapshot of Photovoltaics—March 2017, 2017), for the cell production alone (calculating the facilities producing cells) a total of 63 GW in 2015 was found. Figure 84 indicates the global market concentration for both PV module and cell production. European countries involved in PV module production are mainly Germany and to a small extent the Netherlands and France. For PV modules and cells the EU depends largely on Asian countries (PVPS, 2016). Again, China represents a market concentration of about 60%. With Europe having a PV system market demand of 8.6 GW in 2015, it represents a global market share of about 14%. In 2016 the EU market decreased to 6.7 GW, representing about 9% global market share (Solar Power Europe, 2017). Since the EU demand (6% of global produced PV modules) exceeds the EU production (3% of global produced modules) it can be concluded there is an EU dependency on non-EU countries for PV modules.

[19] Selected data of pure silicon import (99.55% pure silicon)

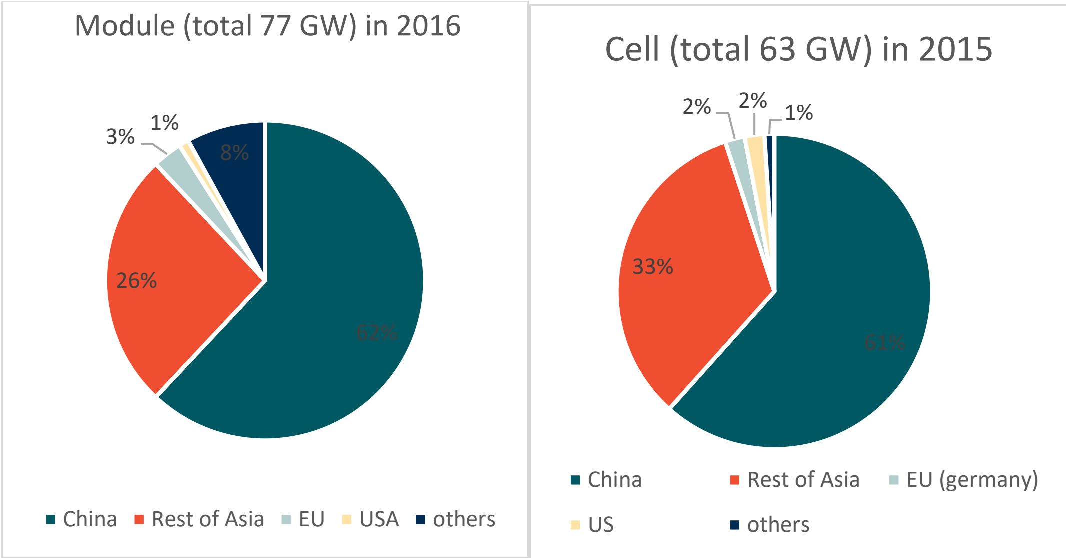


Figure 84: Global market share of PV cell and module production in 2016 (PVPS, 2016) (Jäger-Waldau, Snapshot of Photovoltaics—March 2017, 2017)

In 2016 the total import of photovoltaic devices (to be used in PV cells or modules) in the European union (EU28) was 354 329 000 units with a net worth of € 4 915 605 180. Export was 78 392 000 units worth € 1 697 468 103 (European Commission, 2017).

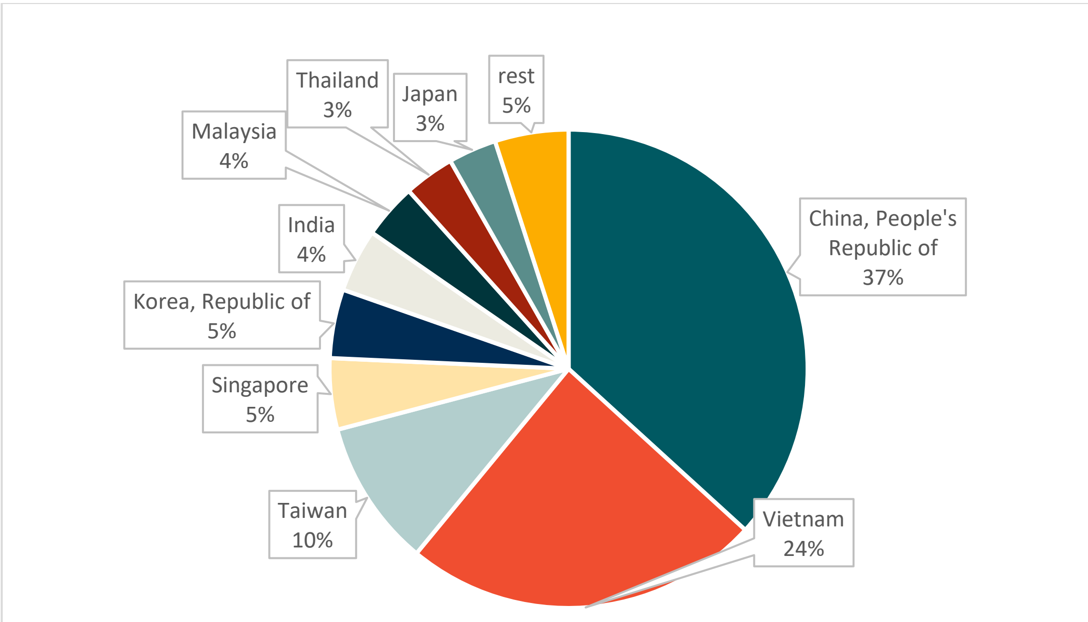


Figure 85: Import of photovoltaic devices in EU from shown countries (showing the top 9 countries) in percentage of the total import (354 329 000 units) in 2016.

Inverter

PV inverters convert DC power to AC power. Typically, string inverters are used for medium sized solar plants (50% market share) and central inverters for larger scale (48% market share). Inverter production is dominated by China with a market share of 40% accumulating to 22 GW in 201,5 of which 19 GW was exported. Second is the USA with 5.2 GW shipped in 2015 (PVPS, 2016). In inverter manufacturing the EU has a market share of 18% mainly due to large companies like SMA and ABB (Trinomics, 2017). The top five inverter companies (Huawei, Sungrow, SMA Solar, ABB, and TMEIC) make up for more than 50% of the global annual production making this a maturing market (REN21, 2017). Since two of these parties are located in the EU (SMA Solar in Germany and ABB in Switzerland) and since the inverter market is further also globally distributed, there is a limited EU critical dependence expected. However, critics have noted that the inverter market is continuously concentrating around large companies (GTMResearch inverter concentration, 2016). Total export of inverters (in terms of financial export) from the EU is 7.5 times as high as the import (namely 1 500 million versus 200 million) (European Commission, 2017).

Regarding the raw materials used within power electronics, the most important ones constitute silicon, copper and gallium. From these, silicon is the most critical, with its import reliance rate reaching 64% and thus considered medium. The most important producers of Silicon metal constitute China (61%), Brazil (9%), Norway (7%), the USA (6%), and France (5%). The most important importers of Silicon to the EU constitute Norway (35%), Brazil (18%), and China (18%), while the sources of the European supply are Norway, France, Brazil, China, Spain, and Germany (Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions on the 2017 list of Critical Raw Materials for the EU, 2017).
Regarding Gallium, the import reliance rate reaches 34% and is the reliance on import is thus considered medium, with the most important producers being China (85%), Germany (7%), and Kazakhstan (5%). The main importers of Gallium to the EU are China (53%), the USA (11%), Ukraine (9%), and South Korea (8%), while the main sources of European supply are China, Germany, the USA, Ukraine, South Korea, and Hungary (Commission, Communication from the Commission to the European Parliament, the Council, the European economic and Social Committee and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU., 2017). The supply of copper is not considered critical.

Balance of System

Apart from the PV modules and inverters, a PV installation consists of a mounting structure (in some cases solar trackers are used), cables, possibly DC combiner boxes, housing for inverters, possibly AC combiner boxes, and transformers (for grid connection). On all these items, no critical dependency of the EU on non-EU suppliers is expected. Transformers are a critical component as they can have delivery times up to 14 months and are often shipped from non-EU countries. Nevertheless, transformers consist of common electronics and are fabricated worldwide.

Critical Materials

Table 59 presents the critical materials for PV products in a recent assessment. The materials mentioned here (tellurium, indium and gallium) are only used for thin-film solar cells. Tellurium is not considered a critical raw material for the EU, while for Indium the import reliance rate is also considered very low (0%). The most important producers of Indium are China (57%), South Korea (15%), and Japan (10%), the main importers constitute China (41%), Kazakhstan (19%), South Korea (11%), and Hong Kong (8%), while the main sources of supply for the EU are China, Belgium, Kazakhstan, France, South Korea, and Hong Kong (Commission, Communication from the Commission to the European Parliament, the Council, the European economic and Social Committee and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU., 2017). Regarding Gallium, the import reliance rate reaches 34% and the reliance on import is thus considered medium, with the most important producers being China (85%), Germany (7%), and Kazakhstan (5%). The main importers of Gallium to the EU are China (53%), the USA (11%), Ukraine (9%), and

South Korea (8%), while the main sources of supply for the EU are China, Germany, the USA, Ukraine, South Korea, and Hungary (Commission, Communication from the Commission to the European Parliament, the Council, the European economic and Social Committee and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU., 2017).

Table 60 shows results of two studies on all metals used for PV production for the world supply in 2010. The demand in that year, and the expected demand[20] in 2020 and 2030, indicating for crystalline silicon that there is no significant dependence on any particular material.

Table 59: EU's import dependence on critical materials (Rabe et al, 2017)

Material	Dependence on china (%)	Other main possible supply sources
Tellurium	Low (20%)	Japan, Belgium, Sweden
Indium	Medium (58%)	Belgium Germany, Italy, Netherlands, UK
Gallium	Medium (69%)	France

Table 60: Materials for PV indicating the global supply in 2010, the demand per MW and the technology where the material is used. (Moss R. T., 2011) (Moss R. T., 2013).

Material	Technology	World Supply (2010) [tonnes]	Demand [tonnes/MW]	Annual EU demand [tonnes] 2020	Annual EU demand [tonnes] 2030	Demand / world supply 2020	Demand / world supply 2030
Te	Thin film	500	0.0047	150.00	126.00	12%	7%
In	Thin film	1,350	0.0045	145.00	121.00	8%	5%
Sn	Thin film	261,000	0.46	14913.00	12505.00	4%	3%
Ag	All	22,000	0.19	619.00	519.00	2%	1%
Ga	Thin film	160	0.00012	4.00	3.00	1%	1%
Cd	Thin film	22,000	0.0061	15.00	13.00	0%	0%
Se	Thin film	3,250	0.0005	109.00	91.00	0%	0%
Cu	All	16,200,000	2.19	70650.00	59241.00	0%	0%
Pb	Thin film	4,100,000	0.27	8672.00	7272.00	0%	0%

12.2 Concentrated Solar Power (CSP)

12.2.1 Description of CSP

CSP is predominantly found in countries with a high and direct irradiance (between 40 degrees north and south of the equator). The global installed capacity was 4.8 GW in 2016 of which 2.3 GW is installed in Spain and 1.7 GW in the USA, together accounting for 80% of the market (REN21, 2017). The technology is less popular then photovoltaics due to the higher capital investment cost and the fact that it is less scalable. However, CSP allows for low-cost thermal energy storage allowing electricity to be generated also outside daily-sun hours (IRENA CSP Brief, 2013). Generally, it is known as a technology which is locally developed (per country). The technique consists of the following variants:

[20] Projections made in 2013, although these expectations have since been adjusted the presented statistics provide a reasonable assessment on critical materials.

- Parabolic trough – concentrating sunlight roughly 70-80 times through a parabolic mirror (one-axis tracking) to heat fluid in a tubing system. This is the predominantly used technology since it is scalable and efficient (IRENA CSP Brief, 2013);
- Tower – concentrating sunlight (>1000 times) using (flat) mirrors (two-axis tracking) onto a single point to heat a fluid or salt, generating electricity from steam. This is a commercially proven technology and the second most used type of CSP (IRENA CSP Brief, 2013);
- Fresnel – concentrating light (around 60 times) using Fresnel mirrors to a single point. Technology is still in an early commercial stage and therefore is not considered in this review (IRENA CSP Brief, 2013);
- Dish (Stirling) – Using a single large dish mirror to concentrate light (>10 000 times) onto a Stirling motor. This technology is in its demonstration phase and therefore will not be considered in this review (IRENA CSP Brief, 2013).

12.2.2 Issues of dependency – CSP

The CSP market shifted largely from Spain and the USA to developing countries during 2015 and 2016. CSP technology has a potential for local manufacturing, engineering, and skills development. Manufacturing can be done locally which limits issues of technology dependency. Abengoa from Spain is the largest developer worldwide, however it has been in decline since 2013 due to changing Feed-in-Tariff (FIT) regulations in Spain. Other significant manufacturing and installer companies are: ACWA (Saudi Arabia); Rioglass Solar (Belgium); Supcon (China); Acciona, ACS Cobra, Sener and TSK (all Spain); and Brightsource, GE and Solar Reserve (all USA). In general, the cost of CSP, although declining, is higher than PV and therefore the technology is less applied (REN21, 2017).

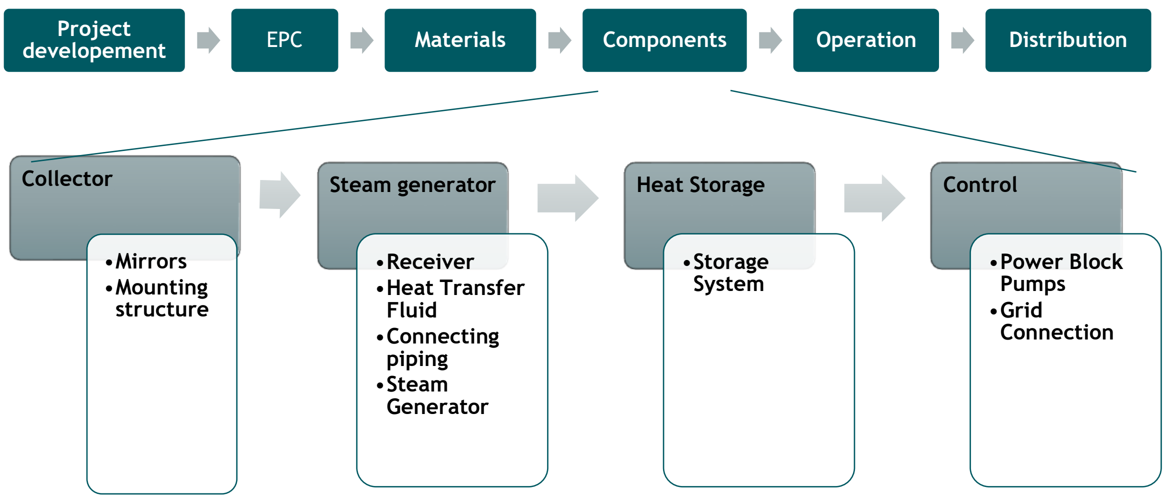


Figure 86: Value chain of CSP with highlighted the components part (Ernst & Young, Fraunhofer ISE, Fraunhofer ISI, 2017)

A basic analysis of the value chain shows a significant amount of (large and international) parties for each element of the value chain (Ernst & Young, Fraunhofer ISE, Fraunhofer ISI, 2017; Clixoo, 2015). This leads to the general conclusion that CSP is not dependent on a single company. More specifically, the following table provides insights on the materials used:

Table 61 : Components in CSP (both parabolic trough and tower)

CSP Components	Materials	Manufacturer[21]
Collector system Mirrors - Receiver - Body armour - Body pylons - Motion system - Fasteners	Steel Plastic Copper Aluminum Concrete	Collectors: European Partners (Europe) Industrial Solar Technology (USA) Luz/Solel (Israel) Solargenix Energy (USA) Solar Millennium AG (Germany) Sopogy (USA) Mirrors: Alanod (Germany) Ausra Manufacturing (USA) Boeing (formerly McDonald Douglas, USA) Cristaleria Espanola SA (Spain) Flabeg (Germany) Glaverbel (Belgium) 3M Company (USA) Naugatuck Glass (USA) Paneltec Corporation (USA) Pilkington (United Kingdom) Reflec Tech (USA) SCHOTT North America (USA)
Steam generator system Oil expansion tank - Heater tanks - Oil pump - Oil pipeline - Valves	Steel Copper Aluminum Concrete Silica	Siemens (USA)
Heat storage system Steel armour - Steel piping - Temperature sensors - Valves - Hot pump - Cold pump - Molten salt	Steel Copper Brass Aluminum Concrete	Luz/Solel (Israel) SCHOTT North America (USA) Siemens (USA) Radco Industries (USA) *Concentrator Structure:* European Partners (Euro Trough) Europe Solargenix Sanford, NC
Central control system Programmable logic controller - Controls - Sensors - Box controls - Circuit boards - Temperature sensors	Plastic Aluminum Electronics	Abengoa Solar (USA)

For each of the above mentioned components there is no critial dependency on materials or components for the EU on non-EU countries.

Critical materials

For CSP the only important material is silver of which about 6.5 kg per MW is required. Since the global supply in 2010 was 22 ktonnes there is no direct threat expected for the silver supply for CSP (Moss R. T., 2011), which would have required for example around 1000 kg

[21] Selection of most noteworthy companies

for its cummulative installation (2016) of 4.8 GW. Also expectation on the requirements of silver for CSP technology for 2020 and 2030 are below 0.1% of the global annual supply (Moss R. T., 2013).

12.3 Solar Heating and Cooling

12.3.1 Description of Solar Heating and Cooling

Solar heating is the direct collection of heat from solar energy and is typically conducted using the following techniques (with indicated global market share in 2014): evacuated tube collectors (71%), glazed flat-plate collectors (22%), unglazed water collectors (6%) and glazed & unglazed air collectors (<1%). Europe is the second largest market with an 18% share of the total global market (China being the first with 71%), and in Europe, in contrast to globally, the flat plate collector has 84% of the market share (Mauthner, Weiss, & Spörk-Dür, 2016).

Solar systems can also be used for cooling when absorbing heat during the day and releasing the heat during the night. In Europe, markets for cooling applications in islands like Sicily, Crete, Canary Islands and Cyprus are limited (IEE SOLCO project, 2009). The market of Solar Cooling in Europe is so small that it is not included in the scope of this study.

In the current analysis glazed flat-plate and evacuated tube collectors are considered due to their European market share. In general, 2016 was a year in which solar heating demand declined relative to the previous years, thereby the manufacturers diversified largely into PV-T a combination of PV and solar heat (REN21, 2017).

12.3.2 Issues of dependency – Solar Heating

Flat plate collectors

For flat plate collectors, production is commonly quite local. Production facilities are placed around the globe (Sun&Wind Energy, 2015). Since the production of flat plate collectors depends only on commonly available materials (glass, copper, etc.) it is not expected to have a large dependency on a single country outside of Europe.

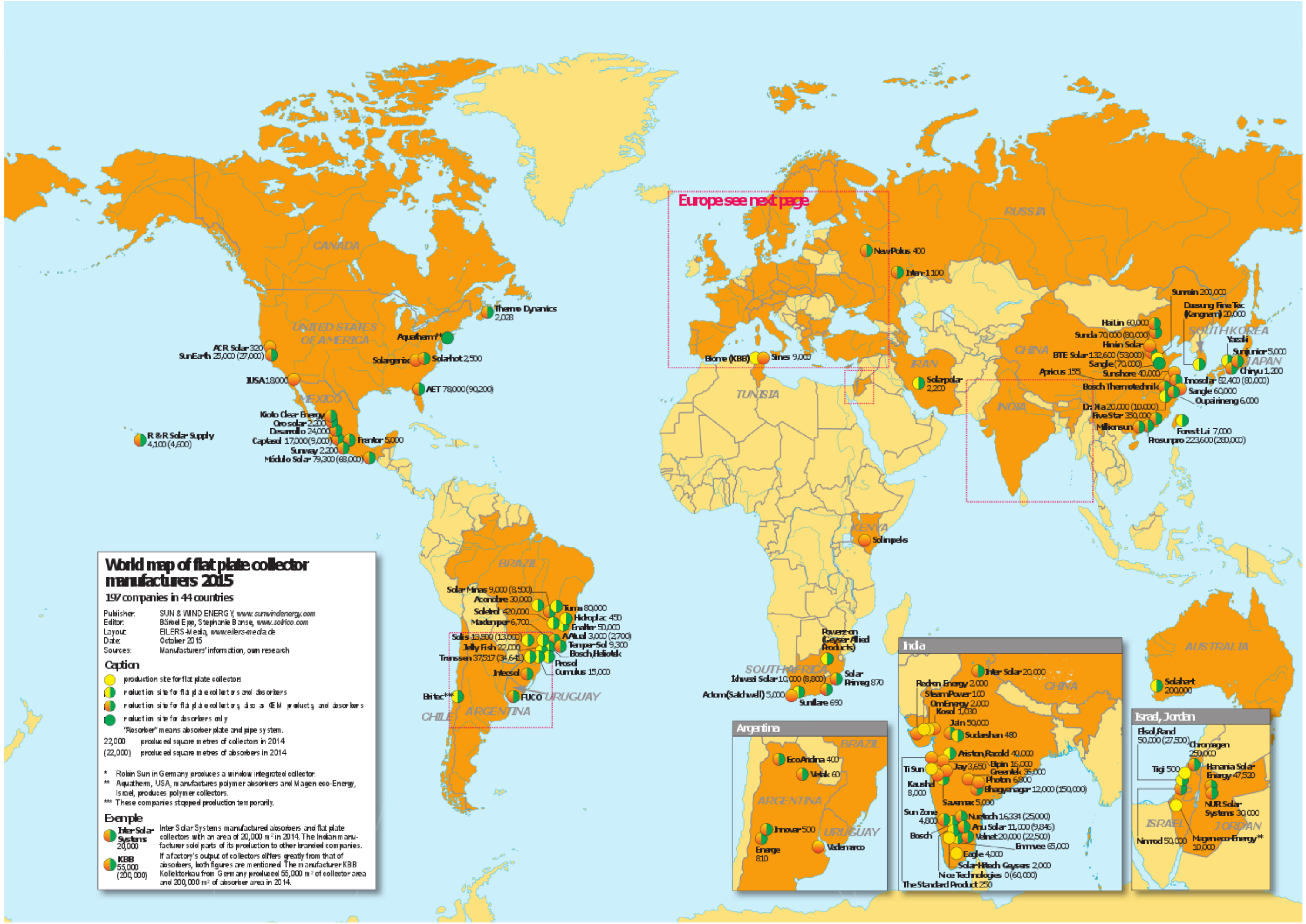


Figure 87: Global manufacturing sites for flat-plate collectors for solar heat. Europe in next figure.

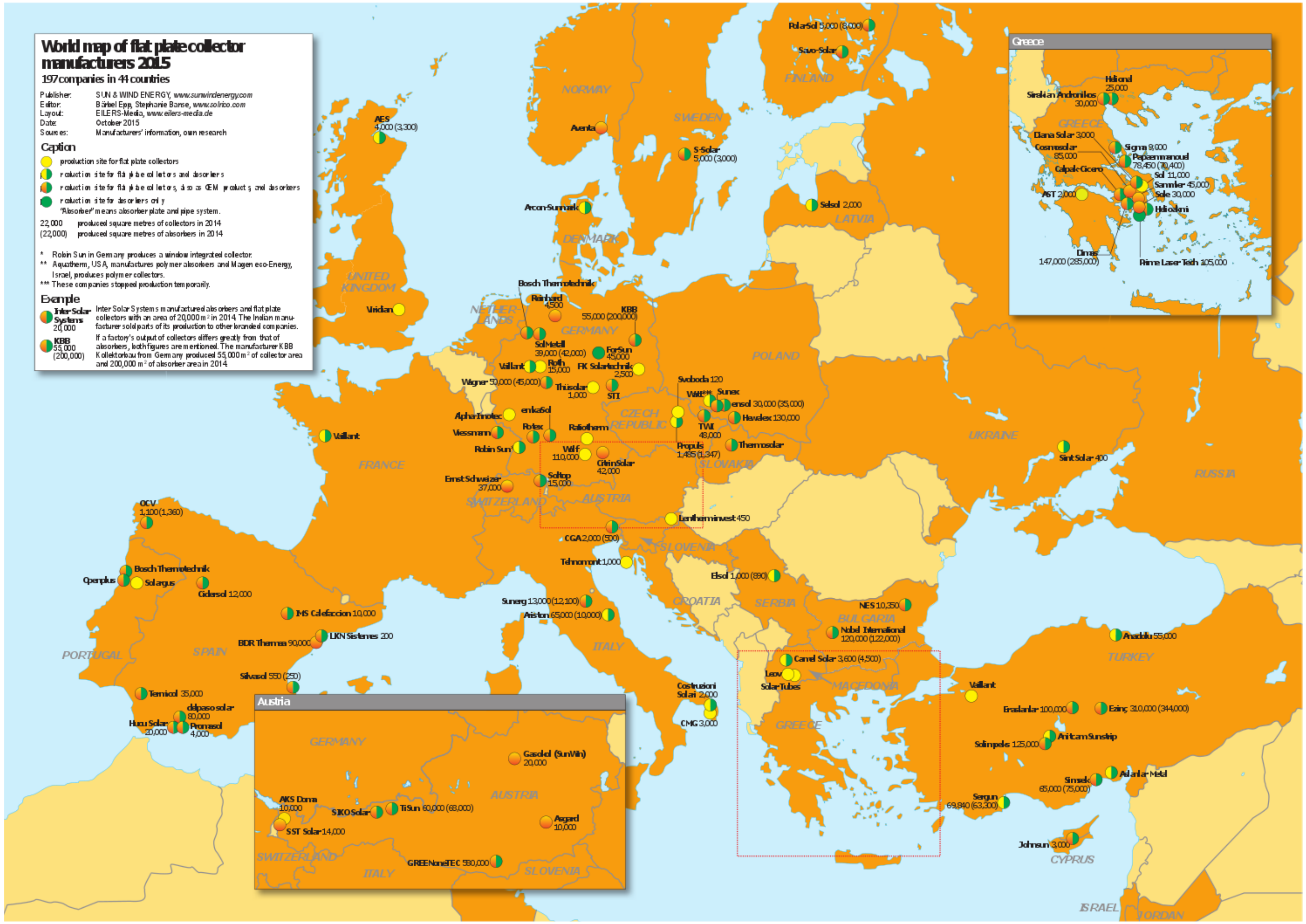


Figure 88: Overview of flat-plate collector manufacturers in Europe (Sun&Wind Energy, 2015)

Evacuated tube collectors

For evacuated tube collectors, the global presence is slightly different from flat-plate since production is more focused in China, however, still manufacturing is spread globally.

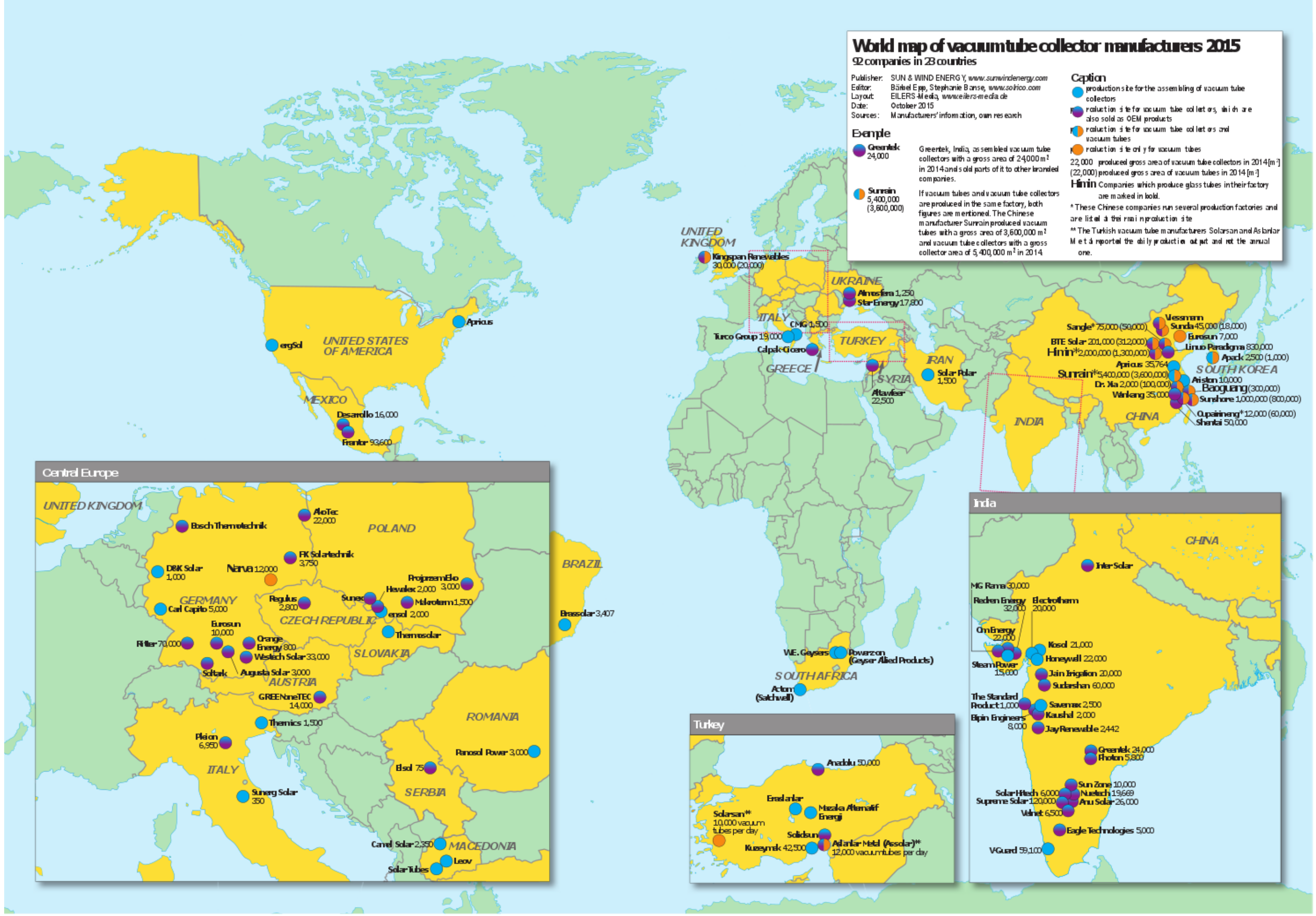


Figure 89: Global manufacturing of evacuated tube collectors

12.4 Conclusions

12.4.1 Critical dependencies

Photovoltaics

For solar PV the fabrication of PV cell and modules is predominantly performed in Asian countries, led by China. The EU cell manufacturers have not been able to match the declining prices of Asian competitors. Therefore, a dependency on PV cells and modules from Asia exists where the market is competitive and many different companies are present. Import regulations have led companies from China to move production elsewhere. This can be seen as beneficial for the market concentration which is spread more evenly over the world.

For other items of solar PV like construction materials and other balance of system components, there are no critical dependencies since they depend on local parties and/or materials and equipment which can be considered quite general (cables, transformers, installation equipment, qualified personnel, etc.). Regarding inverters, two critical raw materials have been identified, Silicon and Gallium with a medium reliance on import.

Concentrated Solar Power

CSP consists mainly of parabolic trough installations and solar towers. For both components, manufacturing and installation depends upon local companies. CSP is predominantly used in high irradiance regions of the world, some of which are within the EU (for example Spain). The current analysis found no significant critical dependencies on non-EU countries. The field of CSP is filled with a wide variety of commonly available materials for the fabrication of components (apart from silver, which is less commonly available, however, is not considered a critical dependence).

Solar Heating and Cooling

Solar heating consists mainly of two technology subvariants namely, flat plate and evacuated tube concentrators. Both technologies rely on materials abundantly present in and out of the EU. The manufacturers for both technologies are scattered world-wide placing themselves near countries in which the technology is popular. There is no clear critical dependency for solar heating for the EU or non-EU countries. Solar cooling is not part of the analysis as the deployment in the EU is limited.

12.4.2 Consideration of variants

There are no common critical dependencies across the three solar technologies (PV, CSP, Solar Heating & Cooling). As such, each variant should be considered separately. Power inverters can be used in all three variants when the purpose of the installation is the generation of electrical power. However, power inverters show no critical dependency. Furthermore, in terms of material dependency, silver as a conductor might be used in all variants (for electricity generation).

13 Wind energy

Wind energy is a technology used for converting kinetic wind energy to other energy carriers. Most wind turbines convert wind energy into electrical energy and feed it into an electrical grid for further conversion or consumption.

Today, most wind turbines consist of a horizontal axis rotor with three rotor blades, a nacelle that houses the drive train (with or without gearbox (direct drive)), a generator, and power electronics on top of a tower. Generators can be either designed using permanent magnets or using electro-magnets. It is important to note that permanent magnets require the use of rare-earth metals. The tower is mounted on top of a foundation. For a more extensive description see (IEA-ETSAP and IRENA, 2016).

Wind energy resource is unevenly spread as can be observed from Figure 90 below, but in large parts of the globe wind energy is available and can be utilised for generating wind power.

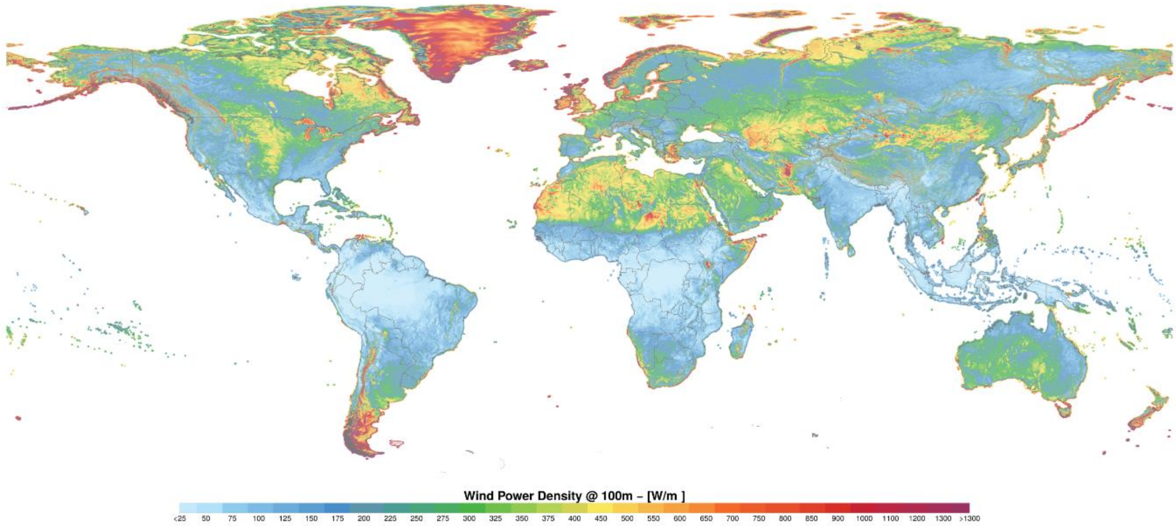


Figure 90 Global wind resource (wind power density (W/m²) at 100 m height) (IRENA, 2015)

In this paper a distinction is made between two variants: onshore and offshore wind energy. Historically, wind energy has been developed for onshore conditions. However, due to spatial restrictions in densely populated areas, there has been a growing interest in the development of offshore wind energy. Onshore and offshore wind turbines have different design drivers.

Offshore wind turbines have become larger, as their cost can be reduced by limiting the number of foundations and installation. Onshore wind turbines must be transported over land, limiting the maximum size of towers, nacelles and blades. In addition, sound emission is a limiting factor to optimize application in populated areas, demanding lower rotor speeds.

Nowadays, there are distinct wind turbine designs for onshore and offshore applications.

13.1.1 Onshore wind energy

Description of onshore wind energy

Onshore wind energy in its present form started to develop around 1975, when the first oil crisis had developed. Before then, wind energy was mainly known for the classical mechanical windmills that were used for milling, sawing and pumping water. The early electrical wind turbines had about 15 meters rotor diameter and 50 kW nominal power. The design was simple with fixed rotor blades (with a fixed rotational speed) which coupled to a gear box and then to a generator connected to the electrical grid. Today, onshore wind turbines have a nominal power of more than 4 MW, a rotor diameter of 130 m and a tip height that exceeds 200 meters. Pitching blades and a variable rotor speed make optimal use of the wind resource. Power electronics are used to convert the varying rotor speed and to connect it efficiently to the electrical grid. The size of onshore wind farms can range from a single solitary wind turbine to more than 1000 MW in remote areas, for which special grid connections are built to transmit power to load centres.

Onshore wind energy has shown strong convergence in the past four decades towards horizontal axis 3-bladed turbines; this paper focuses on this type of wind turbines. Vertical axis turbines, ladder mills or kite energy are excluded as they are still in a research phase and are not yet market ready.

The cost of onshore wind farms will continue to fall (Figure 91). Historically, the installed cost of onshore wind power has declined by 7% every time global installed capacity has doubled. Compared to the current rate, the global weighted average LCOE (Levelized Cost of Energy) of onshore wind could fall by 26% by 2025. The LCOE will fall more rapidly than investment costs, as ongoing technological improvement from improved designs, larger turbines, increased hub heights, and rotor diameters unlock higher capacity factors at the same wind resource (IRENA, 2016). In Germany, the latest auction for onshore wind energy revealed an average bid price of 4.28 €ct/kWh (Bundesnetzagentur, 2017).

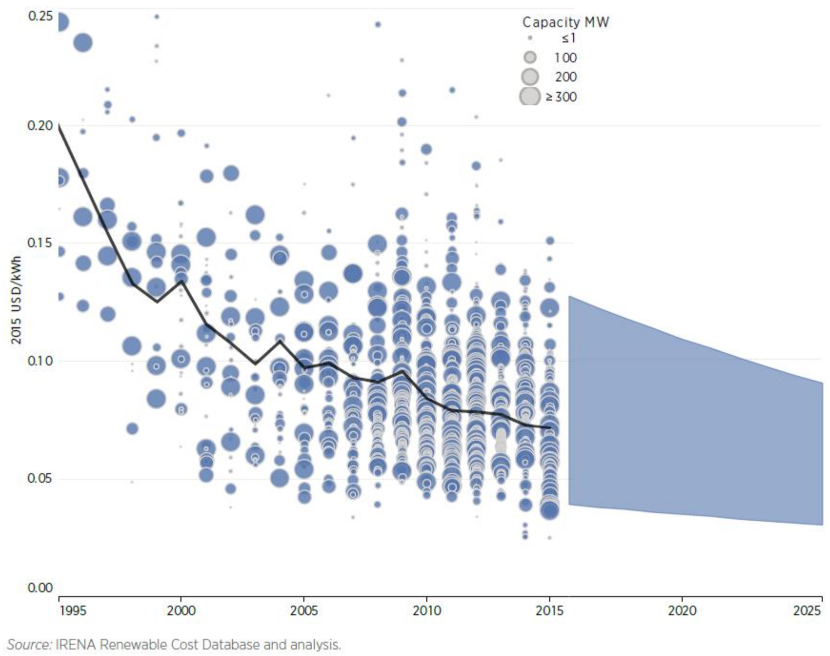
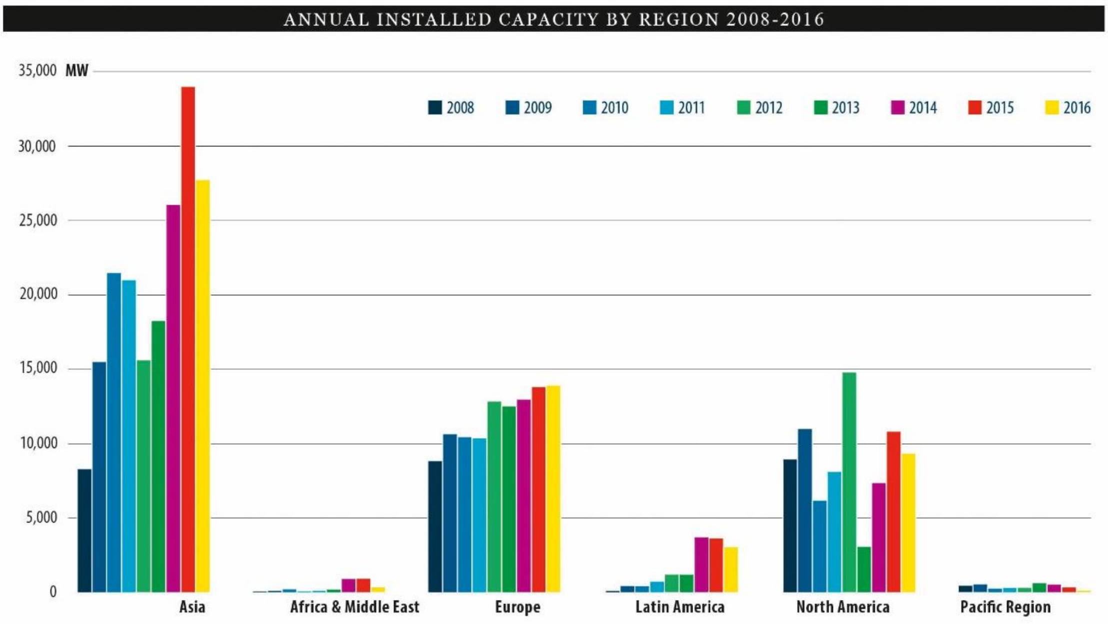


Figure 91 Cost reductions in onshore wind energy (IRENA, 2016).

Figure 92 shows the annual installed capacity by region between 2008 and 2016. It shows the dominant position for Asia (China) with 28 GW of wind capacity additions in 2016, followed by Europe with 14 GW of installed capacity. There is now 140 GW of onshore wind capacity installed in the EU (WindEurope, 2017).

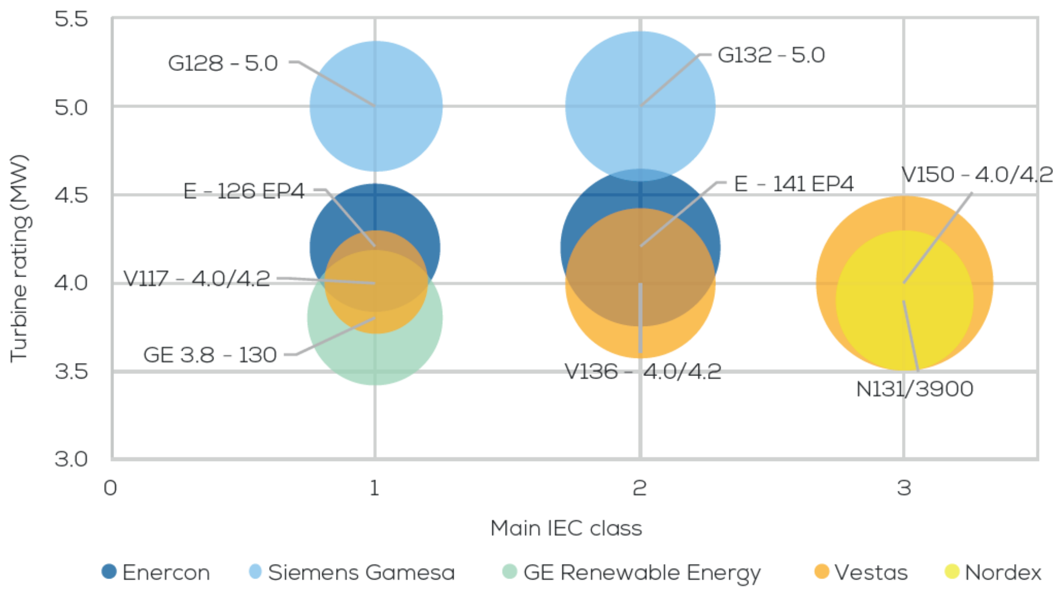
The European market is dominated by European wind turbine manufacturers and developers (see Figure 93).



	2008	2009	2010	2011	2012	2013	2014	2015	2016
Asia	8,320	15,507	21,481	20,981	15,624	18,252	26,058	33,962	27,721
Africa & Middle East	96	251	153	8	131	240	934	953	418
Europe	8,851	10,660	10,466	10,393	12,862	12,524	12,988	13,831	13,926
Latin America	128	471	459	771	1,248	1,240	3,744	3,678	3,079
North America	8,969	11,008	6,208	8,137	14,807	3,112	7,382	10,829	9,359
Pacific Region	482	578	294	345	358	655	568	381	140
	28,854	**38,475**	**39,061**	**40,635**	**45,030**	**36,023**	**51,674**	**63,634**	**54,642**

Source: GWEC

Figure 92 **Annual installed capacity by region 2008-2016 (GWEC, UTS:ISF, 2016).**



Source: WindEurope

Figure 93 Current onshore wind turbines in Europe for various IEC-classes (WindEurope, 2017)

Dependence of onshore wind energy

Most components for onshore wind farms are produced from traditional construction materials, such as steel and copper and concrete for foundations. Although the recent past has shown that these markets can become tight, it is not expected that supply of these materials will become critical. The same holds for the construction of wind turbine blades that use reinforced plastic or carbon materials. Although manufacturers have replaced production sometimes outside the EU, it is believed that this doesn't pose a critical dependency as manufacturing could easily be located in other manufacturing countries.

Material	Annual EU Demand *(in tons)*	
	2020	2030
Solar		
Tellurium	150	126
Indium	145	121
Gallium	4	3
Wind		
Neodymium-Praseodyium[a]	845	1.222
Dysprosium	58	84

[a] The report treats neodymium and praseodymium together, as they are not always separated out (Joint Research Centre, 2013, 76).

Figure 94 Projected demand of critical rare earth materials in EU wind and solar energy (European Commission Joint Research Centre Institute for Energy and Transport, 2013).

Between 2000 and 2004, permanent magnet generators (PMG) had an average share of 5% of all turbine prototypes (European Commission Joint Research Centre Institute for Energy and Transport, 2013). However, since 2007 this share has grown to 35%. In absolute numbers whereas PMG were included in one or two turbine prototypes per year in 2000-03; since 2010 they have been included in 11-13 turbine prototypes. The main reason for using permanent magnets, is that they are lighter and use less space than electromagnets. The permanent magnets require two essential materials, Neodymium and Dysprosium (European Commission Joint Research Centre Institute for Energy and Transport, 2013) (Rabe, Kostka, & Smith Stegen, 2017), see Figure 94. These are rare Earth elements with a very high rate of import reliance of 100%. The main producer is China (95%), while the most important importers and source of supply for these elements constitute China (40%), the USA (34%), and Russia (25%) (European Commission Joint Research Centre Institute for Energy and Transport, 2013). Europe depends on China for 90% of its Neodymium imports and 99% of its Dysprosium imports. There are possibilities to source Neodymium from countries other than China; replacements for Dysprosium are very limited as there are no locations available for the extraction (Rabe, Kostka, & Smith Stegen, 2017). For new onshore wind turbines, prototypes using electromagnets prevail. However, many current wind turbine models use permanent magnet generators, and their global market share still increases. The EU has realized this dependency and has developed initiatives to become less dependent on these materials for instance by changing the design of new turbines or extending the lifetime of currently installed turbines. Onshore turbines are less restricted by weight limitations than offshore wind turbines and are therefore less dependent on the use of permanent magnet generators.

13.1.2 Offshore wind energy

Description of technology

The deployment of offshore wind energy has developed rapidly in the EU, mainly in the North Sea, the Irish Sea, and the Baltic Sea, where favourable site conditions exist due to a high wind resource and relatively shallow water near the coast. Offshore wind farms can be built close to densely populated areas with high energy demand. The wind farms are close to major ports which is ideal for construction and operation & maintenance logistics. Offshore wind energy is starting to be developed in other areas as well (the USA, Taiwan), but in most other areas on the globe at least one of these favourable conditions is missing, hence decreasing the feasibility of offshore wind energy.

Recently the cost of generating offshore wind energy has decreased dramatically. A recent tender for offshore wind energy in Germany was won by parties who claim to be able to generate zero-subsidy electricity in 2025. In Denmark and the Netherlands similar bidding results were obtained.

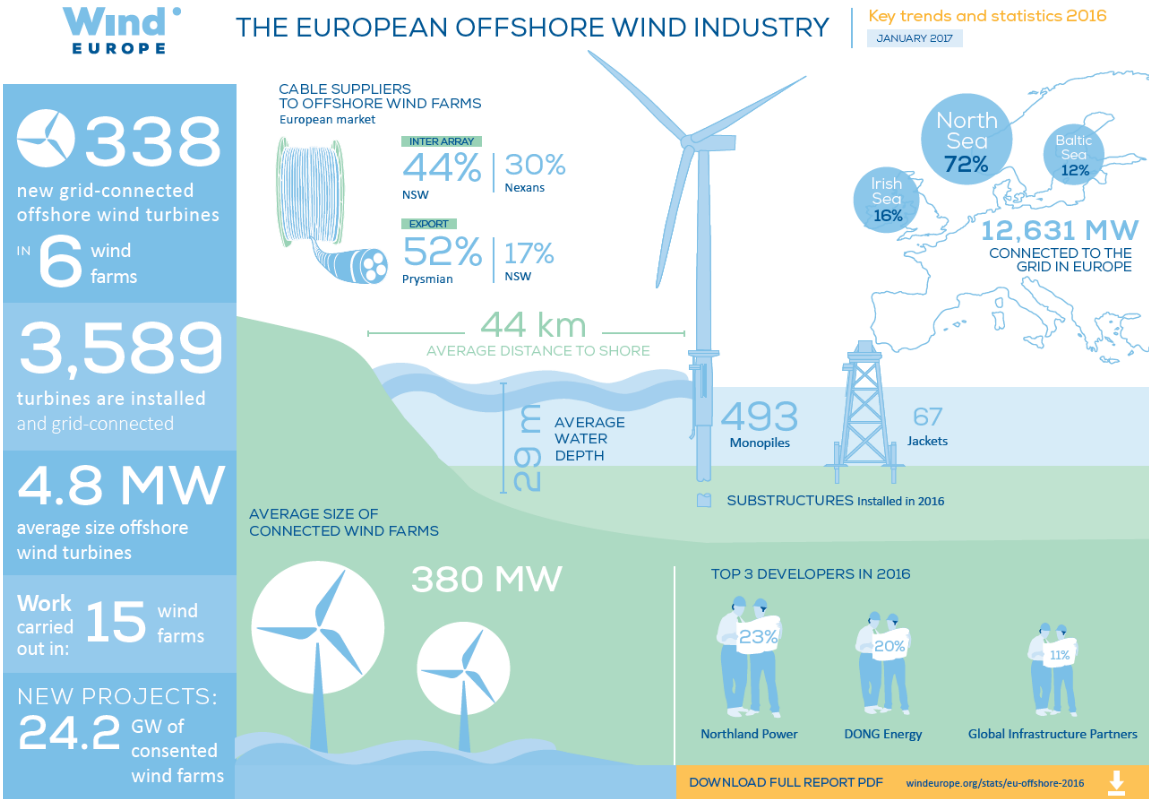


Figure 95 Key trends and statistics 2016 (Wind Europe, 2017)

Cost reduction is an important driver for technological development and innovation in offshore wind energy. Wind turbines have been developed with a rotor diameter of 180 m and a nominal power of more than 8 MW. Extra-large monopiles with diameters more than eight meters were developed to support these wind turbines. With the increase in scale of individual turbines, today an offshore wind farm consists of less turbines and foundations, thereby reducing the logistics of installation and operations & maintenance which is a significant driver for cost reduction. On the other hand, wind farms will be developed in deeper water at greater distances from the coast, which may partly cancel the ongoing cost reductions.

Issues of dependencies

The offshore wind turbine market is dominated by European based manufacturers (predominantly Siemens and MHIVestas).[22] No players from abroad have entered the European offshore market. Recently GE acquired Alstom, who developed an offshore wind turbine. Asian manufacturers have so far mainly focused on onshore wind turbines; Goldwind, however, is developing an offshore wind turbine.

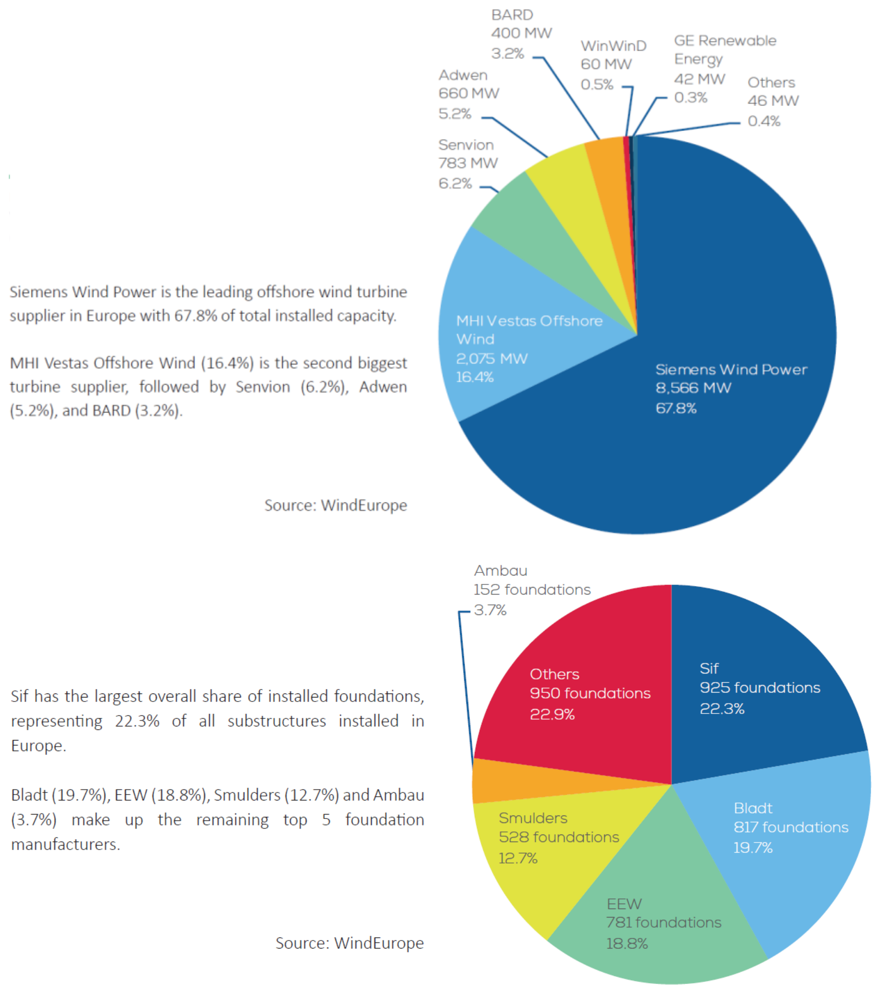


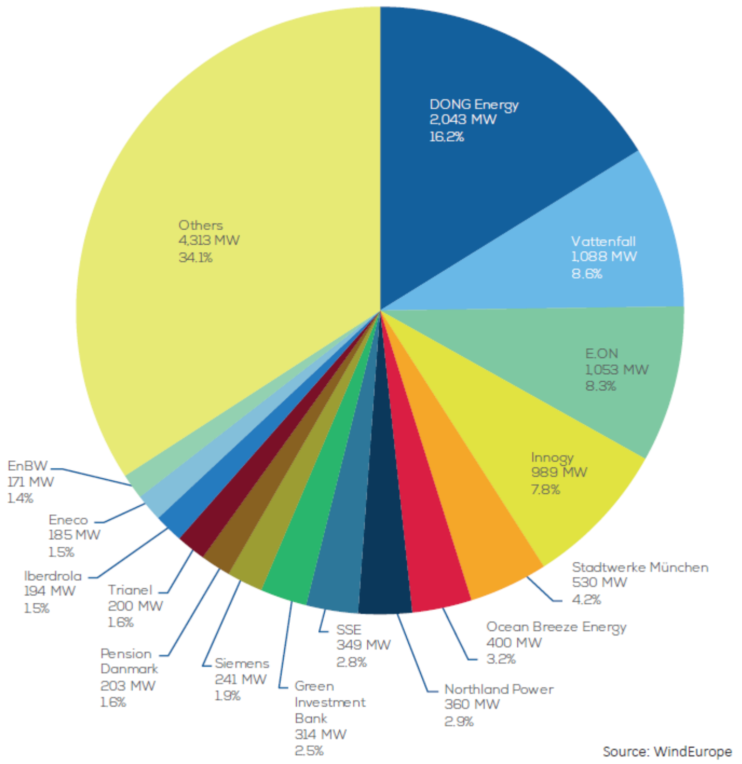
Figure 96 **Market shares of manufacturers in the EU market (Wind Europe, 2017)**

Foundations, substations, and cables are also constructed mainly by European manufacturers. Most export cables are produced by European manufactures, although some cables were produced in Asia.

There is a strong and competitive logistics market in Europe. Specialized installation vessels have been designed by offshore companies, who develop in the direction of offshore EPC providers for the total balance of plant and for the installation of wind turbines.

[22] MHIVestas is a joint venture of Japan's Mitsubishi Heavy Industries and Danish Vestas.

FIGURE 20
Owners' share of installed capacity (MW)



8. RWE rebranded to Innogy as of September 2016.

Figure 97 Developers of offshore wind farms (Wind Europe, 2017)

Development of offshore wind farms is dominated by European utilities. However, the ownership of offshore wind farms attracts international interest and recently North American and Asian parties have taken shares in offshore wind farms.

Most components for offshore wind farms are produced from traditional construction materials, such as steel and copper. Although the past has shown that during economic booms (before 2010) these markets can become tight and prices go up, it is not expected that supply of these materials will become critical (ed: Gasch & Twele, 2011), and therefore no critical reliance on import is identified for these materials. The same holds for the construction of wind turbine blades that use reinforced plastic or carbon materials. Although some manufacturers have moved production outside of the EU, it is believed that this doesn't pose a critical dependency (Navigant, 2013).

Offshore wind turbines must be built as light as possible. Therefore, permanent magnets are used for the construction of electric generators. As was already mentioned when describing critical essential materials for onshore wind turbines, permanent magnets are made of two essential materials, i.e. Neodymium and Dysprosium (European Commission Joint Research Centre Institute for Energy and Transport, 2013) (Rabe, Kostka, & Smith Stegen, 2017), which are both rare Earth elements with a reliance on import rate of 100%. The main producer of these materials is China (95%), while the main importers and sources of supply for the EU are China (40%), the USA (34%), and Russia (25%) (European Commission Joint Research Centre Institute for Energy and Transport, 2013). The EU has realized this dependency and has developed initiatives to become less dependent on these materials for instance by changing the design. However, the drive to lighter turbines especially for offshore wind turbines limits the choice of design and materials.

13.1.3 Conclusions

For wind turbine manufacturing the entire value chain has been considered and there are no critical dependencies other than stated below. Two variants have been investigated onshore and offshore wind turbines.

In general common construction materials are used that are not critical, such as steel, copper and concrete.

For the construction of generators, there is a growing market share for permanent magnet generators, with a critical dependency and a high reliance on import for rare earth materials (Neodymium and Dysprosium), for which the world market is limited and concentrated in China.

For onshore wind turbines, there are possibilities to adapt the design and make use of electromagnets, but offshore wind turbines have a great need for light weight components and therefore will rely on permanent magnets, including the use of mentioned rare earth elements. Permanent Magnets have a large market share for both wind energy variants (onshore and offshore), the volume of onshore turbines is bigger than the offshore variants. It is therefore concluded that both variants should be
assessed separately.

14 References

Abanades, J., Arias, B., Lyngfelt, A., Mattisson, T., Wiley, D., Li, H., . . . Brandani, S. (2015). Emerging CO2 capture systems. *International Journal of Greenhouse Gas Control, 40* , 126-166.

Ad hoc working group. (2014). *Report on critical raw materials for the EU.* European Commission.

Ad Hoc Working Group. (2014). *report on critical raw materials for the EU.* European Commission.

Adler, S. B. (2005). Fuel Cells: Current Status and Future Challenges. *The Bridge, 35*(4), 28-32.

AEBIOM. (2017). *Aebiom statistical report 2016.* Brussels: Aebiom.

Aktiengesellschaft, S. (2017, September 28). Wo/European Patent Patent No. WO 2017162513 A1.

al., P. e. (2017). Sustainable power generation with large gas engines . *Energy Conversion and Management 149*, pp. 1048-2065.

Alkaline Electrolyzer Segment to Record Higher Market Value Whereas PEM Segment to Exhibit Promising Growth. (2017, September 1). Retrieved from Markets Insider: http://markets.businessinsider.com/news/stocks/Alkaline-Electrolyzer-Segment-to-Record-Higher-Market-Value-Whereas-PEM-Segment-to-Exhibit-Promising-Growth-1002302265

Andritz. (2017). *Andritz hydro, large hydro*. Retrieved from https://www.andritz.com/resource/blob/33066/a089bcbebd4f45a38a2dba9fd09f8acb/hy-large-hydro-data.pdf

Andritz. (n.d.). *Research and development*. Retrieved from https://www.andritz.com/hydro-en/about-andritz-hydro/research-development

Azure International, E. S. (2017). *Energy Storage World Markets Report.*

Bailera, M., Espatolero, S., Lisbona, P., & Romeo, L. (2017). Power to gas-electrochemical industry hybrid systems: A case study. *Applied Energy, 202*, 435-446.

Baker Hughes. (2017). *Rig count Overview & Summary Count*. Retrieved from http://phx.corporate-ir.net/phoenix.zhtml?c=79687&p=irol-rigcountsoverview

Biernat, K., & Samson-Brek, I. (2011). Review of technology for cleaning biogas to natural gas quality. *Chemkin*, (65)5 435-444.

Bildea, C., Gyorgy, R., Brunchi, C., & Kiss, A. (2017). Optimal design of intensified processes for DME synthesis. *Computers and Chemical Engineering, 105*, 142-151.

BIO-TIC. (2015). The bioeconomy enabled, A roadmap to a thriving industrial biotechnology sector in Europe.

BIO-TIC. (2017, October 20). Retrieved from http://www.industrialbiotech-europe.eu/about-industrial-biotechnology/.

Bloomberg. (n.d.). Retrieved 10 12, 2017, from https://www.bloomberg.com/news/articles/2017-05-22/move-over-tesla-europe-s-building-its-own-battery-gigafactories

BNEF, M. L. (2017). *State of the Industry London Summit.* Bloomberg New Energy Finance.

Bos, C. (2017, October). Oil and gas upstream supply chain. (A. Wildenborg, Interviewer)

Boyce. (2006). Gas turbine engineering handbook, third ed.

BP. (n.d.). *BP Statistical review of world energy*. Retrieved from https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html

Bundesnetzagentur. (2017). *Ergebnisse der zweiten Ausschreibung für Wind an Land*. Retrieved 2017, from https://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/DE/2017/15082017_WindAnLand.html

Business Insider. (n.d.). Retrieved from http://www.businessinsider.com/countries-that-produce-the-most-steel-2011-7?international=true&r=US&IR=T#10-turkey-1

Carbon8. (2017). *http://c8s.co.uk*. Retrieved 10 26, 2017, from http://c8s.co.uk/carbon8-aggregates/

Carmo, M., Fritz, D. L., Mergel, J., & Stolten, D. (2013, April 22). A comprehensive review on PEM water electrolysis. *International Journal of Hydrogen Energy, 38*(12), 4901-4934.

Carrasco-Maldonado, F., Spörl, R., Fleiger, K., Hoenig, V., Maier, J., & Scheffknecht, G. (2016). Oxy-fuel combustion technology for cement production – State of theart research and technology development. *International Journal of Greenhouse Gas Control, 45*, 189-199.

CemBureau. (2017, October). *European Cement Association - Key facts and figures*. Retrieved from https://cembureau.eu/cement-101/key-facts-figures/

CEMBUREAU. (n.d.). *CEMBUREAU - Facts and figures*. Retrieved November 24, 2017, from https://cembureau.eu/cement-101/key-facts-figures/

Clixoo. (2015). Key Suppliers in Solar Thermal Power Value Chain and Venture Capital Companies.

Commision, E. (2017). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS on the 2017 list of Critical Raw Materials for the EU. Brussels: European Commission.

Commission, E. (2017, December). *2017 list of Critical Raw Materials for the EU.* Brussels: European Commission. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52017DC0490&from=EN

Commission, E. (2017). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions on the 2017 list of Critical Raw Materials for the EU. Brussels.

Commission, E. (2017). Communication from the Commission to the European Parliament, the Council, the European economic and Social Committee and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU. Brussels.

(2017). Communication from the commission to the european parliament, the council, the european economic and solcial committe and the committe of the regions on the 2017 list of critical raw materials for the EU. European Commission.
COMTRADE. (n.d.). Retrieved 10 26, 2017, from comtrade.un.org/data
CSPplaza.com. (17-01-2017). Retrieved from http://en.cspplaza.com/global-csp-installed-capacity-increased-to-5017-mw-by-the-end-of-2016.html
Curtin, S., & Gangi, J. (2014). *Fuel Cell Technologies Market Report 2014.* Washington, D.C.: Office of Energy Efficiency & Renewable Energy.
Curtin, S., & Gangi, J. (2015). *Fuel Cell Technologies Market Report 2015.* Washington, D.C.: Office of Energy Efficiency & Renewable Energy.
de Kler, R. (2017, October 25). Status of hydrogen and fuel cell technology. (L. Brunner, Interviewer)
Deloitte Sustainability; British Geological Survey; Bureau de Recherches Geologiques et Minieres; TNO. (2017). *Study on the review of the list of Critical Raw Materials.* European Commission.
Deloitte Sustainibility; British Geological Survey; Bureau de Recherches Geologiques et Mineres; TNO. (2017). *Study on the review of the list of critical raw materials - Critical Raw materials factsheet.* European Commission.
DiPippo, R. (2012). Geothermal power plants: principles, applications, case studies and environmental impact. Butterworth-Heinemann.
DOE. (2014). *2014 Hydropower market report.* Springfield: U.S. Department of Energy .
Dumas, P., J.D., V. W., Manzella, A., Nardini, I., Angelino, L., Latham, A., & Simeonova, D. (2011). *Towards more geothermal electricity generation in Europe.* European Geothermal Energy Council, Brussels, Belgium.
E3G. (n.d.). Retrieved from https://www.e3g.org/docs/E3G_Trends_EU_Gas_Demand_June2015_Final_110615.pdf
EASE/EERA. (2017). European Energy Storage Technology Development Roadmap for public consultation.
EC. (2016). *EU Reference Scenario 2016 - Main results.* Brussels: European Commission.
EC. (2017). *EC Critical Raw Materials*. Retrieved october 2017, from https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_nl
ed: Gasch, R., & Twele, J. (2011). Wind power plants: fundamentals, design, construction and operation. Springer.
EEA. (2017). Renewable Energy in Europe: Recent growth and knock-on effects.
EGEC. (2016). *Market Report 2015 - Fifth edition.* European Geothermal Energy Council, Brussels, Belgium.
EGEC. (2017). *2016 EGEC geothermal market report. Full report - Members Edition.* Brussels, Belgium.: European Geothermal Energy Council.
Ehimen, E. (2016). Chapter 14 – Algae biomass supply chains. In *Biomass Supply Chains for Bioenergy and Biorefining* (pp. 319-332). Woodhead Publishing.
EHPA. (2015). European Heat Pump Market and Statistics Report 2015 - Executive Summary. Brussels: EHPA.
EHPA. (2017a, December 21). *Energy sources*. Retrieved from www.ehpa.org: http://www.ehpa.org/technology/what-type-of-hp-for-what-use/
EHPA. (2017b, December 19). *Market data*. Retrieved from www.ehpa.org: http://www.ehpa.org/market-data/
Electric, G. (2017, October 4). *Where Turbines Are Born: An Inside Look at GE's Big Iron Maternity Ward*. (General Electric) Retrieved December 8, 2017, from https://www.ge.com/reports/turbines-born-inside-look-ges-big-iron-maternity-ward/
(2017). Electricity Storage and Renewables: Costs and Markets to 2030. International Renewable Energy Agency.
Elliot, D. C. (2016). Review of recent reports on process technology for thermochemical conversion of whole algae to liquid fuels. *Algal Research*, (13) 255-263.
Energy Voice . (2016). *North sea drilling at record low- spells end to regions revival*. Retrieved from https://www.energyvoice.com/oilandgas/north-sea/99551/north-sea-drilling-at-record-low-spells-end-to-regions-revival/
ENPlus. (2017, October 23). *ENPlus-pellets*. Retrieved from http://www.enplus-pellets.eu/
Ernst & Young, Fraunhofer ISE, Fraunhofer ISI. (2017). *Local Manufacturing Potential for CSP Projects in MENA.*
ESPON_EU. (2008). Retrieved October 2017, from http://mapfinder.espon.eu/?p=1381
ETIP. (2017, November 9). *Advanced technologies*. Retrieved from http://www.etipbioenergy.eu/value-chains/conversion-technologies/advanced-technologies
EU. (2017, October 31). *Critical raw materials*. Retrieved from https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_nl
EU statistics energy production and imports. (n.d.). Retrieved from http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_production_and_imports
Eubia. (2017, October 25). *Conversion routes - European Biomass Industry Association*. Retrieved from http://www.eubia.org/cms/wiki-biomass/conversion-route/
EUGINE. (n.d.). Retrieved from http://www.eugine.eu/engine-power-plants/facts-and-figures/index.html
EUGINE. (2015). Engine Power Plants Technology & Applications.
eurelectric. (2011). Hydro in Europe: Powering Renewables.
EurObserv'er. (2016). *Heat pumps barometer.* EurObserv'er. Retrieved December 19, 2017, from https://www.eurobserv-er.org/heat-pumps-barometer-2016/
EuroGeoSurveys Mineral Resources Expert group . (2014). *Minerals in your life.*
EuroGeoSurveys Mineral Resources Expert Group. (2014). *Minerals in Your Life.* Brussels: EuroGeoSurveys.
Euromines. (2014). Metal Ores & Industrial Minerals, Extractive Industry in Europe - Facts & Figures. European Association of Mining Industries.

European Biogas Association. (2011, 12). *Biogas can do it.* Retrieved 12 8, 2017, from http://european-biogas.eu/wp-content/uploads/files/2013/10/broschre_2011_en_versandversion.pdf
European Biogas Association. (2016, 1). *Leading companies in Biogas Technology.* Retrieved 12 8, 2017, from http://european-biogas.eu/wp-content/uploads/2016/06/Companies-Catalogue-2016-web.pdf
European Commision. (2014). Communication from the Commission of the European Parliament, Council, the European Economic and Social Committee of the Regions - On the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative.
European Commission. (2017). *2017 list of Critical Raw Materials for the EU .* Brussels: European Commission .
European Commission. (2017). Communication from the Commission of the European Parliament, Council, the European Economic and Social Committee of the Regions on the 2017 list of Critical Raw Materials for the EU.
European Commission. (2017, 10 10). *http://madb.europa.eu/madb/statistical_form.htm*. Retrieved from Trade Market Database: http://madb.europa.eu/madb/statistical_form.htm
European Commission. (n.d.). *Harnessing the full power of renewable energy with hydrogen*. Retrieved October 16, 2017, from Horizon 2020: http://ec.europa.eu/programmes/horizon2020/en/news/harnessing-full-power-renewable-energy-hydrogen
European Commission Joint Research Centre Institute for Energy and Transport. (2013). *Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector.* Petten: JRC Scientific and Policy Reports.
European_Commission, DG_R&I, & DG_E. (2017). Study on Lessons for Ocean Energy Development (final report+annexes). European Commission.
Eurostat. (n.d.). *Eurostat gas market indicators*. Retrieved from http://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_market_indicators
Eurostat. (n.d.). Prodcom Annual Data, NACE Rev. 2. European Commission. Retrieved October 17, 2017, from http://ec.europa.eu/eurostat/web/prodcom/data/excel-files-nace-rev.2
ExxonMobil. (2017, October 25). *Een supervette groen machine – EnergyFactor*. Retrieved from https://energyfactor.exxonmobil.com/science-technology/algen-biobrandstof/
FI-Powerweb. (n.d.). *Industrial and Marine gas and steam turbine market data*. Retrieved December 8, 2017, from http://www.fi-powerweb.com/Industrial-Marine-Gas-Steam-Turbines.html
Forsén, M., Roots, P., & Bertenstam, A. (2008). *Market status for ground source heat pumps in Europe.* GROUND-REACH. Retrieved December 21, 2017, from https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/ground-reach_market_status_for_gchp_in_europe.pdf
Fraile, D., Lanoix, J.-C., Maio, P., Rangel, A., & Torres, A. (2015). *Overview of the market segmentation for hydrogen across potential customer groups, based on key application areas.* CertifHy. Retrieved from http://www.certifhy.eu/images/D1_2_Overview_of_the_market_segmentation_Final_22_June_low-res.pdf
Fraunhofer ISE & NREL. (2015). CURRENT STATUS OF CONCENTRATED PHOTOVOLTAIC (CPV) TECHNOLOGY.
Fraunhofer ISE. (2017). *Photovoltaic report.*
Fu et al. (2015). Economic measurements of polysilicon for the photovoltaic industry: market competition and manufacturing competitiveness. IEEE Journal of Photovoltaics.
Fuel Cell Today. (2013). *Water Electrolysis & Renewable Energy Systems.* Fuel Cell Today. Retrieved from http://www.fuelcelltoday.com/media/1871508/water_electrolysis___renewable_energy_systems.pdf
Fuel Cell Today. (n.d.). *PEMFC*. Retrieved October 26, 2017, from Fuel Cell Today: http://www.fuelcelltoday.com/technologies/pemfc
Fuel Cells and Hydrogen Joint Undertaking. (2016). *Who We Are*. Retrieved from Fuel Cells and Hydrogen Joint Undertaking: http://www.fch.europa.eu
Fuel Cells and Hydrogen Joint Undertaking. (2017). Industry and research associations' position on EU Institutional Public Private Partnerships in Research and Innovation. Brussels: Hydrogen Europe Secretariat.
Fuel Cells Etc. (2013, March 8). *What is the Difference Between Carbon Paper and Carbon Cloth Based Gas Diffusion Layers (GDL)?* Retrieved October 26 2017, from Fuel Cells Etc: http://fuelcellsetc.com/2013/03/comparing-gas-diffusion-layers-gdl/
Fuel4Me. (2017). D5.7 Development of a full scale integrated microalgalbased process and potential scenarios.
G. V. Tomarov, A. A. (2015). Improving Geothermal Power Plants with a Binary Cycle. *Thermal Engineering 62, 12*, 878–885.
Gahleitner, G. (2013, February 19). Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. *International Journal of Hydrogen Energy, 38*(5), 2039-2061.
Galadima, A., & Muraza, O. (2015). From synthesis gas production to methanol synthesis and potential upgrade to gasoline range hydrocarbons: A review. *Journal of Natural Gas Science and Engineering, 25*, 303-316.
Gas in Focus. (n.d.). Retrieved from http://www.gasinfocus.com/en/indicator/imports-of-natural-gas-into-the-european-union/
GE. (n.d.). *State-of-the -art hydro-mechanical equipment to meet your needs*. Retrieved from https://www.gerenewableenergy.com/hydro-power/large-hydropower-solutions/hydro-mechanical-equipment
GEOELEC. (2017). *Database of deep drilling companies*. Retrieved from http://www.geoelec.eu/database-of-deep-drilling-companies/
GL, D. (2017). Safety, operation and performance of gridconnected, DNVGL-RP-0043.
Global CCS Institute . (2016). The Global Status of CCS: 2016. Volume 2: Projects, Policy and Markets. Melbourne, Australia.
Global CCS institute. (2016). *The global status of CCS.* Global CCS institute.

Global CCS Institute. (2016). The Global Status of CCS: 2016, Volume 3: CCS Technologies. Melbourne, Australia.
Global Oil and Gas Directory . (2017, October). Retrieved from http://www.oildir.com/ogdirectory/default.asp
gmtoday. (n.d.). Retrieved from http://www.gmtoday.com/news/local_stories/2016/06072016-GE-selects-canadian-site-for-waukesha-engine-operations.asp
Gökalp, İ., Uz, Emre, V., Saltan, M., & Tutumluer, E. (2017). Technical and Environmental Evaluation of Metallurgical Slags as Aggregate for. *Transportation Geotechnics, Accepted Manuscript*.
Greenpowerco. (2017, December 21). *www.greenpowerco.com.au*. Retrieved from Heat pump: http://greenpowerco.com.au/wp-content/uploads/2017/08/Ground-source-heat-pump.png
Greentech Media. (n.d.). Retrieved 10 12, 2017, from https://www.greentechmedia.com/articles/read/10-battery-gigafactories-are-now-in-progress-and-musk-may-add-4-more#gs.U9QGtaY
GTMResearch inverter concentration. (2016, november). *www.greentechmedia.com/research*. Retrieved from https://www.greentechmedia.com/research/report/the-global-pv-inverter-and-mlpe-landscape-h2-2016#gs.SYxwX=A
Gunning, P., & Hills, C. (2014). *gala.gre.ac.uk.* Retrieved 11 30, 2017, from http://gala.gre.ac.uk/13580/1/13580_Hills_Carbon_negative_first_commercial_application_%28conf._paper%29_AAM__2014.pdf
GWEC, UTS:ISF. (2016). *Global Wind Energy Outlook.* GWEC.
Hartmann, H. (2017, November 10). E-mail conversation. (M. Cremers, Interviewer)
Holstein, J. (2017, 12 7). Head of Section Gas Testing and Analysis DV GL.
Hopmans, P. (2017, October). Well supply chain. (A. Wildenborg, Interviewer)
Hydrogen Electrolyzer Market: Alkaline Electrolyzer Product Type Segment Projected to Account for over Half the Global Market Value During the Forecast Period: Global Industry Analysis 2012-2016... (2017, October 25). Retrieved from Markets Insider: http://markets.businessinsider.com/news/stocks/Hydrogen-Electrolyzer-Market-Alkaline-Electrolyzer-Product-Type-Segment-Projected-to-Account-for-over-Half-the-Global-Market-Value-During-the-Forecast-Period-Global-Industry-Analysis-2012-2016-1005618942
Hydropower, V. (n.d.). *Cutting-edge technology from Voith*. Retrieved from http://www.voith.com/ca-en/markets-industries/hydro-power/corporate-technology-549.html
ICDA. (2017, October). *International Chromium Development Association*. Retrieved from http://www.icdacr.com
IEA. (2012). Technology Roadmap, Bioenergy for heat and power. International Energy Agency.
IEA. (2014). Technology Roadmap Energy Storage.
IEA_Task_32. (2015). Status overview of torrefaction technologies - A review of the commercial status of biomass torrefaction. IEA Bioenergy Agreement - Task 32.
IEA-ETSAP and IRENA. (2016). *Wind Power Technology Brief E07.* IEA-ETSAP and IRENA.
IEA-ETSAP, I. (2015). Hydropower: Technology Brief.
IEE SOLCO project. (2009). Removal of non-technological barriers to Solar Cooling technology across southern European islands.
IFC. (n.d.). Hydroelectric Power: A guide for developers and investors.
Intelligent Energy Europe, S. S. (2013). *Biomethane guide for decision makers.* Oberhausen: Fraunhofer UMSICHT, research group biogas technology.
International Energy Agency. (2016). 20 Years of Carbon Capture and Storage - Accelerating Future Deployment. www.iea.org.
Investing News. (n.d.). Retrieved 10 12, 2017, from https://investingnews.com/daily/resource-investing/critical-metals-investing/cobalt-investing/top-cobalt-producing-countries-congo-china-canada-russia-australia/
Investing News. (n.d.). Retrieved 10 12, 2017, from https://investingnews.com/daily/resource-investing/critical-metals-investing/cobalt-investing/top-cobalt-producing-countries-congo-china-canada-russia-australia/
Investing News. (n.d.). Retrieved 10 12, 2017, from https://investingnews.com/daily/resource-investing/agriculture-investing/phosphate-investing/top-phosphate-producing-countries/
IRENA. (2013). Thermal Energy Storage Technology Brief.
IRENA. (2014). *Ocean Energy: .* IRENA.
IRENA. (2014). Ocean Thermal Energy Conversion. IRENA.
IRENA. (2014). *Salinity gradient energy.* technology brief.
IRENA. (2014). *Tidal Energy.* IRENA.
IRENA. (2014). *Wave Energy.* IRENA.
IRENA. (2015). *Globalwindatlas.com*. (DTU) Retrieved 2017, from https://irena.masdar.ac.ae/GIS/irena.html?map=103
IRENA. (2016). The Power to Change: Solar and Wind Cost Reduction Potential to 2025. Masdar: IRENA.
Irena. (2017). Rethinking energy.
IRENA CSP Brief. (2013). Concentrated Solar Power - Technology Breif.
ITA. (2017). *Global Steel Trade Monitor.* Washington D.C.: International Trade Administration.
Jadhav, S., Vaidya, P., Bhanage, B., & Joshi, J. (2014). Catalytic carbon dioxide hydrogenation to methanol: A review of recent studies. *Chemical Engineering Research and Design, 92*, 2557-2567.
Jäger-Waldau. (2016). *PV status report 2016.*
Jäger-Waldau. (2017). Snapshot of Photovoltaics—March 2017.
Jansen, D., Gazzani, M., Manzolini, G., van Dijk, E., & Carbo, M. (2015). Pre-combustion CO2 capture. *International Journal of Greenhouse Gas Control*, 168-169.
Jenbacher Engine Parts. (n.d.). Retrieved from https://www.gepower.com/services/jenbacher/parts

Jones, D. (2017). *Perfluorosulfonic Acid Membranes for Fuel Cell and Electrolyser Applications.* Sigma-Aldrich (Merck). Retrieved October 24, 2017, from http://www.sigmaaldrich.com/technical-documents/articles/materials-science/perfluorosulfonic-acid-membranes.html
Journals, B. (2017, November 16). *Big cuts in Siemens gas turbine business could be felt in Charlotte*. (Charlotte Business Journal) Retrieved December 8, 2017, from https://www.bizjournals.com/charlotte/news/2017/11/16/big-cuts-in-siemens-gas-turbine-business-likely-to.html?s=print
JRC. (2014). *JRC Geothermal energy status report .* Luxembourg: Publications Office of the European Union.
JRC Scientific and policy reports. (2013). *Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector.* Luxembourg: Publications Office of the European Union.
KL Energy Publishing . (2016). Retrieved from http://www.klenergypublishing.com/north-sea-rig-market/4583559723
Koytsoumpa, E. I., Bergins, C., & Kakaras, E. (2017). The CO2 economy: Review of CO2 capture and reuse technologies. *The Journal of Supercritical Fluids, In Press, Corrected proof*.
Kuppler, J., Atakan, V., Smith, K., & Hu, X. (2015, December 29). *United States of America& Canada Patent No. US 9221027 B2.*
Lab, E. (2016). EU28: Reference scenario.
Laboratories, S. N. (n.d.). *DOE Global Energy Storage Database*. Retrieved from http://www.energystorageexchange.org/projects
Larminie, J., & Dicks, A. (2003). *Fuel Cell Systems Explained* (2nd ed.). West Sussex: John Wiley & Sons Ltd.
Li, B., Duan, Y., Luebke, D., & Morreale, B. (2013). Advances in CO2 capture technology: A patent review. *Applied Energy, 102*, 1439-1447.
Maclaurin, D., & Slater, S. (2007). Hydrogen and Fuel Cells - A Handbook for Communities, Volume A: Introduction. Roads2HyCom.
Madehow. (2017, December 19). *Heat pump*. Retrieved from www.madehow.com: http://www.madehow.com/Volume-3/Heat-Pump.html
Maisonnier, G. (2007). PART II: Industrial surplus hydrogen and markets and production. Roads2HyCom.
Major Potassium Hydroxide Facilities are Located in APAC, Americas and Europe. (2015, February 27). Retrieved from Merchant Research & Consulting Ltd.: https://mcgroup.co.uk/news/20150227/major-potassium-hydroxide-facilities-located-apac-americas-europe.html
Masih, A., Albinali, K., & DeMello, L. (2010). Price dynamics of natural gas and the regional methanol markets. *Energy Policy, 38*, 1372-1378.
Mauthner, F., Weiss, W., & Spörk-Dür, M. (2016). Solar Heating Worldwide - Markets and Contribution to the Energy Supply 2014. IEA.
Metz, B., Davidson, O., Coninck, H. C., Loos, M., Meyer, L. A., & (eds.). (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
Milburn, S. M., & Adamson, K.-A. (2012). *Executive Summary: The Fuel Cell Stack Supply Chain.* Boulder: Pike Research.
Mordor Inteligence. (2017, November). Retrieved from http://blog.mordorintelligence.com/top-10-oilfield-and-drilling-services-companies/
Moss, R. T. (2011). Cristial metals in strategic energy technologies. European commission.
Moss, R. T. (2013). Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector. European Commission.
Moss, R., & Tzimas, E. (2013). Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector, Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies. Joint Research Centre.
Muktinutalapati, N. R. (2011). Materials for Gas Turbines - An Overview.
Navigant. (2013). U.S. Offshore Wind Manufacturing and Supply Chain Development.
News, I. (n.d.). Retrieved from https://investingnews.com/daily/resource-investing/critical-metals-investing/cobalt-investing/top-cobalt-producing-countries-congo-china-canada-russia-australia/
Nikam, A. (2017, October 23). *Sodium Hydroxide Market Global Industry Analysis, Trends and Forecast, 2017-2027*. Retrieved from Find Market Research: http://www.findmarketresearch.org/2017/10/sodium-hydroxide-market-global-industry-analysis-trends-and-forecast-2017-2027/
Niven, R., Monkman, G., & Forgeron, D. (2017, 8 30). *United States & Canada Patent No. US 8845940 B2.*
Ocean_Energy_Forum. (2016). Ocean Energy Strategic Roadmap, Building Ocean Energy for Europe. Ocean Energy Forum.
OEC. (2017, October 25). *OEC – Activated carbon*. Retrieved from http://atlas.media.mit.edu/nl/profile/hs92/3802/#Exporters
Office of Energy Efficiency & Renewable Energy. (2013, August 14). *Hydrogen Fuel Basics*. Retrieved October 16, 2017, from Energy.gov: https://energy.gov/eere/energybasics/articles/hydrogen-fuel-basics
Office of Energy Efficiency & Renewable Energy. (2016). *Types of Fuel Cells*. Retrieved from Energy.gov: https://energy.gov/eere/fuelcells/types-fuel-cells
Oil Conservation Division . (2017, October). *Oil and gas Education*. Retrieved from http://www.emnrd.state.nm.us/OCD/education.html
Park, S., & Popov, B. N. (2011, January). Effect of a GDL based on carbon paper or carbon cloth on PEM fuel cell performance. *Fuel, 90*(1), 436-440.
Peighambardoust, S., Rowshanzamir, S., & Amjadi, M. (2010, September). Review of the proton exchange membranes for fuel cell applications. *International Journal of Hydrogen Energy, 35*(17), 9349-9384.
Perez. (2009). A fundamental look at the energy reserves for the planet. IEA/SHC SOLAR UPDATE.
Pires, J. C. (2017). COP21: The algae opportunity. *Renewable and Sustainable Energy Reviews*, (79) 867-877.

POWERTECH, V. (n.d.). Hydropower: Part of the Renewable Family.
PVPS. (2016). *Trends in 2016.* IEA.
Rabe et al. (2017). China's supply of critical raw materials: Risks for Europe's solar and wind industies? Elsevier.
Rabe, W., Kostka, G., & Smith Stegen, K. (2017). China's supply of critical raw materials: Risks for Europe's solar and wind industries? *Energy Policy, 101*, 692-699.
Ray Moss and Evangelos Tzimas (Institute for Energy and Transport, J. P. (2013). *Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector.* Luxembourg: Luxembourg: Publications Office of the European Union.
REN21. (2017). Global Status Report.
(2017). Rethinking Energy 2017 - Accelerating the global energy transmission. International Renewable Energy Agency.
Sakai, Y. (2004). SCC Growth behavior of materials for geothermal steam turbines. *Corrosion Engineering* , 175-185.
Samer, M. (2012). M. Samer (2012). Biogas Plant Constructions, Biogas, Dr. Sunil Kumar (Ed.), ISBN: 978-953-51-0204-5,. In *Biogas Plant Constructions.* InTech, Available from: http://www.intechopen.com/books/biogas/biogas-plant-constructions.
Siemens. (n.d.). *Siemens expands global manufacturing network for gas turbines*. (Siemens) Retrieved December 8, 2017, from https://www.siemens.com/press/en/events/2011/energy/2011-11-charlotte.php
Solar Power Europe. (2017). Global Market Outlook for solar power 2017-2021.
Solidia Technologies, . (2017). Retrieved 10 26, 2017, from http://solidiatech.com/applications/
Sousa, G. (2017, April 25). *The Top Platinum Producing Countries In The World*. Retrieved from WorldAtlas: http://www.worldatlas.com/articles/the-top-platinum-producing-countries-in-the-world.html
Sreedhar, I., Nahar, T., Venugopal, A., & Srinivas, B. (2017). Carbon capture by absorption – Path covered and ahead. *Renewable and Sustainable Energy Reviews, 76*, 1080-1107.
Sreedhar, I., Vaidhiswaran, R., Kamani, B., & Venugopal, A. (2017). Process and engineering trends in membrane based carbon capture. *Renewable and Sustainable Energy Reviews, 68*(1).
Statista. (n.d.). Retrieved 10 12, 2017, from https://www.statista.com/statistics/268790/countries-with-the-largest-lithium-reserves-worldwide/
Statista. (n.d.). Retrieved 10 12, 2017, from https://www.statista.com/statistics/235323/lithium-batteries-top-manufacturers/
Statista. (n.d.). Retrieved from https://www.statista.com/statistics/267364/world-cement-production-by-country/
Statista. (n.d.). *Iron ore mine production worldwide by country from 2010 to 2016 (in million metric tons)**. Retrieved 2016, from Statista: https://www.statista.com/statistics/267380/iron-ore-mine-production-by-country/
(2017). Study on the review of the list of Critical Raw Materials. European Commission.
Sun&Wind Energy. (2015). World Map of the Solar Thermal Industry.
Task33, I. (2017, November 9). *IEA Bioenergy Agreement: Task 33*. Retrieved from http://task33.ieabioenergy.com/content/publications/Fact%20sheets
Tata Steel. (2017). *Nickel-plated steel*. Retrieved October 24, 2017, from Tata Steel: https://www.tatasteeleurope.com/en/products-and-services/flat/electro-plated/nickel-plated/nickel-plated
Technavio. (2017, December 19). *Global Heat Pump Market 2016-2020*. Retrieved from www.technavio.com: https://new.technavio.com/report/global-tools-and-components-global-heat-pump-market-2016-2020
The Global CO2 initiative. (2016). *Global Roadmap for implementing CO2 Utilisation.* The Global CO2 initiative.
Theo, W. L., Lim, J. S., Hashim, H., Mustaffa, A. A., & Ho, W. S. (2016). Review of pre-combustion capture and ionic liquid in carbon capture. *Applied Energy, 183*, 1633-1663.
Thermal barrier coatings. (n.d.). Retrieved from https://en.wikipedia.org/wiki/Thermal_barrier_coating
Transparency Market Research. (n.d.). *Yttria-stabilized Zirconia (YSZ) Market - Global Industry Analysis, Size, Share, Growth, Trends and Forecast 2017 - 2025*. Retrieved October 26, 2017, from Transparency Market Research: https://www.transparencymarketresearch.com/yttria-stabilized-zirconia-market.html
Trinomics. (2017). *Assessment of Photovoltaics (PV).* European Commission.
Tzimas, E., Georgakaki, A., Cortes, C. G., & Peteves, S. (2005). *Enhanced Oil Recovery using Carbon Dioxide in the European Energy System.* Petten, The Netherlands: DG JRC, Institute for Energy.
UN. (2017, December 19th). *UN Comtrade Database*. Retrieved from Comtrade.un.org: https://comtrade.un.org/
UN Comtrade Database . (2017, October). Retrieved from https://comtrade.un.org/
United Nations. (2017, November 27). *UN Comtrade Database*. Retrieved from Comtrade.un.org: https://comtrade.un.org/
United Nations Trade Statistics. (n.d.). UN Comtrade Database. United Nations. Retrieved October 18, 2017, from https://comtrade.un.org/data
USGS. (n.d.). Retrieved 10 12, 2017, from https://minerals.usgs.gov/minerals/pubs/commodity/silicon/mcs-2017-simet.pdf
Valmet. (2017, November 9). *Valmet CFB gasifier for biomass and waste*. Retrieved from http://www.valmet.com/energyproduction/gasification/
van Breevoort, P., Koornneef, J., Hendriks, C., Hulsman, A., Noothout, P., & de Visser, E. (2011). *Barriers to implementation of CCS - Capacity Constraints.* Ecofys.
VentureRadar. (n.d.). *Top SOFC Companies*. Retrieved October 25, 2017, from VentureRadar: https://www.ventureradar.com/keyword/sofc

VGB. (2017). Retrieved 2017, from https://www.vgb.org/en/_hydro_download.html?dfid=83974
Viessmann. (2017, December 21). *Vitocal 300-A – efficient heating with air*. Retrieved from www.viessmann.co.uk: https://www.viessmann.co.uk/en/residential-buildings/heat-pumps/air-source-heat-pumps/vitocal-300-a.html
Viklund, P. (2013). Superheater corrosion in biomass and waste fired boilers. Sockholm: Doctoral Thesis, KTH.
VVD, CDA, D66 & ChristenUnie . (2017). Vertrouwen in de toekomst - Regeerakkoord 2017 – 2021 (Netherlands Coalition Agreement).
Wang, Y., Chen, K. S., Mishler, J., Cho, S. C., & Adroher, X. C. (2011, April). A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research. *Applied Energy, 88*(4), 981-1007.
Wärtsilä. (n.d.). *Materials*. Retrieved from https://www.wartsila.com/sustainability/environmental-responsibility/products-and-environmental-aspects/materials
Wideskog, M. (2017). Introducing the world's largest gas engine. Wärtsilä.
Wilson, M. (2016, September). *Why the Chinese are buying European waste assets*. Retrieved from CATALYST: http://www.catalystcf.co.uk/thinking/why-the-chinese-are-buying-european-waste-assets
Wind Europe. (2017). The European offshore wind industry - Key trends and statistics 2016.
WindEurope. (2017). *Wind in Power - 2016 European statistics.* Brussel: Wind Europe.
(2016). *World Energy Outlook 2016.* International Energy Agency.
(2016). *World Energy Resources.* World Energy Council.
(2016). World Energy Resources E-Storage. World Energy Council.
Zarrouka, S. &. (2015). Geothermal steam-water separators: Design overview. *Geothermics 53*, 236-254.
Zhang, D., Ghouleh, Z., & Shao, Y. (2017). Review on carbonation curing of cement-based materials. *Journal of CO2 Utilization, 21*, 119-131.
Zirconium. (n.d.). Retrieved from https://en.wikipedia.org/wiki/Zirconium
Zuo, C., Liu, M., & Liu, M. (2012). Solid Oxide Fuel Cells. In M. Aparicio, & L. C. Klein (Eds.), *Sol-Gel Processing for Conventional and Alternative Energy* (pp. 7-36). New York: Springer.
姜坤, 张. 黄. (2015, December 16). China Patent No. CN 105154128 A.

Appendice – A2 Full Dataset

(Sub-)family	EU (MW)		World (MW)		Knowledge position		
	Current installed capacity	Net capacity additions until 2030	Current installed capacity	Net capacity additions until 2030	EU share of EPA patent applications	EU share of global patent families	EU share of publications
Solar - Photovoltaic	100,414	49,436	290,791	658,426	36%	9%	25%
Solar - Concentrated solar power	2,308	2,569	4,873	29,376	59%	17%	38%
Solar - Heating & cooling	34,357	84,541	416,675	297,049		24%	31%
Wind - Onshore	141,814	97,123	452,424	590,430	69%	29%	54%
Wind - Offshore	12,469	19,851	14,081	62,192			47%
Hydro - Run-of-river	79,613	6,075	1,102,313	379,088	64%	13%	24%
Hydro - Reservoir	42,585						
Hydro - Pumped storage	37,364		140,648				
Biomass - Thermochemical (combustion - solid fuels)	409,953	127,000	3,388,266	223,606	56%	21%	40%
Biomass - Biochemical (biogas and liquids)	42,047		288,582		42%	13%	
Geothermal - High enthalpy (dry steam and flash steam)	814	945	12,628	18,651	50%	14%	35%
Geothermal - Low enthalpy (Binary-ORC)	64						
Ocean - Wave	Negligible	2,513	Negligible	5,299	57%	22%	33%
Ocean - Tidal	248		537				
Ocean - Salinity	Negligible		Negligible				
Ocean - OTEC	Negligible		Negligible				
Hydrogen & fuel cells - Renewable hydrogen	Negligible	Negligible / Uncertain	Negligible	Negligible / Uncertain	36%	22%	21%
Hydrogen & fuel cells - Proton-exchange membrane fuel cells							
Hydrogen & fuel cells - Solid oxide fuel cells							
Storage - Batteries	350	2,650	1,400	12,600	28%	11%	20%
CO2 Capture - All variants	Negligible	1,083	Negligible	Uncertain	38%	13%	33%
CO2 Storage - All variants	Not applicable	Not applicable	Not applicable	Not applicable			
CO2 Reuse - Carbonate mineralisation	Not applicable	Not applicable	Not applicable	Not applicable	Not available		26%
CO2 Reuse - CCU fuels	Not applicable	Not applicable	Not applicable	Not applicable	Not available		
Flexible conventional - Gas engines	212,280	79,512	1,562,558	699,818	Not available	Not available	31%
Flexible conventional - Gas turbines					Not available	Not available	33%
Heat pumps - Air-source	30,000	26,000	84,000	76,000	Not available	24%	29%
Heat pumps - Ground-source					Not available		

Appendice – A3 Broad Brush assessment step-by-step manual

TABLE OF CONTENT

1 Introduction

This manual provides step-by-step instructions for undertaking part of the Energy Technology Dependence (ETD) assessment which has been developed for DG RTD under Framework Contract PP-02161-2014. The ETD assessment consists of two parts: a broad brush assessment and a detailed assessment. This document is the broad brush assessment step-by-step manual. The detailed assessment step-by-step manual can be found in *Task 4 report.*

The **aim** of the broad brush assessment step-by-step manual is to standardise a broad analysis of all energy technology families/variant listed in Table 62 against indicators of critical dependence, EU security of supply and EU leadership in renewables.

The overall **objective** of the broad brush assessment is to gain an understanding of the critical dependency issues which create the conditions for potential threats to European energy technology interests, defined as:

- Increasing the cost of meeting European climate and energy objectives;
- Reducing productivity and employment in the European energy industry;
- Limiting the potential for European technology leadership.

Furthermore, the overall **objective** is also to select which energy technology families/variants should be subject to an in-depth assessment (Task 4).

The overall **tasks** of the broad brush assessment are to:

- Identify critical dependency elements for each energy technology family/variant and report in summary papers. This will be carried out in stage 1;
- Gather data on energy technology family/variant installed capacity, patents and publications. This will be carried out in stage 2;
  Select energy technology families/variants which are most important in terms of risk to EU energy security of supply and in terms of potential for EU leadership. This will be carried out in stage 3.

The **outputs** of this analysis are detailed in the overview section of each stage in the report below. Overall, task 3 will provide recommendation for energy technology families/variants to proceed to an in-depth assessment (Task 4 – detailed assessment).

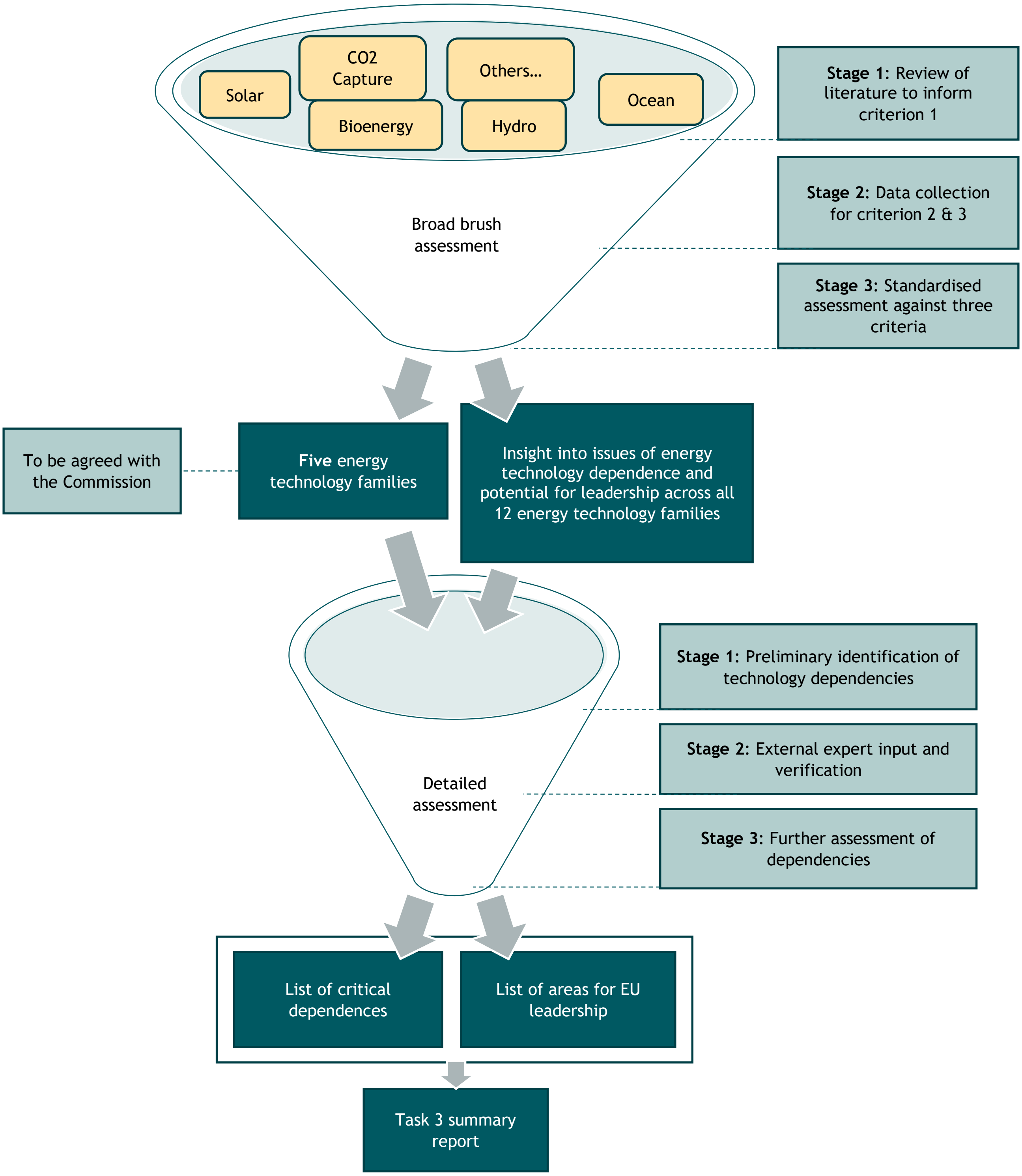
Table 62 Energy technology families (and their variants)

Energy technology families	Variants of the energy technology families
Solar Energy	Photovoltaic
	Concentrated solar power
	Solar Heating & Cooling
Wind Energy	Onshore
	Offshore
	Floating offshore
Hydropower	Large
	Small
Bioenergy	Biochemical
	Thermochemical
	Algae
	Enzymes
Geothermal Energy	Dry steam
	Flash steam
	Binary steam
	Enhanced geothermal
Ocean Energy	Wave
	Tidal
	Marine
	Ocean thermal conversion
Renewable energy for Hydrogen & Fuel Cells	
Energy storage linked to renewable energy systems	Heat
	Mechanical
	Chemical
	Electrical
CO2 capture	Pre-combustion
	Post-combustion
	Oxy-fuel combustion
CO2 storage	Depleted gas and oil fields
	Deep saline aquifers
	Enhanced hydrocarbon recovery
CO2 Utilization	
Flexible conventional thermal power plants	

2 Overview of assessment process

The overall energy technology dependence assessment methodology is illustrated in Figure 98.

Figure 98 Summary of energy technology dependence assessment methodology



3 Criteria and indicators

Each energy technology family (or variants) will be assessed against the three criteria in Table 63. Indicators for each criterion are listed in the table below.

Table 63 Broad brush assessment criteria and indicators

Criterion	Indicators/input	Expected insight into the...
Critical dependence (criterion 1)	Summary paper, for each energy technology family, covering reliance on non-EU supply and market concentration.	Threat of supply disruptions for the EU.
EU security of energy supply (criterion 2)	Indicator 2.1: Energy technology installed capacity / EU total installed capacity.	Importance of the technology for meeting EU's day-to-day energy needs.
	Indicator 2.2: Expected rate p.a. of EU net capacity additions.	Volumes that the EU needs to buy.
EU technology leadership (criterion 3)	Indicator 3.1: Energy technology installed capacity / global total installed capacity.	Importance of the technology for meeting the world's day-to-day energy needs.
	Indicator 3.2: Expected rate p.a. of global net capacity additions.	Volumes that the world needs to buy.
	Indicator 3.3: EU % share of global publications.	EU knowledge position.

4 Broad Brush assessment

The broad brush methodology consists of three stages:

Stage 1: Prepare energy technology family summary papers

Stage 2: Select data for criterion 2 and 3 indicators

Stage 3: Prioritise energy technology families (or variants)

This manual provides guidance on how to undertake the assessment including methods, techniques and sources. Assessment templates for the broad brush are indicated in this document using *italics* with more detail provided in section 4. The key responsibilities and outputs are summarised in Figure 99.

Figure 99 Broad brush assessment overview

	Summary of key outputs	Summary of key responsibilities
Stage 1: Energy technology family summary papers	**Summary Papers: Prepare an approximately 1,500 word (plus figures and charts) summary paper for each of the energy technology families. Each summary paper must adequately cover the two key topics relevant to critical dependence (criterion 1):** **• reliance on non-EU supply** **• market concentration** **Summary papers will be based on literature review and expert interviews where required.** **Literature tracker and results template: Keep a record of the literature review and populate tracker with search history and search results. Score each source in terms of credibility and relevance.**	Each summary paper should be produced by one person with expertise in the subject area. Experts may need to carry out external interviews to develop a complete summary paper (step 3). One reviewer will review all summary papers (step 4). This person should have a general understanding of all energy technologies.
Stage 2: Select data for criterion 2 and 3 indicators	**Populated broad brush data set template: with data for each of the criterion 2 and criterion 3 indicators. Notes on sources used and key assumptions should also be included in the data set template.** **Raw data sets** should be retained. **Add to results template** using the literature review tracker and the final data sets. This will include written summary of key stage 2 findings, presentation of final data sets, and explanation of data sources and any key assumptions.	This stage can be carried out by one or more data experts to create a consistent data set across all energy technology families (or variants), where ever possible. Each technology expert (from stage 1) will verify the final data set collated for their energy technology family.
Stage 3: Identify priority energy technology families	**Table of results** ranking each energy technology family (or variant) against the three criteria based on its overall priority in terms of critical dependency, energy security and EU leadership. **Selection of five energy technologies** which will proceed to the detailed assessment. Explanation should be provided on key differences between each of the energy technology families (or variant) including commentary on 1) potential areas for EU leadership 2) areas where mitigation measures and policy interventions should be targeted.	Two to three experts should first review each of the energy technology summary papers. They should provide a score for each energy technology family (or variant) against criterion 1. The same experts should rank each energy technology family, based on assessment against the three criteria, and suggest the five energy technologies which should proceed to detailed assessment. The results from each expert assessment can be compared and a final recommendation determined.

4.1 Stage 1 – Energy technology family summary papers

Overview

Figure 100 Summary of stage 1 key outputs

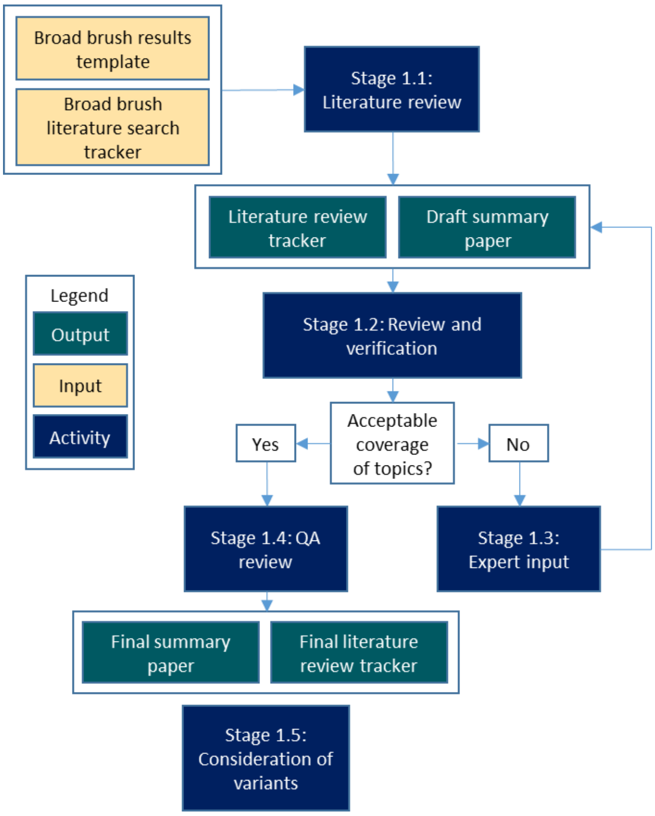
Summary Papers: prepare an approximately 1,500 word (plus figures and charts) summary paper for each of the energy technology families. Each summary paper must adequately cover the two key topics relevant to critical dependence (criterion 1): reliance on non-EU supply and market concentration. Summary papers will be based on literature review and expert interviews where required.

Literature tracker: Keep a record of the literature review and populate tracker with search history and search results. Score each source in terms of credibility and relevance.

The overall purpose of stage 1 is to build an understanding of the issues of EU reliance on non-EU supply and market concentration, with regard to each energy technology family. These issues should be communicated in summary papers for each energy technology family.

The purpose of each summary paper is to inform the assessment and comparison (against criterion 1 only) of each energy technology family, which will be carried out in stage 3.

Figure 101 Stage 1 process diagram



Summary papers should be produced in a consistent manner across all energy technology families to aid a robust comparison; guidance is provided in the steps below as well as templates (*broad brush results template* and *literature search tracker).*

It is important that all key literature is included in the assessment and that the credibility of the literature is considered and transparently recorded through the use of the literature search tracker.

It is expected that there will be variation between the extent, quality and credibility of available literature across the energy technology families. Weak evidence can be supported by expert input (stage 1.3).

It should be determined whether variants of an energy technology family should be assessed separately (in stage 3) or whether they can be assessed as one energy technology family. Assessing variants as one energy technology family will reduce the work required to carry out stage 2 and 3. Refer to stage 1.4.

Figure 101 illustrates the process that will be carried out for each energy technology family.

It is suggested that for each energy technology family stage 1.1, 1.2 and 1.3, as seen in Figure 101 are led by one expert, and that this is an expert on the subject matter. The following subsections provide guidelines for carrying out stage 1.

Stage 1.1 – Literature review

C**arry out a literature review and produce a draft summary paper** for each energy technology family. Summary papers for each energy technology should be written in the appropriate section of the *broad brush results template (*see section **Error! Reference source not found.***).*

Search for literature using the search engines, databases and any relevant organisational websites listed in Table 64. For each of the search engines and databases, use all of the key search terms listed in Table 65. Using the standard set of key search terms (Table 65) and all search engines and data bases listed in Table 64 should ensure that the extent of the search for literature is consistent across each of the energy technology families. Additional routes to information and search words may be used as necessary e.g. if there is unacceptable coverage of topics (see stage 1.2).

Table 64 Search /engines, websites and databases

Routes to information	Examples from those used in pilot
Search engines	Google scholar Google or equivalent
Data base	Science direct
Relevant trade associations	IEA JRC GWEC (relevant to offshore wind) WindEurope ((relevant to offshore wind)
Relevant institutions	
Relevant consultancies	Navigant (BTG)
Relevant businesses	

Table 65 Search phrases/terms

Search terms	Example for search phrases used for the offshore wind pilot
Energy technology family (or variant)	"Offshore wind energy"
Energy technology family (or variant AND EU dependence	"Offshore wind energy" AND "EU dependence"
Energy technology family (or variant) AND raw materials	"Offshore wind energy" AND "raw materials"
Energy technology family (or variant) AND imports	"Offshore wind energy " AND "imports"
Energy technology family (or variant) AND reliance on non-EU imports	"Offshore wind energy" AND "reliance on non-EU imports"
Energy technology family (or variant) AND market concentration	"Offshore wind energy" AND "market concentration"
Other search terms as necessary	

Add sources found during the search for literature to the *literature source tracker (*see section **Error! Reference source not found.***)*. It is not necessary to add sources to the l iterature source tracker if they are deemed to be irrelevant. In the *literature source tracker*, the following information should be added per source (see Table 65). The *literature source tracker* will be used to collate all "search history" and "search results" across all energy technology families. Note that all pick fields must be prefilled in the "pick list" tab. Add a summary of the "search history" tab to the *broad brush results template*.

Rate each relevant source used in terms of credibility and relevance. This should be done in the *literature source tracker* following the criteria suggested in Table 66. The final source score is calculated automatically in the *literature source tracker* by summing the credibility and relevance score (see Table 74 in see section **Error! Reference source not found.**).

Table 66 Suggested criteria for literature source tracker

Score	Credibility	Relevance
High (3)	The source used is an official standard or internationally recognised publication.	The source provides **full coverage** of the topic of relevance (e.g. market concentration). The source should also be acceptably current.
Medium (2)	The source is reputable and has been peer reviewed.	The source provides **good coverage** of the topic of relevance (e.g. market concentration), but should be supported by additional literature where possible.
Low (1)	The source has not been peer reviewed (e.g. Grey literature).	The source provides **minimal coverage** of the topic of relevance (e.g. market concentration), and must be supported by additional literature or expert input.

Produce a draft summary paper for the energy technology family using relevant information gathered during the literature search. Note that technology variant listed in Table 62 should be assessed separately and given its own subsection in its energy technology family summary paper, as variants may need to be assessed separately against criterion 1 in stage 3.1.

Remember that the summary paper should only provide information related to criterion 1. The draft summary paper must be written in the *broad brush results template* and must follow these general guidelines:

- Approximately 1500 words, plus useful figures/charts (length will depend on the number of variants);
- Summarise literature and expert view on the following key critical dependence topics (both for the overall energy technology family (or variants), and for any key elements e.g. components, services, etc.):
    - Reliance on non-EU imports ;
    - Market concentration.

Note that summary papers for energy technology families with numerous variants (e.g. bioenergy and geothermal energy) will likely need a higher word count to cover all key topics for all variants.

Note that an internal peer review of the draft summary paper would be advisable at this stage.

Stage 1.2 – Assess coverage of key topics

Determine whether the summary paper provides sufficient coverage of the key topics for each energy technology family variant (or energy technology family in the case that there are no variants). Recall that in stage 1.1 each source will have been added to the *literature source* tracker and scored based on credibility + relevance.

For each key topic (i.e. Reliance on imported products or components, Evidence of market concentrations in the supplier market), assess whether the combination of sources is "sufficient" or if external expert input is required; this can be determined using the matrix in Table 67Table 73, where the left most column indicates the # of relevant sources reviewed for each key topic. The top row indicates the score of each individual source. The area between the top row and left column indicates the minimal number of sources which must have the score indicated at the top of the column. For example, for the combination of sources to be deemed as "sufficient":

- If there is only one source it must have a score of 6;
- If there are three sources, they must all have a score of 5 or above;
- If there are four sources, at least two of them must have a score of 5, and the other two must have a score of 3 or above;
- If there are five sources, at least one of them must have a score of 5, and the other four must have a score 3 or above;
- If there are six or more sources, any combination of scoring is acceptable.

Table 67 Suggested minimal number of sources (with specific scores) for each key topic

<table>
<tr><td colspan="2" rowspan="2">Minimal # of sources required under each score</td><td colspan="5">Score</td></tr>
<tr><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td></tr>
<tr><td rowspan="7"># of sources</td><td>1</td><td></td><td></td><td></td><td></td><td>1 source</td></tr>
<tr><td>2</td><td></td><td></td><td></td><td></td><td>2 sources</td></tr>
<tr><td>3</td><td></td><td></td><td></td><td>3 sources</td><td></td></tr>
<tr><td>4</td><td></td><td colspan="2">2 sources</td><td>2 sources</td><td></td></tr>
<tr><td>5</td><td></td><td colspan="2">4 sources</td><td>1 source</td><td></td></tr>
<tr><td>6</td><td></td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>X</td><td></td><td colspan="2"></td><td></td><td></td></tr>
</table>

If there is deemed to be "insufficient" literature, external expert input should be sought. Guidance is provided in stage 1.3 below.

Review of the adequacy of sources should be added to the *results template* e.g. including Table 68 populated appropriately.

Table 68 Summary of sources against each key topic (indicative example)

Key Topics	Score allocated to each source	# of sources with the score indicate in column to the left	Sufficient information?
Reliance on imports	6	1	Sufficient information i.e. 1 source with a relevance/credibility score of 6
	5		
	4		
	3		
	2		
Market concentration	6		Insufficient information
	5	1	
	4	3	
	3		
	2		
[Scope for adding additional topics if needed]	6		
	5		
	4		
	3		
	2		

Stage 1.3 – Expert input

Interview external experts on key topics where there is "insufficient" literature available, as determined in stage 1.2. The interviews should focus on filling information gaps on the key topics. The interviews can be informal. It is suggested that a list of key questions are identified prior to the interview to ensure that all key points are covered.

Following external expert input, update the draft summary paper. Update the literature review tracker to include details of the interview (e.g. who was interviewed); provide a summary of interviews in the table provided in the *broad brush results template.* More than one expert input may be necessary to adequately cover the key topics.

Stage 1.4 – QA review

Review draft summary paper. Ensure that the summary paper adequately covers all key topics and that the paper will enable the assessment of the energy technology family (or variant) against criterion 1 (in stage 3).

During stage 1.4, the reviewer may make any necessary additions, amendments, and ultimately verify the accuracy and thoroughness of each summary paper.

Furthermore, the reviewer should review the *literature search tracker* and *results template* to accuracy and completeness.

During task 3, the summary papers produced as part of the pilot may be used as a reference point for ensuring consistency across each of the energy technology family summary papers. Ideally, this step will be carried out by the same person across all of the energy technology families.

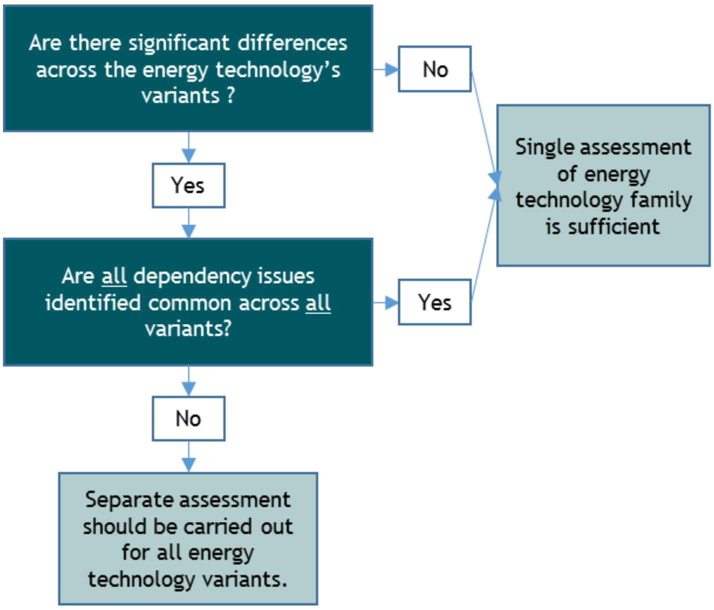
Stage 1.5 – Can variants be assessed as one energy technology family?

The decision on whether variants should be assessed during stage 3, as separately technologies, should be made with regard to the commonality of elements across the energy technology family variants. This should be carried out at the end of stage 1 (following the completion of the summary papers) by each technology expert. More fundamental differences across the variants would suggest the variants should be assessed separately in stage 3. This will require judgment by the technology expert.

The judgement should take account of whether the differences between energy technology family variants are in areas where there are potential dependencies. Where the differences between variant dependency profiles are markedly different, they should be assessed separately.

For example, where the literature suggests that offshore wind foundations are unlikely to be associated with any dependency concerns, then the variation is of lower importance and offshore wind can be considered a single energy technology family with onshore wind.

Figure 102 Assessing variants



The necessity of assessing each variant separately can be determined by following guidelines in Figure 102.

Note that assessing variants as one energy technology family should be done wherever possible, as it reduces the workload for stage 2 and 3 i.e. reduced number of final data sets to be determined in stage 2 and reduced the number of energy technology variants to be accessed during stage 3.

4.2 Stage 2 – Gather and select data for key indicators (criterion 2 and 3)

Overview

Figure 103 Summary of stage 2 key outputs

Populated broad brush data set template: with data for each of the criterion 2 and criterion 3 indicators. Notes on sources used and key assumptions should also be included in the data set template.

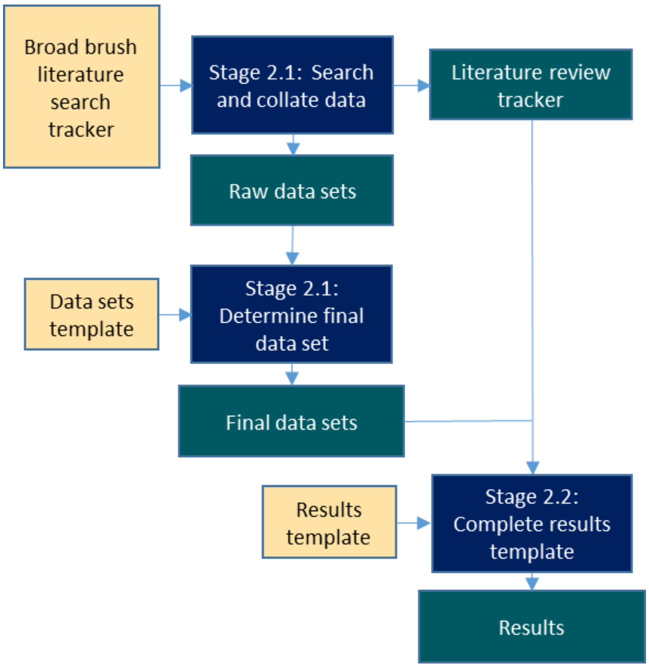
Raw data sets should be retained.

Add to results template using the literature review tracker and the final data sets. This will include written summary of key stage 2 findings, presentation of final data sets, and explanation of data sources and any key assumptions.

The purpose of stage 2 is determine data sets across all energy technologies (and variants) for each indicator – to enable a consistent and credible assessment of all energy technology families or variants against criterion 2 and 3.

In stage 2, data relating to criterion 2 and 3 indicators (see Table 63) will be collated and presented (in tables and graphs as appropriate) for each energy technology family (or variants). The process is illustrated in Figure 7.

Figure 104 : Stage 2 process diagram



Use the same data sources across energy technology families (or variants) for each indicator, wherever possible. This will aid the comparison of energy technology families (or variants). Use the most up to date data sources available.

Data collated in stage 2 will be used to inform the Stage 3 assessment (see section 4.3).

Stage 2.1 – Determine data sets across all energy technology families

Search for data sets for all energy technology families (or variants) simultaneously. This step can be carried out by one or more experts working in unison. See Table 69 for data required for criterion 2 and 3 indicators. Note that multiple sources may needed to ensure complete data sets for each indicator across all energy technology families.

All relevant data sources should be logged in the *literature source tracker,* and should be indexed as "criterion 2" or "criterion 3" data under the "topic of relevance" drop down box.

For energy technology families where installed capacity is not the best measure of scale of deployment, the numerical value may be left as N/A. In this case, expert view can be used provide a score (e.g. high, medium or low).

Table 69 – Criterion 2 & 3 data required for each energy technology family (figures for present day, 2030 and 2040 where appropriate)

Criteria	Indicators (including data needed to determine indicator figure)	Unit of Measurement (adapt as necessary)	Suggested source as per pilot
Criterion 2	EU total installed capacity	GW	**Primary source:** IEA World Energy Outlook (2015) OECD Europe: New Policies Scenario **Secondary sources:** IRENA. Renewable Energy Statistics 2017 data: Used to estimate 2013 offshore to onshore breakdown. Greenpeace Energy Revolution 2012 (revised edition of 9 August 2012): Used to estimate projected 2030 and 2040 offshore to onshore breakdown. **Key assumptions:** Note that projections for offshore and onshore, provided by Greenpeace, are global figures only. These were used for estimating EU onshore and offshore breakdown.
	% share of EU total installed capacity	%	
	Annual generation in the EU per year	TWh p.a.	
	% share of EU annual generation	%	
	Rate of annual net additions in the EU	GW p.a.	
Criterion 3	Global total installed capacity	GW	Same as criterion 2.
	% share of Global total installed capacity	%	
	Global generation per year	TWh p.a.	
	% share of global annual generation	%	
	Rate of global annual net additions	GW p.a.	
	EU % share of global patents relating to the energy technology family	%	Eurostat. Search based on available classification. Note that this information was not used during the pilot study.
	EU % share of global publications relating to the energy technology family	%	Web of Science - Thomson Reuters (2016) Web of Science Core Collection
	Approximate aggregated EU exports	Currency (or other appropriate metric for flow)	Eurostat. Easy Comext. Dataset DS-045409 - EU Trade Since 1988 by HS2, 4, 6 and CN8 . Product Code 841011 and 841090. Extracted on July, 2017

Collate all data gathered for each indicator across all energy technology families (or variants) for current, 2030 and 2040 where possible but please ensure that the year is consistent across all energy technology families being assessed. Raw data should be retained for quality assurance purposes.

Determine the final data sets for criterion 2 and 3 indicators by selecting the most appropriate combination of data sets for each indicator across all energy technology families. Priority should be to use the most complete data set (per indicator) across all energy technology families. For example, one data set which states the installed capacity of all renewable energy technologies in the EU in 2015. Where complete data sets are not available it may be necessary to combine multiple data sets. This must be done carefully to ensure meaningful comparison between energy technology families.

Populate the *broad brush data set* spreadsheet with the criterion 2 and 3 final data sets. This includes the "Criterion 2 – Final data set" and "Criterion 3 – Final data set" tabs as well as the "final summary table". Note that the table in "final summary table" is populated with the data from the other tabs.

Expert review of final data sets should be carried out to confirm its accuracy. This review should be carried out by the appropriate technology expert.

Stage 2.3 – Complete results template with information gathered during stage 2
Complete the results template using the information gathered in the *literature search tracker* and *final data sets template*. Completing the results template for stage 2 will include:

- Providing a written summary of the findings from stage 2 e.g. explanation of the importance that energy technology plays in EU security of supply (criterion 2) and EU leadership (criterion 3).
- Presenting final data sets for each energy technology family (or variants) using the output from the "final summary table" tab in the *broad brush data set* template.
- Provide an explanation of data sources used including detail on data availability, assumptions used to determine final data sets, and any other issues.

4.3 Stage 3 – Prioritising energy technology families

Overview

Table of results ranking each energy technology family (or variant) against the three criteria based on its overall priority in terms of critical dependency, energy security and EU leadership.

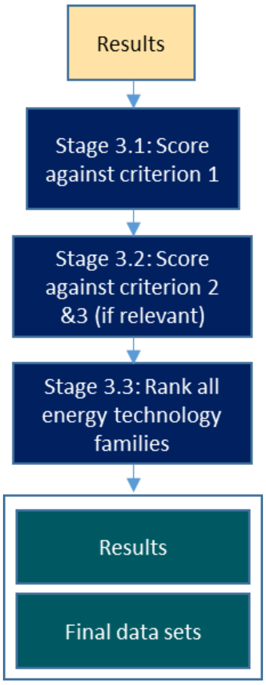
Selection of five energy technologies which will proceed to the detailed assessment. Explanation should be provided on key differences between each of the energy technology families (or variants) including commentary on 1) potential areas for EU leadership 2) areas where mitigation measures and policy interventions should be targeted.

The purpose of stage 3 is to identify the five most critical energy technologies (or variants) to be assessed in in-depth during task 4, and to provide insight into areas where the EU could provide leadership.

In stage 3, energy technology families and variants will be ranked in terms of their overall criticality of dependence, importance to EU security of supply and importance for EU leadership. This assessment will be based on the information provided in the summary papers, and the data provided against each of the criterion 2 and 3 indicators. Stage 3 will follow the process outlined in Figure 105.

The final output of this stage will be a table summarising the assessment of each energy technology family (or variants) against the 3 criteria: criticality of dependence (criterion 1); importance for EU security of supply objective (criterion 2); and, importance for EU leadership in renewables objective (criterion 3).

Figure 105: Stage 3 process



In addition, a written summary of key observations i.e. key differences between energy technology families (or variants), etc. will be necessary to understand the rationale behind the prioritisation of energy technology families. From the results of stage 3, it is expected that it will be possible to identify five energy technology families/variants that should proceed to the detailed assessment. The results of stage 3 will also provide insight into potential areas for EU leadership.

Recall that variants may not need to be assessed separately (refer to stage 1.5).

Stage 3.1 – Score energy technology families against criterion 1

Review all energy technology family summary papers written in the *broad brush results template*.

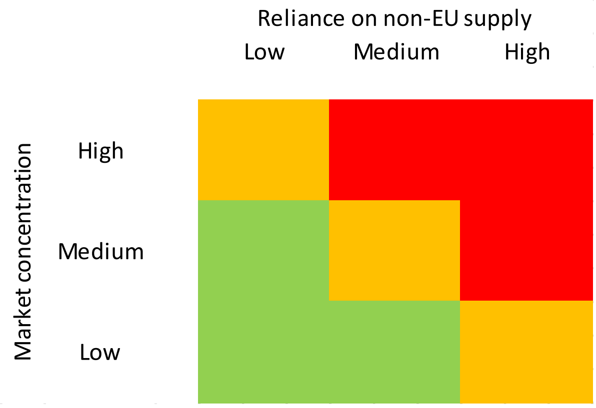
1. List all potential critical dependence elements in the *broad brush data sets template* tab (in *criterion 1 – elements tab*).;
2. List each critical dependency element under the relevant energy technology family (e.g. Geothermal) or variant (e.g. Geothermal – low enthalpy) depending on the conclusions made in each summary paper;
3. Categorise each critical dependence element by element type: raw material, component, sub-component, equipment, machinery, service, or other;
4. Where no potential critical dependencies have been identified for an energy technology family or variant, the energy technology family or variant should still be in the *criterion 1 elements tab* and categorised appropriately (i.e. element category: overall technology/variant);
5. Furthermore, elements which are deemed to be non-critical do not need to be listed;
6. Score each potential critical dependence element against criterion 1 indicators - reliance on non-EU supply (indicator 1) and market concentration (indicator 2) – in the *broad brush data sets template* using the scoring guide in Table 70.;
7. Write a brief note justifying the scores selected for each element against each indicator.

Table 70 - Score guide for each element against criterion 1 indicators

Information / Indicator	Scoring guide: High	Medium	Low
Reliance on non-EU supply	High EU reliance on non-EU suppliers (e.g. >70% of EU demand is imported).		Low EU reliance on non-EU suppliers (e.g. <30% of EU demand is imported).
Market concentration	Element market is highly concentrated (less than 5 countries and less than 5 firms supplying the element to the global market).		Element market is highly competitive (greater than 10 countries and 10 firms supplying the element to the global market).

8. **Enter each element's final score (extent of critical dependence)** in the *broad brush data sets template* "Criterion 1-elements" using the scoring guidance in Figure 106, where red is high, amber is medium, and green is low. Note that the extent of critical dependence is based on reliance on non-EU supply (indicator 1) and market concentration (indicator 2).

Figure 106 – Scoring guidance for each element against criterion 1 : extent of critical dependence



9. **Score all energy technology families/variants against criterion 1** using the scoring guide in Figure 107 below and considering the number and extent of critical dependence elements associated with each energy technology family/variant, as listed in the *broad brush data sets spreadsheet* "criterion 1 – elements" tab. 3-5 experts will carry out this step in parallel. Compare scores provided by each expert to identify any variation; discuss any differences in scores and reach a consensus.

Figure 107 Score guide for energy technology families/variants against criterion 1

Criterion	Information / Indicator	Scoring guide: High	Medium	Low
Criterion 1	Dependence Score	One or more elements identified as high extent of critical dependence.	No elements identified with high extent of critical dependence & one or more elements identified with medium extent of critical dependence.	No elements identified with medium or high extent of critical dependence.

10. **Record the final energy technology family/variant scores against criterion 1** in the *broad brush data sets* spreadsheet "final summary table" tab for all energy technology families/variants (i.e. high, medium, or low). Also include the number of elements identified with a high and medium extent of critical dependence as indicated in the *broad brush data sets* spreadsheet "criterion 1 – elements" tab.

Stage 3.2 – Score energy technology families against criterion 2 & 3

Score an energy technology (ONLY where no data is available) using expert opinion and the score guide in Table 10.

It is expected that this stage will apply in two general situations:

- There is limited or no data available across an entire indicator. In this case, multiple experts should provide scores against criterion 2 and a consensus reached on the final scoring against criterion 2;
- There is no data available against an indicator for a few energy technology families (or variants). In this case, the technology expert for that energy technology family (or variant) should provide a score against criterion 2.

Table 71Providing a score of high/medium/low where data is not available will aid in considering all three criteria. Update the "final summary table" in the *broad brush data sets* spreadsheet accordingly.

It is expected that this stage will apply in two general situations:

- There is limited or no data available across an entire indicator. In this case, multiple experts should provide scores against criterion 2 and a consensus reached on the final scoring against criterion 2;
- There is no data available against an indicator for a few energy technology families (or variants). In this case, the technology expert for that energy technology family (or variant) should provide a score against criterion 2.

Table 71 Score guide for criterion 2 (importance for EU security of supply) and criterion 3 (importance for EU leadership in renewables objectives)

Criteria	Information / Indicator	Scoring guide		
		High	Medium	Low
Criterion 2	Share of EU total installed capacity and generation	This ETF will play a significant role in EU renewable energy generation.		This ETF will play an insignificant role in EU renewable energy generation.
	Expected rate p.a. of EU net capacity additions. Does not include replacements.	A significant increase in EU additional installed capacity is expected by 2030		Limited or no increase in EU additional and replacement capacity is expected by 2030.
Criterion 3	Share of Global total installed capacity and generation	This ETF will play a significant role in global energy generation.		This ETF will play a limited role in global renewable energy generation.
	Expected rate p.a. of Global net capacity additions. Does not include replacements.	A significant increase in global additional installed capacity is expected by 2030		Limited or no increase in global additional and replacement capacity is expected by 2030.
	EU % share of EPA	EU holds a significant		EU holds an

Criteria	Information /	Scoring guide		
	patent applications	portion of EPA patent applications pertaining to the energy technology family.		insignificant portion of EPA patent applications pertaining to the energy technology family.
	EU % share of global publications	EU holds a significant portion of global publications pertaining to the energy technology family.	.	EU holds an insignificant portion of global publications pertaining to the energy technology family.

Stage 3.3 – Rank energy technology families

3-5 experts will rank all energy technology families using expert judgement and considering overall criticality of dependence, importance to EU security of supply and importance for EU leadership. This will require considering all energy technology families against the 3 criteria: criticality of dependence (criterion 1); importance for EU security of supply objective (criterion 2); and, importance for EU leadership in renewables objective (criterion 3). This should be carried out in parallel by multiple people (e.g. 3-5). The results of each expert's ranking should be documented as a separate "final summary table" tabs in the broad brush data sets. Each expert should write a brief summary supporting the rationale behind their ranking.

When ranking energy technology families/variants, consider the following:

- The core concept of the study is technology dependence. Hence, technologies with a low extent of critical dependence are not in focus;
- Technologies with a medium or high extent of critical dependence do not necessarily warrant mitigation measures or intervention, and thus many not be most appropriate to proceed to detailed assessment;
- Intervention is justified if the technology is highly relevant for either security of supply or technology leadership and if a medium or high extent of critical dependence is observed.

Compare rankings and reach consensus on the final ranking of energy technology families. Variation between expert rankings of energy technology families should be explained in the *broad brush results template.*

Populate "Broad brush data set", specifically, "Final summary table" tab with the final results of the final rating. See

Table 72 for an example.

Provide a summary of the analysis carried out in stage 3. Explanation should be provided on key differences between each of the energy technology families (or variants) including commentary on criticality of dependence (criterion 1); importance for EU security of supply objective (criterion 2); and, importance for EU leadership in renewables objective (criterion 3).

Table 72 – Proposed presentation of final scoring of energy technology families

Technology	Dependence score (Criterion 1)	Importance for EU security of supply objective (Criterion 2)		Importance for EU leadership in renewables objective (Criterion 3)				Priority of managing dependence
	Composite indicator of the dependence assessment of the main elements (reliance on imports, market concentration)	2013, 2030 and 2040 share of EU total installed capacity (and generation)	Expected rate (per year) of EU net capacity additions. Does not include replacements.	2013, 2030 and 2040 share of global total installed capacity (and generation)	Expected rate (per year) of global net capacity additions. Does not include replacements.	% share of global publications relating to the energy technology family	Aproximate aggregated EU exports (1988 - 2016)	Composite indicator based on preceding scores
Explanation	Provides insight into the threat of supply disruptions for the EU	Provides insight into the importance of the technology for meeting EU's day-to-day energy needs	Provides insight into the volumes that the EU needs to buy including both capacity additions and replacement.	Provides insight into the importance of the technology for meeting the world's day-to-day energy needs	Provides insight into the volumes that the world needs to buy including both capacity additions and replacement.	Provides insight into the EU knowledge position	Provides insight into the EU industry position	Determines where mitigation measures and public interventions should be aimed at. Also drives the selection of technologies for the detailed assesment
Unite	High/medium/low	X% - 2013 Y% - 2030 Z% 2040	GW per year	%	GW per year	%	€	Ranking (1-highest priority, 2 -lowest priority)
Solar PV	High	7.5% (2.2%) - 2013 11.4% (4.2%) - 2030 11.9% (4.7%) - 2040	4.1 GW p.a.: 2013 - 2030 1.6 GW p.a.: 2030 - 2040	2.3% (0.6%) - 2013 8.1% (2.9%) - 2030 10.1% (3.9%) - 2040	34.8 GW p.a.: 2013 - 2030 33.8 GW p.a.: 2030 - 2040	25%: 2014- 2016	1,689 million €	1
Offshore wind	Medium	0.7% (0.5%) - 2013 1.8% (1.9%) - 2030 2.6% (3.1%) - 2040	1.0 GW p.a.: 2013 - 2030 1.3 GW p.a.: 2030 - 2040	0.13% (0.08%) - 2013 1.0% (0.85%) - 2030 1.4% (1.3%) - 2040	4.6 GW p.a.: 2013 - 2030 6.2 GW p.a.: 2030 - 2040	47%: 2014- 2016	1,800 million €	2
Example	Low	No data	No data	No data	No data	37%: 2014-2016	2,000 million €	3
Add energy technology family								

5 Templates and guidance documents

5.1 Broad brush literature search tracker

Purpose of this template is to:

- **Keep record of all sources and interview contacts future reference**
- **Help with assessing whether the literature review carried out is sufficient**
- **Help to ensure consistency across all energy technology family variants**

This spreadsheet will be used by each expert to track the search history and search results from all literature and data searches (for each energy technology family or variant) carried out during the broad brush assessment.

A "Search History" and "Search Results" tab should be created for each energy technology family or variant. This can be done by creating a copy of "Search History (Add technology)" and "Search Results (Add technology)" tabs. Experts may wish to create their own working copy of the *broad brush literature search tracker*, and compile tabs for each energy technology into the final *broad brush literature search tracker* upon completion of the broad brush assessment.

Note that sources should be saved on SharePoint using reference numbers indicated in the search results tab e.g. "Wind-offshore-0".

If sources cover multiple topics, enter it as a separate line for each topic.

Regarding criterion 2 and 3 data sources: scoring is not needed and it is not necessary to log searches carried out in the search history tab.

Search History tab

Row 2 through 5 is used to document the search conditions applied. This includes the scope of search (e.g. English language only), date range (e.g. 2000+) and type of search (e.g. apply to document title and abstract only).

Row 8 through 28 is used to document details of the search including: date of search; the database, search engine or other, used to search; key words or other search terms used; number of items found; any notes on the search results.

Note that all pick fields must be prefilled in the "pick list" tab.

Search Results tab

Row 2 indicates the energy technology family or variant documented in the tab. Note that each energy technology variant will need its own tab.

Row 6 through 54 is used to document each relevant source found. The information listed in Table 5 should be provided for each relevant source. Note that the search results tab will also be used to track any interviews carried out. Parameters which should be filled out for interview are modified e.g. Publication date becomes "Date of interview". Note further that some cells are automatically generated (as noted in the table below).

Table 73 Literature search tracker spreadsheet inputs (see current version of literature search tracker)

<table>
<tr><th>Parameter</th><th>Example entries</th><th>Notes</th></tr>
<tr><td>Reference #</td><td>AUTOMATICALLY GENERATED</td><td>Use this reference # when saving sources onto the SharePoint.</td></tr>
<tr><td>Source type</td><td>Journal article
Website
Report
Conference proceedings
Book section</td><td></td></tr>
<tr><td>Publication date (Date of interview)</td><td>2016
(21/09/2017)</td><td></td></tr>
<tr><td>Title</td><td></td><td></td></tr>
<tr><td>Author/organisation (Name and company of interviewee)</td><td>John Harvey/Ricardo</td><td></td></tr>
<tr><td>Link (interview contact details)</td><td></td><td>For interviews. Provide telephone number and email if possible.</td></tr>
<tr><td>Sub-family</td><td>(Solar energy example)
PV
CSP
Thermal</td><td></td></tr>
<tr><td>Topic of relevance</td><td>Reliance on imports
Market concentration
Other (please specify in the "pick list" tab)</td><td>It will be important to understand whether the literature review, for each energy technology family, has covered all key topics and where there are gaps.
Some sources will cover multiple topics – these sources should be input as separate lines to isolate by topic of relevance.</td></tr>
<tr><td>Relevance score</td><td>High(3) / Med(2) / Low(1)</td><td>Refer to<table>
<tr><th>Score</th><th>Credibility</th><th>Relevance</th></tr>
<tr><td>High (3)</td><td>The source used is an official standard or internationally recognised publication.</td><td>The source provides full coverage of the topic of relevance (e.g. market concentration). The source should also be acceptably current.</td></tr>
<tr><td>Medium (2)</td><td>The source is reputable and has been peer reviewed.</td><td>The source provides good coverage of the topic of relevance (e.g. market</td></tr>
</table></td></tr>
</table>

<table>
<tr><th>Parameter</th><th>Example entries</th><th>Notes</th></tr>
<tr><td></td><td></td><td>
<table>
<tr><td></td><td></td><td>concentration), but should be supported by additional literature where possible.</td></tr>
<tr><td>Low (1)</td><td>The source has not been peer reviewed (e.g. Grey literature).</td><td>The source provides minimal coverage of the topic of relevance (e.g. market concentration), and must be supported by additional literature or expert input.</td></tr>
</table>
.</td></tr>
<tr><td>Credibility score</td><td>High(3) / Med(2) / Low(1)</td><td>Refer to
<table>
<tr><th>Score</th><th>Credibility</th><th>Relevance</th></tr>
<tr><td>High (3)</td><td>The source used is an official standard or internationally recognised publication.</td><td>The source provides full coverage of the topic of relevance (e.g. market concentration). The source should also be acceptably current.</td></tr>
<tr><td>Medium (2)</td><td>The source is reputable and has been peer reviewed.</td><td>The source provides good coverage of the topic of relevance (e.g. market concentration), but should be supported by additional literature where possible.</td></tr>
<tr><td>Low (1)</td><td>The source has not been peer reviewed (e.g. Grey literature).</td><td>The source provides minimal coverage of the topic of relevance (e.g.</td></tr>
</table>
</td></tr>
</table>

Parameter	Example entries	Notes
		market concentration), and must be supported by additional literature or expert input. .
Referenced in summary paper	Yes / No	Indicate whether the source has been used in the summary paper.
Extent of use	High(3) / Med(2) / Low(1)	

The following matrix is used to determine the overall score for each source.

Table 74 Score matrix (relevance + credibility scoring)

		Credibility		
		Low	Medium	High
Relevance	Low	2	3	4
	Medium	3	4	5
	High	4	5	6

5.2 Broad brush data sets template

Purpose of this template is to:
- **Keep record of final data sets for each indicator**
- **Keep record of sources and assumptions used for each indicator and technology**
- **Keep record of expert scoring during stage 3, and including individual scores and final consensus**

The broad brush data set template provides tabs, for criterion 2 and criterion 3 indicators, to enter final data set figures which will be used for the scoring of each energy technology against criterion 2 and 3 and for the final scoring of all energy technology families assessed.

Final Summary Table tab
This table presents the collated results of the broad brush assessment. Add a column for each energy technology family or variant assessed as part of the broad brush assessment. Please follow the format indicated in the solar PV example provided in the template. The values used to populate this table should be taken from the "Criterion 2 – Final data set" and "Criterion 3 – Final data set" tabs.

Criterion 2 – Final Data Set tab
This tab can be used to collate and present key figures against each of the criterion 2 indicators. Add additional energy technology families or variant under each indicator. The results in the grey box are to be used to populate the *final summary table* tab.

Column H can be used to indicate any issues with the data sets and whether the figure is appropriate for use.

Criterion 3 – Final Data Set tab
This tab can be used to collate and present key figures against each of the criterion 3 indicators. Add additional energy technology families and variants under each indicator. The results in the grey box are to be used to populate the *final summary table* tab.

Column H can be used to indicate any issues with the data sets and whether the figure is appropriate for use.

Sources tab
This tab can be used to indicate the primary and secondary sources used to create a complete data set, across all energy technology families, against each indicator. Notes on the quality of the data used and any assumption to collate a complete data set can be recorded here.

5.3 Broad brush results template

The broad brush results template is self-explanatory.

Getting in touch with the EU

IN PERSON
All over the European Union there are hundreds of Europe Direct information centres.
You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

ON THE PHONE OR BY EMAIL
Europe Direct is a service that answers your questions about the European Union.
You can contact this service
– by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),
– at the following standard number: +32 22999696 or
– by email via: https://europa.eu/european-union/contact_en

Finding information about the EU

ONLINE
Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU PUBLICATIONS
You can download or order free and priced EU publications at: https://publications.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en)

EU LAW AND RELATED DOCUMENTS
For access to legal information from the EU, including all EU law since 1952 in all the official language versions, go to EUR-Lex at: http://eur-lex.europa.eu

OPEN DATA FROM THE EU
The EU Open Data Portal (http://data.europa.eu/euodp/en) provides access to datasets from the EU. Data can be downloaded and reused for free, for both commercial and non-commercial purposes.

The overarching objective of this study was to better understand the dependence of the European Union on energy technologies and to specifically consider the impact of this dependence on the security of energy supply in the EU and on the EU objective of becoming a world leader in renewable energy technologies. The deliverables of this study include a set of relevant definitions on the concept of energy technology dependence (ETD), a methodology for assessing energy technology dependencies, a broad brush and detailed assessment of current energy technology dependencies, and policy recommendations for addressing such dependencies. This document includes the methodology for and results of the broad brush assessment.

Studies and reports

Publications Office
of the European Union