European Commission

Study on clean energy R&I opportunities to ensure European energy security by targeting challenges of distinct energy value chains for 2030 and beyond

Annex

Independent
Expert
Report

Research and Innovation

Study on clean energy R&I opportunities to ensure European energy security by targeting challenges of distinct energy value chains for 2030 and beyond: Annex

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Annex

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ABBREVIATIONS

Acronym	Definition
AC	Associated Country
ACT	Advanced Control Technologies
AEM	Anion Exchange Membrane
AMI	Advanced Metering Infrastructure
BIPV	Building-Integrated Photovoltaics
CAES	Compressed Air Energy Storage
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CETO	Clean Energy Technology Observatory
CGR	Computable General Equilibrium
CH_4	Methane
CHP	Combined Heat and Power
CN	China
CO_2	Carbon Dioxide
CO_2e / CO_2eq	CO_2-equivalent
CRM	Critical Raw Materials
CRMA	Critical Raw Materials Act
DAC	Direct Air Capture
DBT	Dibenzyl Toluene
DG RTD	Directorate General Research and Innovation
EC	European Commission
EOL	End-of-Life
ETIP	European Technology & Innovation Platform
EU	European Union
EV	Electric Vehicle

GHG	Greenhouse Gas
GW	Gigawatt
HEMS	Home Energy Management System
HVAC	Heating, Ventilation, and Air Conditioning
HVDC	High-Voltage Direct Current
IEA	International Energy Agency
IRA	Inflation Reduction Act
JU	Joint Undertaking
LCOE	Levelised Cost of Electricity
LCOH	Levelised Cost of Heating
LOHC	Liquid Organic Hydrogen Carriers
LREE	Light Rare Earth Elements
MFF	Multi-Annual Financial Framework
MJ	Megajoule
MS	Member State
Mtoe	Million Tonnes of Oil Equivalent
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
NZIA	Net Zero Industry Act
OEM	Original Equipment Manufacturer
PEM	Proton-Exchange Membrane
PESTLE	Political (P), Economic (E), Social (S), Technological (T), Legal (L), and Environmental (E) analysis
PFAS	Perfluoroalkyl Substances
PFSA	Perfluorosulfonic Acid
PTFE	Polytetrafluoroethylene
PV	Photovoltaics
R&I	Research and Innovation

RAG	Red-Amber-Green rating
RD&D	Research, development and demonstration
RED	Renewable Energy Directive
RFB	Redox Flow Batteries
RFNBOs	Renewable fuels of non-biological origin
RRF	Recovery and Resilience Facility
ScMI	System Control and Management Interface Software
SDGs	Sustainable Development Goals
SET Plan	Strategic Energy Technology Plan
S-O	Strength-Opportunity
SOE	Solid Oxide Electrolysis
S-T	Strength-Threat
SWOT	Strength, Weakness, Opportunity, Threat analysis
TCP	Technology Collaboration Programme
TEN-E	Trans-European Networks for Energy
TES	Thermal Energy Storage
TFEU	Treaty on the Functioning of the European Union
TOR	Terms of Reference
TRL	Technology Readiness Level
TWh	Terawatt Hours
US	United States of America
UTES	Underground Thermal Energy Storage
VIPV	Solar Cells in Vehicles
W-O	Weakness-Opportunity
W-T	Weakness-Threat

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ANNEX A: METHODOLOGY

1. Overview of the study conceptualisation and approach

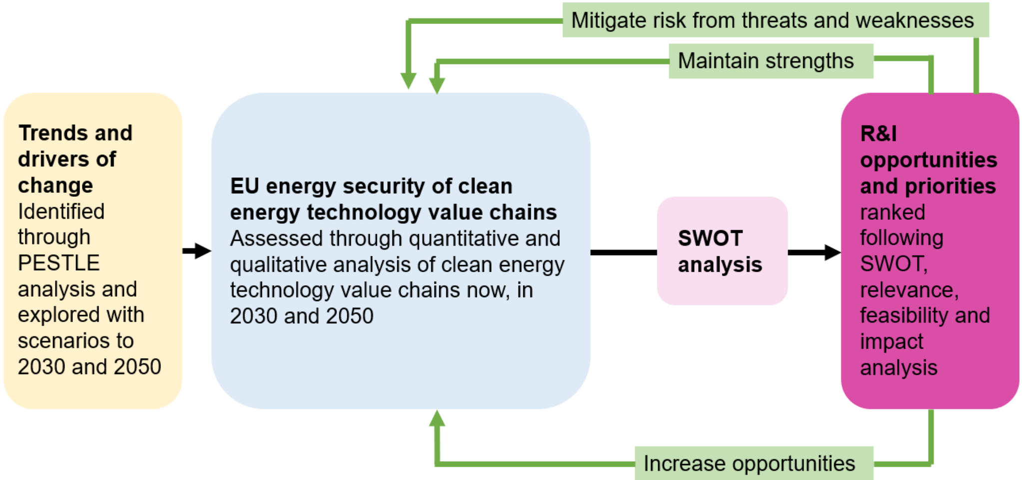
The energy security of clean energy technology value chains can be directly and indirectly influenced by a series of interconnected external drivers and trends, including technological development, energy policy and R&I programmes. An evidence- and foresight-based approach exploring plausible futures can help determine near-term actions to mitigate future risks – and better anticipate, and taken advantage of, future opportunities. Combining deep understanding of clean energy technology value chains with exploration of possible futures can support strategic planning to increase European energy security in the context of the transition to clean energy technologies.

The methodology proposed for this study brings together foresight- and futures-based methods, producing plausible scenarios to explore trends and uncertainty on 2030 and 2050 horizons, complemented with macro-economic modelling from GEM-E3 and in-depth analysis of the energy security components of clean energy technology value chains. The GEM-E3 model, described in detail in the methodology (Chapter 9), both supported the assessment of the EU's vulnerability to different clean energy technology value chains – in particular bilateral trade flows and market projections – and helped evaluate the performance of alternative R&I spending on clean energy technologies in improving energy security and accelerating growth.

With this understanding of internal strengths and weaknesses for energy security, as well as external opportunities and threats, potential R&I interventions were identified and strategically prioritised based on their relevance, feasibility and potential to deliver increased European energy security. SWOT and least regrets analyses were used to identify interventions that are either required in all scenarios or across multiple technology value chains, making them essential – or of potentially higher impact – and therefore valid candidates for prioritisation.

The conceptualisation of the study is presented in Figure A.1.

Figure A.1 Conceptualisation of the study



The study was delivered as four tasks, as specified in the study terms of reference (TOR). In Task 1, the study team refined the overall methodology and developed the scenarios for use throughout the study. Task 2 consisted of in-depth analysis of the security of clean energy technology value chains, both now and – by bringing together technology-specific analysis and context explored in future scenarios – to 2030 and 2050 horizons, assessed on specific energy security criticalities. Task 3 identified R&I interventions to maintain, boost, or mitigate risks of energy security across whole technology value chains. It also and drew on SWOT analysis to develop an action plan for the next 10 years. As part of Task 4, a validation workshop convened experts and key stakeholders from across the different in-scope technologies and refined the study findings, feeding into final results and this report.

2. Scope and definitions

2.1. Energy security

This study used the International Energy Agency (IEA) definition of energy security as 'the uninterrupted availability of energy sources at an affordable price'[1]. For clean energy technology value chains, energy security does not only depend on the source of energy, but also on the availability of all relevant materials and components of the underlying technology value chain.

The availability of all relevant components of the underlying energy value chains, the source of energy, and the broader system including skills and regulation are in scope of this study.

Climate adaptation and consideration of extreme weather is considered in scope with regards to how they affect the availability of the source of energy and conditions for operation, such as wind or sun. The potential physical vulnerability of technology value chains to climate events and climate adaptation is also considered as part of the assessment of energy security of clean energy value chains. Climate-related energy security criticalities are also considered for R&I interventions. However, the study assumes that planning for climate adaptation and

[1] International Energy Agency (IEA). Energy Security (accessed 2023).

impacts on individual physical facilities (for example flooding of a manufacturing facility) is carried out by the relevant stakeholders or authorities and this is out of scope for the development of R&I interventions.

Risks from malicious actors, such as sabotage or cyber-attacks, is considered as part of the assessment of energy security of clean energy value chains. Cyber-related risks will be considered as part of the study due to their interconnection and interdependence to research and innovation in energy technology and the changing security landscape from increased digitalisation. Sabotage is considered out of scope for the development of R&I interventions.

2.2. Clean energy technologies

The clean energy technologies of interest for this study are, as defined by the Directorate-General for Research and Innovation (DG RTD): advanced biofuels, bioenergy, concentrated solar energy, geothermal energy, hydropower, ocean energy, photovoltaics (PV), wind energy, renewable and solar fuels, carbon capture utilisation and storage, electricity and heat storage (including batteries), hydrogen and intermediate energy carriers, heat pumps, smart energy grid technologies, energy building and district technologies, off-grid energy systems, energy transmission and distribution technologies, and smart cities.

Nuclear energy is out of scope, as defined in the study TOR. Fossil fuel value chains and the future of fossil fuels and legacy assets are also out of scope.

2.3. R&I opportunities and interventions

R&I opportunities are those areas where an R&I intervention has potential to maintain or strengthen the EU energy security of clean energy technology value chains.

R&I interventions enable the development of solutions to resolve a particular challenge or realise a particular opportunity. Interventions may aim to address a weakness in the technology value chain with support to develop an EU alternative or novel technology, strengthen EU capabilities and supply chains, mitigate threats and identify opportunities for energy security that might not be otherwise be realised. Example R&I interventions include collaborative R&I programmes, missions, support for start-ups and innovative businesses, and support for networks.

R&I interventions are considered within scope of this study if they can be implemented or influenced by the European Commission and DG RTD. Education and skills interventions will generally not be directly in scope, but the study will consider those that constitute critical interventions for specific clean energy technology value chains. This study focuses on R&I interventions that could be initiated within the next 10 years, with their expected delivery and impact extending beyond.

3. Assumptions and limitations of the methodology

3.1. Assumptions

The study made three key assumptions, presented here for transparency and clarity:

- As set out in the study TOR by DG RTD, domestic EU energy production is considered more secure than imported energy.

- For both the development of scenarios and assessment of energy security criticalities, the study assumed that current EU policies (for example environmental protections) and decarbonisation ambitions will be maintained or increase in ambition over the coming years and decades.

- This also translates into the assumption that where energy technologies require energy for the operation of their value chain, this energy is clean.

3.2. Limitations

While energy security is a systemic characteristic, the scope of this study is analysis at the value-chain level. The study findings present energy security criticalities for individual value chains but do not consider how the value chains interact with each other within the energy system or how management of the system itself can mitigate risks to energy security. Energy system consideration or questions are highlighted throughout the findings of this study where relevant and appropriate. Further work taking an energy systems view would be valuable and complementary. Similarly, the study focuses on the energy security of value chains, rather than needs or considerations for deployment, or measures to meet energy decarbonisation objectives.

The technology categories in the scope of the study are broad and analysis was carried out by examining between one and four representative value chains per category. Analysis may not be applicable to every value chain in the technology category. Technology categories and applications are non-exhaustive.

The granularity of assessment is carried out at the level of the main value chain elements (e.g. 'advanced electronics', not specific types of chips). This pragmatic approach was taken with consideration of the feasibility of delivering the study, and where specifics were identified by the study team or experts in the validation workshop, they are included in the findings.

4. Methodology for scenario development

This section sets out the methodology used to develop the scenarios for use throughout the study.

4.1. PESTLE trends analysis

As a first methodological step, an understanding of trends and drivers of change with potential to influence the energy security of clean technology value chains was developed, with trends on 2030 and 2050 time-horizons considered. The drivers of change identified formed the basis for scenario development in the next step, and an understanding of external factors, including threats and opportunities to consider for SWOT analysis. At this stage, evidence gathering and analysis was technology-agnostic.

The PESTLE framework was used for evidence analysis, with drivers identified across political (P), economic (E), social (S), technological (T), legal (L) and environmental (E) dimensions. This framework enabled analysis to consider technological and microeconomic factors, energy and industrial diversification in a global context, energy and energy technology trade balances, macroeconomic factors, policy, and sustainable development, such as the UN Sustainable Development Goals (SDGs). The trends identified are listed in Table A.1. Evidence gathering activities included desk-based research and a literature review building on relevant studies, as well as interviews with expert stakeholders. The literature review included grey literature from the EU and internationally, and academic papers where relevant. Short key word searches were used as anchor terms (e.g. energy security AND clean energy transition; energy security AND legislation OR regulation; energy security AND clean energy transition AND behaviour change). This exercise both supported the identification of trends and the refining of energy security indicators for use throughout the study. The SDGs form part of the context of the study and were considered where relevant in the PESTLE analysis and scenario development, as well as during the development of the R&I action plan to ensure R&I actions are consistent with the SDGs and other relevant EU regulation and standards.

Expert interviews explored the trends identified in desk-based research and teased out the relationship between trends and energy security indicators to validate the findings of desk-based research and identify gaps. Interviewing key experts from different stakeholder groups enables the study team to develop a rounded picture of key trends and obtain deeper insights into the drivers of change for energy security of clean energy technology value chains. The study team interviewed 11 experts. Expertise covered in interviews is outlined in Table A.1. The interview data was analysed based on the PESTLE categories, adding nuance to the PESTLE analysis where relevant, and to better understand interaction between different drivers of change and plausible projections for use in the scenario development described in detail in this section.

Table A.1 List of areas of expertise for consultation for the PESTLE analysis

Area of expertise
International political economy, comparative public policy, energy security and energy policy
Energy transitions and societal change
Social dimension of the energy transition, just transition, EU policy
Geopolitics, China and energy security
Circular economy and energy value chains
Climate adaptation and energy security
Energy security, digitalisation and cybersecurity
Digitalisation, EU energy market
Wind energy R&I, economics of clean energy technologies
Geology, critical raw materials (CRM)
Strategic decision-making and R&I interventions

Experts were identified through desk-based research and the study team's networks, creating a list of interviewees covering subject matter expertise across a wide breadth of disciplines, such as economics and geopolitics, scientific, industrial and market expertise, as well as considering diversity in geography, industry sectors, public sector and academia, and seniority. The opportunity for a diverse range of stakeholders to contribute their expertise and ideas through individual interviews enabled different voices to be heard with equal importance. Interviews lasted up to an hour and took a semi-structured approach, with all stakeholders to be asked a similar set of questions while also allowing for emergent issues to be explored. This allowed responses to be compared across interviewees, while leaving the interviewer free to follow up emerging issues with additional questions not covered in the original protocol. The interviews focused on the following themes:

- Understanding the interviewee's background and expertise.
- Understanding key indicators for energy security of clean energy technology value chains to refine the definition of energy security and key indicators used in the study.
- Identifying PESTLE trends relevant to energy security and their possible evolutions to 2030 and 2050.
- Understanding the interplay and connections between different trends, and what might trigger or drive change.
- Testing and validating trends and drivers of change identified during the literature review.
- Gathering information on additional literature to consider.

An internal study team workshop was then held to conduct a detailed assessment of the evidence collected. Specifically, the workshop assimilated the evidence gathered through desk-based research and interviews to refine the definition of energy security and key indicators for use in this study and identify common themes or divergence from the different sources of evidence analysed, through the mapping of the various critical factors, challenges and opportunities within the context of energy security for clean energy technology value chains. This analysis was technology-agnostic, with specific trends for each technology value chain of interest explored in further detail within the scenarios.

4.2. Scenario development

In this study, we used a structured approach to develop scenarios for energy security of clean energy technology value chains for 2030 and 2050 – mapping out key factors in future energy systems, developing a range of plausible projections for them, and identifying a range of scenarios where these projections could logically co-exist. Energy security is characterised by a multi-factor interrelated system, taking into account external influences, and does not rely solely on one or two main drivers. This method was particularly suited to this study as the future evolution of energy security indicators must be considered in sufficient depth to enable the development of a strategic action plan.

To develop the scenarios, we used the framework presented in Gausemeier,[2] which identifies critical drivers of change and combines cross-impact analysis, consistency analysis and cluster analysis to identify scenarios. This approach is operationalised in four steps (Figure

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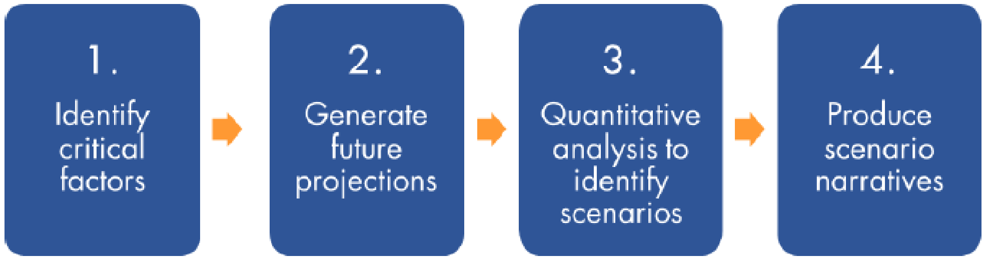
[2] Gausemeier et al. 1998. Scenario management: an approach to develop future potentials. *Technol. Forecasting Social Change*, 59 (2) (1998), pp. 111-130.

A.2). The ScMI software suite was used to support the scenario development (Scenario Management International AG n.d.).

Figure A.2 Operationalisation of the scenario development



Step 1: Identifying critical factors

A key output of the PESTLE analysis was a longlist of 40 potential factors or drivers of change for the energy security of clean technology value chains (see Section 6). The longlist was reviewed in an internal workshop involving core members of the study team, to define an initial shortlist of 23 factors. The shortlist was then used to identify 14 critical factors, defined as those most interlinked, important and uncertain. Factors for which future development is well understood are not used in the scenario analysis, as they remain relatively constant across scenarios. However, they may still be important as they provide constraints or contextual background for the scenario narratives and to inform SWOT analysis.

To shortlist the critical factors, we first undertook a cross impact-analysis of the longlist to understand potential links between factors (how interlinked they are), and to identify the most important factors. Here we explored 'active' factors with the most influence on other factors in the system, and 'passive' factors, which are most influenced by others. The cross-impact analysis was undertaken by team members with scenario analysis and subject matter expertise. Where appropriate, we drew on inputs from the experts interviewed for the PESTLE analysis. To mitigate against potential bias towards or against certain solutions, evidence was gathered from diverse sources, triangulated and iterated with internal analysis.

The cross-impact analysis process and scoring rubric is elaborated in Box 1.

In addition to the overall systemic impact scores produced by the cross-impact analysis, factors were also scored in terms of:

- Relevance: defined as the extent to which each critical factor in its current state, and possibly in the future, is likely to have an impact on the energy security of clean energy technology value chains.
- Timeliness: defined as how long it will take for each factor – in its current form and in the future – to have an impact on the energy security of clean energy technology value chains.
- Uncertainty: degree to which each factor is predictable.

Factors were then ranked based on their cumulative scores across these four criteria to develop the final shortlist of critical factors.

Box 1 Cross-impact analysis example

Cross-impact analysis

In a cross-impact analysis, subject experts were asked to qualitatively score the relationship between pairs of factors. The scoring scale was:

0 = no impact

1 = weak and delayed impact

2 = medium impact

3 = strong and direct impact

We focused on direct relationships between factors. Every combination of factors was given a score based on the degree to which one factor influences another, for example the degree to which factor X (row) influences factor Y (column). In the extract below, *productivity in the economy* was deemed to have influence on *ICT research*. The influence of *ICT research* on *productivity in the economy* was scored separately (not shown).

Influence matrix

How does Factor A (row) influence Factor B (column)?

Please activate the matrix field you want to start with and click on the "Start" button.

			Digitalisation policy & strategy	European digital single market	Governance approaches	Demand for oil/oil price	Productivity in the economy	Adoption of technologies on a large scale	High use of mobile phones	Consumer, business and industry demand	Digital divide	Demographic changes	Digital skills and competence	Increasing volume of data in the world	Developments in artificial intelligence	Increase in processing capacity of computers and netw	ICT research
Political	1	Digitalisation policy & strategy		1	2	0	1	2	1	2	0	0	0	1	1	1	1
	2	European digital single market	2		2	1	0	3	1	2	1	0	1	1	2	2	2
	3	Governance approaches	3	3		1	0	3	1	1	0	0	0	1	1	2	2
Economic	5	Demand for oil/oil price	0	2	0		2	1	0	2	1	1	0	2	1	2	2
	6	Productivity in the economy	1	1	1	2		0	1	2	0	2	1	1	1	0	0
Societal	7	Adoption of technologies on a large scale	2	2	2	2	1		2	2	1	1	1	2	3	2	3
	8	High use of mobile phones	1	1	1	1	1	2		1	1	2	1	2	2	2	2
	9	Consumer, business and industry demand	1	2	1	1	1	2	1		1	2	1	2	2	2	3
	10	Digital divide	0	0	0	2	2	1	1	2		2	2	2	2	2	2
	11	Demographic changes	0	0	0	2	2	1	2	2	3		2	3	2	2	2
	12	Digital skills and competence	1	0	0	2	2	1	2	1	2	3		2	2	2	2

Cross-impact analysis was undertaken by at least three individuals. Where scores differed by two or more, these were discussed and revised scores agreed.

Step 2: Projections

Following shortlisting of critical factors, projections were produced for each factor within the time horizons (2030 and 2050) of interest to the study. Projections are a key component of the scenario development process as they represent divergent future outcomes that could occur in different scenarios due to uncertainty over a factor's evolution. Starting from evidence on current trends for the factors, the projections indicated possible future development trajectories, and were qualitative in nature. Quantitative projections can be used to provide order-of-magnitude estimates for future changes that may be useful for later discussions on the impact of strategic actions, but they were not used directly in the scenario analysis in this case. Three to four projections were generated for each factor.

Step 3: Scenario identification: consistency and cluster analyses

A consistency assessment was then carried out in a study team workshop (elaborated in Box 2) to assess the degree to which critical factor projections could, or could not, logically co-exist in a given scenario. This analysis was undertaken by completing a scoring matrix across all projections for all critical factors, with each projection pairing given a score between 1 (projections are highly inconsistent with one another) and 5 (projections are highly consistent with one another).

Cluster analysis is then performed by the ScMI software to identify and group clusters of consistent projections. Each cluster has different and distinct characteristics, with one cluster representing one distinct scenario. We selected three scenario clusters to develop into three scenarios covering the period up to 2050, accompanied by a description of the corresponding scenario pathway through 2030. Clusters were selected to ensure a diverse range of future scenarios, reflecting a broad range of challenges for European energy security. For this study, scenarios provide a valuable tool to effectively stress test conditions and assess the energy security of clean energy technology value chains. For example, a scenario with stable global trade and limited competition for resources may not provide as valuable a tool to highlight potential vulnerabilities in value chains compared to more challenging scenarios.

Box 2 Consistency matrix example

Consistency analysis

In the consistency analysis, the relationships between pairs of projections were scored qualitatively. Every combination of projections was given a score based on the degree to which one projection was consistent with another. The direction of influence was not important. Some combinations of projections may not directly affect one another but could appear together in the same future. The rating scale was:

5 = highly consistent

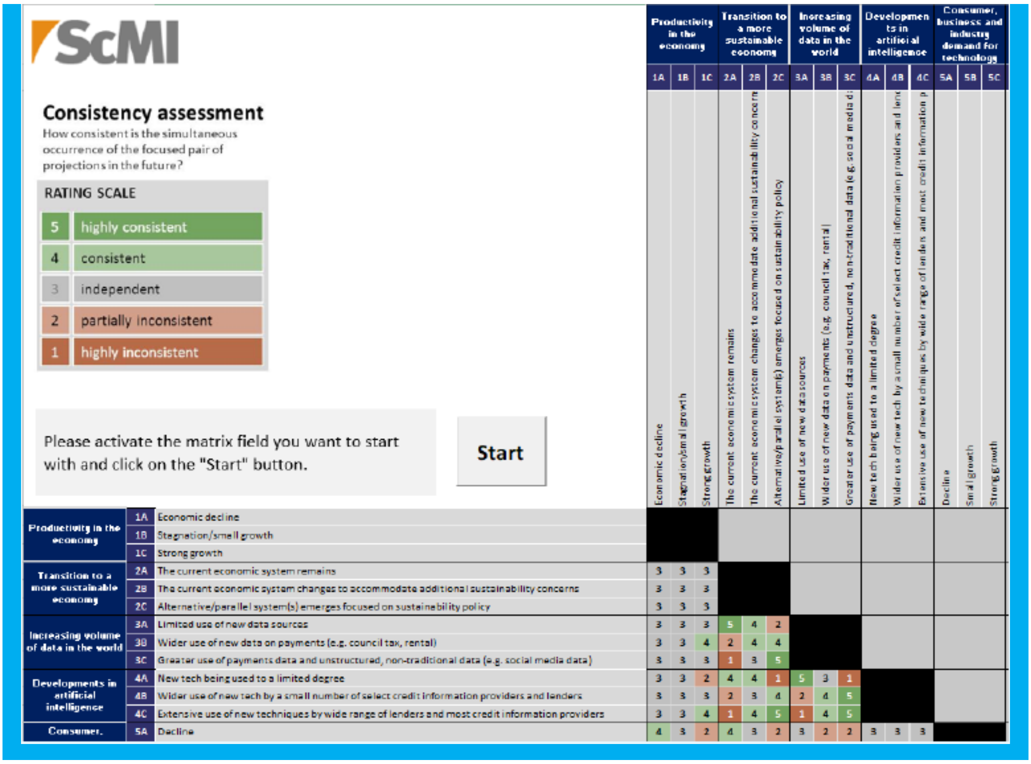
4 = consistent

3 = independent

2 = partially inconsistent

1 = highly inconsistent

The consistency analysis was used to create our scenarios. Using the consistency scores as inputs, cluster analysis was used to identify clusters of projections that consistently appeared together. These helped form the basis of our scenarios. An example of a consistency analysis for technology and digitalisation factors is included below.



Step 4: Scenarios

An important part of the scenario process is to build a concise narrative around the projections for each scenario, with sufficient detail to support subsequent project phases, including modelling, R&I action ideation and stress-testing. The narrative outlines a holistic vision of future scenarios to facilitate this analysis and engage the reader. The narratives provided a description of different and plausible futures, designed to provide sufficient information to test the energy security of individual clean technology value chains and potential impact of R&I interventions. Where necessary, the narrative provided an indicative development pathway for how the scenario has developed relative to the present day. The scenario narratives identify the relative importance of relevant energy security indicators, informed by cross-impact analysis and consistency matrix, with a scoring system to facilitate the use of the scenarios.

5. Description of the GEM-E3 model and its use in the study

Where possible, the scenario narratives will be complemented by quantitative outputs of the GEM-E3 model. The GEM-E3 model was used to quantify the EU's degree of dependence on imported clean energy technologies under different social, economic, energy and climate pathways. GEM-E3 is comprehensive, empirical, large multi-regional and multi-sectoral. The technical basis for the model is a recursive dynamic computable general equilibrium (CGE) model. The model provides detailed insights regarding the interactions of the macro-economy with the environment and the energy system. The following technology value chains are covered and of interest to this study: photovoltaic (PV) panels, wind turbines, batteries, EVs, biofuels, and carbon capture and storage (CCS) technologies.

The GEM-E3 model covers 46 countries/regions and 55 products and is calibrated to a wide range of datasets that include input-output tables (EUROSTAT, GTAP), financial accounting matrices, institutional transactions, R&D expenditures, greenhouse gas (GHG) emission inventories and energy balances (EUROSTAT, IEA), bilateral trade (EUROSTAT, COMEXT, GTAP), investment matrices and household budget surveys, employment (EUROSTAT, International Labour Organization/ILO).

GEM-E3 is an optimisation model which features bilateral trade flows, where the origin and destination countries are defined. Moreover, the model places special emphasis on the representation of the energy system featuring specialised bottom-up modules of power generation, buildings and transport. The model adopts a sequential dynamic mechanism (solved period by period) where agents assume that current prices and demand will persist. The model delivers projections of the economic and energy systems in five-year periods from 2015 to 2050.

The model has been extended to separately represent the manufacturers of clean energy technologies (e.g. supply of wind turbines, PV modules, batteries, biofuels, etc.) by country. This enables better projections of clean energy technology markets and key suppliers (countries). The size of the market in the model depends mainly on climate/energy policies, trade policies (e.g. autarky vs trade openness), R&D, and dynamics in production techniques and consumption patterns. The model represents these factors endogenously and is able to estimate market size in different contexts. Regarding the dynamics of the suppliers, the model is largely constrained by base year market shares unless explicit policies are exogenously introduced. This means that changes in market mix that are driven by substitution elasticities are not enough to structurally/significantly change the composition of the market, as opposed to explicit R&D, investment or trade policies (e.g. imposition of trade restrictions). The model captures the production structure of clean energy technologies, identifying the share of intermediate and imported inputs to total production and supply, while it endogenously computes bilateral trade flows (endogenous representation of the technology flow matrices).

In this study, the model has been used to project the market of the different clean energy technologies under different climate policies aimed at reducing GHG emissions, different prioritisation of R&D and different trade policies. In each scenario, the model calculated the costs and capacity of countries required to meet domestic demand. The model calculates the gap between supply and demand per country and under the different scenario settings and presents the potential of each country to minimise this gap (when in deficit) for each technology represented in the model.

Figure A.3 Schematic representation of the GEM-E3 model

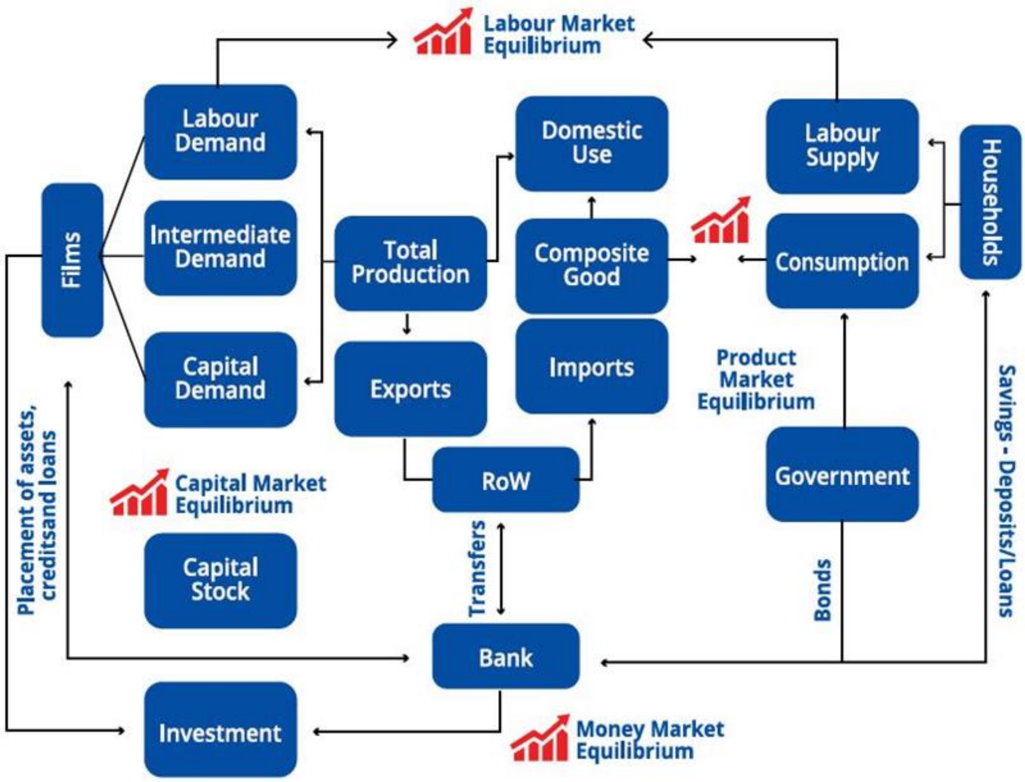


Table A.2 presents the key climate and trade assumptions used to quantify the different scenarios. In Scenario 1, the EU attains net zero emissions by 2050, while non-EU countries do not actively pursue efforts to reduce GHG emissions. Scenario 2 replicates Scenario 1, but with non-EU countries successfully decarbonising by 2050. In Scenario 3, the EU falls significantly short of the net zero target, with non-EU countries maintaining the same ambition as in Scenario 1. Notably, an additional facet of Scenario 3 is the introduction of trade restrictions – specifically almost complete bans on imported industrial and agricultural products to the EU from any non-EU trade partner. Scenario 3B (high EU ambition) mirrors the assumptions of Scenario 1, but with additional implementation of trade restrictions. The percentages presented in Table 9.1 signify the reduction in GHG emissions from 1990 levels. In Scenarios 1, 2 and 3B (high EU ambition), the EU successfully attains its nationally determined contribution (NDC) targets and achieves net zero emissions by 2050. However, in Scenario 3, the EU meets the targets outlined in the EU Reference Scenario 2020. Non-EU countries reach their NDC targets by 2030 in all scenarios; between 2030 and 2050, these countries generally do not actively pursue significant decarbonisation efforts, with the exception of Scenario 2, where non-EU countries attain net zero emissions by 2050 based on the net zero pledges announced at COP26.

Table A.2 Scenario assumptions[3]

Scenario Label:	GHG emission reduction from 1990 levels		Trade restriction
	EU	Non-EU	
Scenario 1	55% (2030), net zero (2050)	72% increase (2030), 74% increase (2050)	No
Scenario 2	55% (2030), net zero (2050)	72% increase (2030), 2% increase (2050)	No
Scenario 3	40% (2030), 65% (2050)	72% increase (2030), 74% increase (2050)	All industries, ethanol, agriculture
Scenario 3B (high EU ambition)	55% (2030), net zero (2050)	72% increase (2030), 74% increase (2050)	All industries, ethanol, agriculture

6. Methodology for the energy security assessment of clean energy value chains

The energy security assessment of clean energy value chains was carried out in five main steps:

1) Identification of representative value chains under each of the clean energy technology categories within scope.

2) Definition of a comprehensive set of energy security indicators to operationalise the energy security assessment of the value chains.

3) Assessment of the energy security indicators for each of the clean energy value chains.

4) Compilation of a longlist of energy security criticalities for 2030 and 2050

5) Definition of a shortlist of key energy security criticalities

The shortlist of key energy security criticalities formed the main outcome of the energy security assessment, providing the basis to identify R&I interventions, as described in Section 6.5.

All five steps of the methodology are explained in more detail below.

[3] US Inflation Reduction Act (IRA) and REPowerEU investments plans are not included in the scenarios.

6.1. Value chain selection

6.1.1. Selecting energy value chains

In this study, we assessed energy security risks associated with the 17 technology categories listed in the TOR for this study: advanced biofuels, bioenergy, concentrated solar energy, geothermal energy, hydropower, ocean energy, photovoltaics, wind energy, renewable and solar fuels, carbon capture utilisation and storage, electricity and heat storage (including batteries), hydrogen and intermediate energy carriers, heat pumps, smart energy grid technologies, energy building and district technologies, off-grid energy systems, energy transmission and distribution technologies, and smart cities. Each of these categories refers to a broad technology and may encompass several distinct energy value chains. In selecting the value chains for assessment, balance was sought between compiling a representative set of value chains, capturing those aspects of each category most relevant for energy security, and limiting the total number of value chains for feasibility reasons.

For practical reasons considered during the identification of the value chains, we slightly adjusted or rearranged some of the technology categories listed above. We separated electricity and heat storage (including batteries) into: 1) batteries and 2) other electricity and heat storage technologies. We separated hydrogen and intermediate energy carriers into 1) hydrogen and 2) intermediate energy carriers; however, the latter category was considered redundant since other intermediate energy carriers are already discussed in other categories. Instead, we included renewable fuels of non-biological origin as a distinct category that covers the utilisation part of the carbon capture, utilisation and storage category. We renamed renewable and solar fuels as direct solar fuels.

6.1.2. Gathering and defining energy value chains

The 2022 Clean Energy Technology Observatory (CETO) reports were used as a starting point to identify energy value chains associated with each of the 17 categories. It should be noted that the representative energy value chains we selected represent a subset of all the possible energy value chains that could have been included. Indeed, there is no single level at which a value chain can be defined, as any value chain could be replaced at will by allowing for variation in one of its elements. Therefore, we had to balance the level of detail offered by a high number of distinct value chains against depth of assessment possible for each value chain, given limited resources.

At the same time, the selection should be representative regarding its aim – namely assessment of energy security risks. If the distinction between two value chains is not expected to impact energy security, it is not useful to include them both. This implied a preliminary, broad understanding of the main drivers for energy security, without pre-empting the energy security assessment of the value chains themselves, which was achieved by selecting the energy security indicators (see Annex A, Section 4.1 and Annex B) in parallel.

Combining the considerations above, we roughly defined a distinct, representative value chain based on similarity in four aspects, with the focus on (potential) energy security risks:

1. The value chain uses a distinct source of energy (e.g. solar, wind etc.).

2. The value chain has a specific technological principle or mechanism or technological specifications.

3. The value chain is used, applied or deployed in a similar manner within the energy system, and/or at a similar location.

4. The value chain contains or uses a specific set of material inputs, where we focus on CRM[4].

Furthermore, as specified in the TOR, our selection included a mix of energy value chains that already fulfil important roles in Europe's energy system (high technology readiness level/TRL), or that are currently being researched or developed and may fulfil a role in Europe's future energy system (low TRL).

In Section 7.4 of the main report, we present the selected energy value chains by technology category, referring to the four principles mentioned above where applicable. For each technology category, between one and four distinct value chains were selected, making a total of 48 value chains for further assessment in this study.

6.2. Energy security indicators

The energy security risks associated with the 48 identified value chains were assessed by evaluating and scoring 10 energy security indicators: geopolitical availability of CRM, abundance of CRM (or biomass), circularity, supply chain complexity, supply chain location, digital vulnerability, physical vulnerability, broader sustainability, affordability and skills. These indicators were selected in consultation with the client based on TOR guidance and literature, while limiting the maximum number of indicators to 10 for feasibility reasons.

As a broad understanding of energy security was used in this study, the indicators include geopolitical, technical and socio-economic aspects. Although not exhaustive, they represent the most important features of energy security for the expansion of (emerging) clean energy technologies, while retaining mutual independence and preventing overlap as far as possible. Table A.3 provides a general definition of the energy security indicators used in this study. In the next Section, we provide more detail of how these indicators were deployed in the energy security assessments – i.e. how they were interpreted and scored.

Table A.3 Energy security indicators

Indicator	Definition/relevance to energy security
Geopolitical availability (CRM)	Geopolitical availability of CRM (as defined in the EU's list of CRM) is defined by the number of countries from which they are available and the political risks associated with dependence on those countries. The CRM required to build and operate the technology are ideally available within (multiple countries in) the EU. Importing raw materials from outside the EU is a potential threat to energy security, especially if there are only a limited number of countries exporting the materials.
Abundance (CRM)	Critical raw materials are available in finite quantities, limited by the scale of mining and/or natural reserves. Sufficient raw materials required to

[4] As defined in the Study on the critical raw materials for the EU 2023 - Publications Office of the EU (europa.eu). https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

Indicator	Definition/relevance to energy security
	operate the technology should be available. High dependency on low-abundance materials poses a threat to energy security.
Circularity	Technologies can be recycled at end-of-life within the EU to supply resources for new products within the EU economy. This reduces reliance on external suppliers and promotes resource autonomy and energy security. Also, EU legislation will increasingly require standards in terms of circularity and recycling, making non-recyclable technologies more vulnerable to future upscaling.
Supply chain complexity	Supply chain complexity is defined by the length of the supply chain as well as the number of components required to produce a technology. Technologies that require highly specialised components or expert knowledge to build and operate can be disrupted more easily than simpler technologies. The same applies to long supply chains, with a relatively high number of steps.
Supply chain location	As per the assumptions made by this study, if a large part of the supply chain lies outside the EU, the energy value chain is considered more vulnerable.
Digital vulnerability	Technologies that are more reliant on digital infrastructure can potentially be disrupted. This can apply to comparatively decentralised technologies, or technologies that are more reliant on continuous information inputs, with varying vulnerability to cyberattacks.
Physical vulnerability	Physical vulnerability refers to the physical infrastructure and situation of clean energy technologies and their value chains. Some value chains are vulnerable to physical disruption, for example from extreme weather events or deliberate sabotage. Centralised value chains (e.g. offshore wind turbines) are also more vulnerable to physical threats than decentralised value chains (e.g. solar PV).
Broader sustainability	Broader sustainability considers broad aspects of the UN Sustainable Development Goals (SDGs), where non-compliance is viewed as a risk. For example, social (e.g. poor working conditions) or environmental conditions (e.g. threats to local water/food availability, biodiversity impacts, pollution) may pose a risk to the energy security provided by clean energy technology value chains to – due to increasingly strict legal requirements (compliance with which is assumed) or public opposition by EU citizens, for example.
Affordability	Technologies with high costs (relative to other technologies with a comparable role in the energy system) threaten energy security because

Indicator	Definition/relevance to energy security
	higher societal costs limit options to mitigate other energy security issues and may lead to disruption for consumers unable to afford energy.
Skills	Value chains that require a large or specifically skilled workforce can limit the large-scale deployment of a technology.

6.3. Energy security assessment of value chains

All 48 clean energy technology value chains were assessed using the same format. The resulting factsheets are presented in Annex C.

The first part of the factsheet, covering 'characteristics', provides a brief description of the technology, including the value chain's role in the energy system and some technical information such as its primary energy source (if applicable), TRL, and a description of its life cycle phases (construction, use, end-of-life). In the second part of the factsheets, the 10 energy security indicators were evaluated and scored. For each indicator, a qualitative assessment was given, followed by a score based on this assessment. Three different scores could be assigned: 1 (low risk), 2 (moderate risk) or 3 (high risk). The assessment reflects a time-independent risk level – i.e. the extent to which each value chain is intrinsically vulnerable to the energy security risks associated with the indicators[5]. The scores are intended as relative to risk levels for the other value chains, to enable conclusions on which risks are most pronounced across the technologies in scope.

The relative nature of the energy security risk assessment meant that harmonisation of the assessment of indicators and the resulting scores was key. Understanding of the indicator and the three scoring levels were therefore pre-defined. In addition, for some value chains a specific, more quantitative methodology was developed to assess all value chains (e.g. geopolitical availability) in the same way. **Error! Not a valid bookmark self-reference.** shows how each indicator was interpreted in the context of the assessment, and which criteria were used to assign scores.

All assessments based on in-house expertise and literature research, with the sources used indicated in the factsheets in Annex C. In some specific cases, external expertise was used. Commission experts were given the opportunity to feed back on assessments of the value chains in their area of expertise.

Table A.41 Harmonisation of interpretation and energy security indicator scores

Indicator	Interpretation, method and/or definition of scoring
	Methodology

[5] The time aspect is introduced by the scenarios, which determine the extent to which risks materialise. See Annex A, Section 6.4 on compilation of the longlist.

Geopolitical availability (CRM)	Based on the 2023 Study on the Critical Raw Materials for the EU, supply-risk was used as a proxy for our indicator. This covers sourcing and geopolitical risk, import reliance, trade restrictions, supply chain bottlenecks, end-of-life recycling input rate and substitution index. The score for each CRM in the value chain is indicated. Next, the scores of different CRM were averaged and rounded to the nearest whole number, providing the total score for the value chain.
	Definition of scores Only defined for CRM. If a technology does not contain CRM, this indicator is not applicable (N/A). For each CRM: - Score 1: supply risk <2 - Score 2: supply risk 2–3 - Score 3: supply risk >3
Abundance (CRM)	**Methodology** On basis of the abundance risk level (ARL) values, i.e. abundance in Earth’s crust [ppm]. ARL ranges from 1 to 5 (1 meaning >10 000 ppm, i.e. low risk, and 5 meaning <0.01 ppm, i.e. high risk).
	Definition of scores Only defined for CRM and for biomass in cases where biomass is the feedstock needed for a value chain. For each CRM: - Score 1: ARL 1–2 - Score 2: ARL 3 - Score 3: ARL 4–5 For biomass scores are established based on assessment of (sustainable) biomass availability from literature.
Circularity	**Interpretation** Situation in the reuse, repurposing and recycling of assets of the technology. Which materials can already be recycled? Which cannot, and what is the implication of this? What policies are in place or expected regarding recycling?
	Definition of scores - Score 1: Most materials are already being recycled or there is a concrete policy (in the making) to recycle a large part of the technology (e.g. batteries). - Score 2: Definition of Score 1 is not met, but there is significant potential to recycle key materials used in the technology (e.g. solar PV). - Score 3: Key materials used in the technology are very difficult to recycle at all.
Supply chain complexity	**Interpretation** This indicator poses a higher energy security risk if the chain is longer (many intermediate products), if more supply (sub) chains come together at

	the same time, and if the technology contains (many) complex/specialist components.
	Definition of scores - Score 1: There are no significant complexities involved in the supply chain. - Score 2: There are some aspects that introduce complexity to the supply chain. - Score 3: The supply chain is particularly complex compared other supply chains.
Supply chain location	**Interpretation** This indicator poses a higher energy security risk if a large part of the supply chain is located in non-EU countries and/or the number of suppliers is very limited globally. As far as CRM are concerned, there is a correlation with the geopolitical availability indicator, but supply chain location also applies to other links in the supply chain. **Note:** if a value chain is geographically limited to certain locations (e.g. geothermal energy, or concentrated solar energy), this is not considered an energy security risk, but an (external) system limitation.
	Definition of scores - Score 1: Technology components are manufactured in the EU and/or there are multiple global suppliers. - Score 2: Components/materials are partly available in EU countries or have the potential to be sourced/manufactured in EU. -Score 3: Most of the supply chain is located outside the EU.
Digital vulnerability	**Interpretation** Degree to which the technology is digitalised, or depends on digital infrastructure with associated vulnerability to cyberattacks and/or data theft.
	Definition of scores - Off-grid: N/A - Score 1: The technology is decentralised (damage very local). - Score 2: A digital attack can cause significant (physical) damage. - Score 3: the technology is ‘smart’ and highly dependent on digital connection (e.g. autonomous driving). If the value chain is highly dependent on electricity supply, a score of 2 is given as the electricity grid itself is also vulnerable to cyberattacks.
Physical vulnerability	**Interpretation** Extent to which the value chain can be (negatively) affected by physical circumstances/disruptions: for example vulnerability to extreme weather, risk of sabotage, but also dependence on certain physical circumstances (sunlight, stable electricity network, etc.).
	Definition of scores - Score 1: There are no significant physical risks associated with this technology.

	- Score 2: There are some additional physical vulnerabilities, compared to similar value chains scoring a 1. - Score 3: Severe consequences are identified with respect to physical vulnerability.
Broader sustainability	**Interpretation** In principle, this indicator covers all SDGs, but the most relevant sustainability aspects for energy security are land/water use (with food/water availability as a derivative), environment and biodiversity. In some cases, labour conditions in the value chain and health are relevant. Energy security risks run through legislation, but also through public opinion/support related to broader sustainability issues.
	Definition of scores - Score 1: Technology is not related to any broader sustainability issue. - Score 2: There are some broader sustainability issues. - Score 3: Severe issues are identified with respect to broader sustainability.
Affordability	**Interpretation** Where applicable and available in data sources: levelised costs of energy/heat (LCOE/H) in EUR/kWh, otherwise (e.g. due to low TRL): estimate in relation to comparable technologies with the same role in the energy system. Exceptionally, for this indicator the risk is less intrinsic to the technology as it is time-bound and driven by external circumstances. Therefore, whether costs are expected to decrease (significantly) in the future is also indicated.
	Definition of scores - Score 1: Technology is cheaper than competing technologies. - Score 2: There are strong indications that technology will be highly cost competitive in the future and/or is somewhat more expensive similar competing technologies. - Score 3: Costs are very high for this technology, and/or TRL is not mature enough to give a reliable future cost estimate.
Skills	**Interpretation** This indicator concerns the size of the skilled workforce (related to expected implementation of the technology) and the specific skills needed (availability of potential labour and time needed for training). Typically, installation skills and research skills are distinguished.
	Definition of scores - Score 1: Workforce is readily available or has potential to be. - Score 2: There are some aspects that limit the availability of required workforce. - Score 3: Labour demand is very high, or will be in the future, but there are severe supply side limitations.

6.4. Longlist of energy security criticalities

In this step, assessment of the energy security indicators for each value chain was combined with information from the three scenarios to add the time dimension to the energy security assessment. This resulted in a longlist of energy security criticalities for 2030 and 2050. Below, we explain in more detail how the longlist was compiled.

As explained in Annex A, Section 5, the scenarios used in this study stress certain combinations of energy security indicators, for both 2030 and 2050. The longlist of energy security criticalities should then reflect any energy security risk that may materialise in 2030 and 2050, resulting from both intrinsic risks (the indicator scores from the value chain assessments) and how the energy security indicators would be further stressed in the three scenarios (the RAG ratings).

Table A.5 Scoring approach for energy security indicators

Energy security indicator score/scenario RAG rating of energy security indicator	green	amber	red
1	Not on longlist	Not on longlist	For discussion – to include on longlist
2	Not on longlist	For discussion – to include on longlist	Include on longlist
3	Include on longlist	Include on longlist	Include on longlist

As a general approach, the list should include energy security indicators that already have high intrinsic risk based on the value chain assessment, as well as energy security indicators that have a low or moderate intrinsic risk but are additionally stressed under the assumptions of the scenarios considered. To harmonise our approach and explicitly define our cut-off strategy for the longlist, we developed the matrix below (Table A.5). The energy security indicator core assessment score shown vertically combined with the RAG rating for the under a certain scenario/projection year on the horizonal yields three possible outcomes: not on the longlist, always on the longlist, or up for discussion. The longlist of energy security criticalities was created by evaluating this matrix for each indicator and each value chain, and included a to-be-discussed category for which inclusion was conditional on the outcome of further assessment[6].

For example, if the indicator "geopolitical availability of CRM" was assigned a score of 1 for a certain value chain, it was not included on the longlist if the RAG rating for the scenario/projection year combination was either green or amber. If the RAG rating was red, inclusion on the longlist was up for discussion. The combination 1/red would reflect the

[6] This discussion was carried out as part of the assessment leading to the shortlist of key criticalities (see main report, Section 7.3). 'To-be-discussed' items on the longlist were checked to ensure no key issues had been overlooked, effectively awarding them a 'wild card' to end up on the shortlist should there be strong reasons to include them. All items on the 'to-be-discussed' were thus either included on the shortlist or dropped altogether.

geopolitical availability of raw materials not generally being an important issue for a value chain's energy security, but geopolitical relations being highly stressed in this specific scenario and projection year, making the availability of almost any raw material from outside Europe a challenge.

If "geopolitical availability" was considered a high risk (3), it was included on the longlist regardless of the RAG rating of the scenario, as this reflects an intrinsic risk for energy security for the value chain. Where "geopolitical availability" was assigned a score of 2, it was not included if the RAG rating was green, always included if red, and up for discussion if amber.

Thus, for each value chain and each scenario, the matrix was used to determine whether each energy security indicator was included on the longlist, or if inclusion remained to be discussed. Energy security criticalities were thus defined as combinations of technology value chains and security indicators – for example, 'hydropower dam – physical vulnerability' or 'perovskite cells – affordability'.

Each scenario was built around two projection years (2030 and 2050) with different RAG ratings for each year. The methodology described above thus yielded two separate longlists, one for 2030 and one for 2050. At this stage of the energy security assessment, we deemed this a useful distinction in the context of how the scenarios were developed: the energy security situation, and hence the criticalities, can be different for 2030 and 2050.

According to this methodology, the same criticality can enter the longlist through different routes. For instance, if a certain indicator was assigned a score of 2, it would be included on the longlist through any scenario with a red RAG rating for that indicator, and additionally on the discussion list through any scenario with an amber RAG rating for that indicator. Any indicator scoring a 3 would always enter the longlist through all three scenarios.

At this stage, we did not assign relevance to the number of scenarios through which criticalities were included in longlist, which should include any significant energy security risk. However, the number of scenarios through which a criticality entered the longlist was important to shortlisting key energy security criticalities (see next paragraph). Therefore, the longlist presented in Annex D is presented as a 'heatmap', showing indicators longlisted through 1, 2 or 3 scenarios (or 0, so not longlisted) for each value chain. We also made a distinction between indicators directly included on the longlist, and those in the to-be-discussed category, as well as between the projection years 2030 and 2050.

6.5. Shortlist of key energy security criticalities

To sharpen the focus of the study, we developed a shortlisting methodology to select the most relevant criticalities. Contrasting the score-based approach to longlisting, shortlisting took the form of a qualitative assessment based on expert judgment across several criteria[7]. Our aim was to select which of the longlisted criticalities are most crucial to address for the future energy security of the EU (key criticalities for energy security).

Also in contrast to the longlist, the shortlist was compiled at the technology-, rather than value-chain, level. Shortlisted criticalities thus took the form of a technology category combined with an energy security indicator: 'wind energy – physical vulnerability', for example. The shortlist does not distinguish between projection years, as R&I interventions based on the shortlist would not use this distinction. Rather, the time-based development

[7] Carried out at a whole-day internal consortium workshop involving experts from both CE Delft and RAND Europe.

apparent from longlisting for both 2030 and 2050 was used as one of the criteria in the shortlisting process (see below).

To define the shortlist of key criticalities for energy security, the following steps were carried out. First, the number of scenarios through which the energy security criticalities were included on the longlist was considered, making use of the ‘heatmap’ in Annex D. Without predicting the future, the scenarios represent plausible future trajectories. Thus, if an aspect of energy security appears as a criticality in all three scenarios, it is more crucial to address than those considered a criticality in only one scenario.

As the shortlisting was done at technology level, this step also entailed aggregation of assessment results from the value-chain level to technology category level. Indeed, if an energy security indicator was critical across all four value chains assessed under a particular technology category, this would strengthen the case for it to be considered a key criticality for energy security for that technology. If the same indicator rated as a criticality for only one value chain, there would be less reason to consider it a criticality for the technology as a whole[8].

Where the heatmap did not conclusively define whether a criticality should be shortlisted, other criteria were considered. These included:

- Development in time: was the criticality longlisted only in 2030 or 2050, or in both years? Would the criticality only delay transition towards a secure clean energy system, or disrupt it?

- Nature of criticality for a specific value chain: what concrete risks were identified in the assessment? Was there a single risk or an accumulation of smaller risks under the same indicator (e.g. for physical vulnerability or broader sustainability)?

- Expected scale: how great a contribution is the expected share of the technology expected to make to the future energy system – for example, in terms of share of generation capacity or external limitations?

- Expected role: what is the (current and) expected role of the technology in the future energy system? Are there alternatives?

After a preliminary decision was taken on the shortlisting of each criticality on the longlist, the shortlist was further rationalised and harmonised by looking across all technology categories and comparing key criticalities. This led to two concrete adjustments:

- Some common CRM, in particular copper and aluminium, were longlisted as a criticality for a high number of value chains. Because these CRM are not particularly rare but identified as CRM because they are required for almost all basic devices and electronics, they were considered more of a system criticality than a criticality for specific technologies. Therefore, we decided to shortlist geopolitical availability and/or abundance of CRM in all cases where these were initially longlisted, to avoid making arbitrary distinctions.

- In our assessment, the vulnerability of value chains requiring high volumes of (renewable) electricity to disruptions in the electricity network was noted several times.

[8] For instance, if broader sustainability was longlisted as a criticality for all value chains under a technology category, this suggests there would be little room to bypass these sustainability issues for the technology – reason to consider it a key criticality. If it appeared on the longlist for only one value chain, there would be less of an argument for including it on the shortlist of key criticalities.

To ensure consistency, ‘physical vulnerability’ was therefore shortlisted as a key criticality for all technologies using high volumes of electricity.

Lastly, the shortlist was finalised by including brief descriptions of the specifics of each key criticality identified. For instance, if for a certain technology category ‘physical vulnerability’ was shortlisted, the characteristics of this vulnerability were briefly explained. The shortlisted key criticalities were shared with the validation workshop participants in this format as preparatory material.

7. Methodology for the development of the R&I action plan

This section presents the methodology used to develop an R&I action plan to strengthen the energy security of European clean energy technologies.

7.1. Landscape review and mapping of existing and relevant EU and national R&I programmes

We carried out a literature review to identify existing relevant EU and national R&I programmes, focusing on the top 10 largest funders (identified in Table A.6). This enabled the study team to identify where action is being taken, with a view to identifying any gaps regarding criticalities for energy security – and ensuring that potential R&I interventions later identified would be complementary, relevant and effective. The review included R&I programmes announced as part of the Multiannual Financial Framework, the Recovery and Resilience Facility, Next Generation EU, Horizon Europe and the ETS Innovation Fund, the communication on a global approach to research and innovation, and the New European Innovation Agenda. The review was non-exhaustive, with an initial high-level search for R&I taking place for each technology in scope, followed by a more targeted review to identify R&I specifically related to the key energy security criticalities identified.

In additional to EU programmes, the study team also carried out desk-based research to identify non-EU countries with R&I programmes, or interest, in the relevant clean energy technology value chains, including countries associated with Horizon Europe or Mission Innovation, other third countries in the G7, and five additional G20 or African Union countries. This was a relatively light touch to provide a basis for further research on promising, relevant R&I interventions, and to identify potential international collaborations. The landscape review focused on the prominent energy R&I funders listed in Table A.6 below.

Elements of clean energy technology value chains may not necessarily fall within the scope of energy R&I programmes (e.g. cybersecurity and semiconductor chips), and further desk-based research was carried out to identify relevant R&I activities. However, this study did not identify significant evidence in these areas relevant to the energy technologies of interest.

Ongoing and planned R&I programmes identified in this stage were included in the SWOT analysis for each technology.

Table A.6 Top funders for the landscape review of EU and national R&I programmes[9]

Top 10 energy R&I funders in the EU
EU (including Horizon Europe, European Commission Cohesion Fund, Connecting Europe Facility, European Investment Bank, European Regional Development Fund, Invest EU, European Innovation Council, Just Transition Mechanism, LIFE: Clean Energy Transition, Recovery and Resilience Fund, Innovation Fund, European energy programme for recovery, European structural and investment funds, European Cooperation in Science and Technology), France, Germany, Italy, Netherlands, Belgium, Sweden, Austria, Spain and Poland
Top international energy R&I funders for consideration in collaborations
Horizon Europe-associated countries: Norway, New Zealand, United Kingdom, Canada, Turkey
G7 countries: Japan, United States
G20 countries: South Korea, Mexico, South Africa
African Union countries

7.2. Methodology to develop the R&I action plan

One central aim of this study is to develop an action plan for R&I to maintain and strengthen the energy security of EU clean energy value chains. The study team drew on the technology value chain analysis, the landscape analysis of planned EU R&I programmes, strategic management tools (SWOT and least regrets) and the wider expertise of participants in the validation workshop to develop a feasible action plan to be delivered in the next 10 years, with potential impact by 2030 and beyond.

7.2.1. Development of a longlist of R&I challenges for energy security criticalities of clean energy value chains

Taking the shortlisted energy security criticalities from the value chain analysis, the study defined corresponding R&I challenges – tangible initiatives or missions targeted at a criticality area to increase energy security. For example, for the energy security criticality 'wider sustainability and environmental impacts', the corresponding R&I challenge was 'how can environmental impacts be reduced or mitigated?'.

An initial filtering was carried out in the process of defining of R&I challenges, to exclude measures outside of the scope of the study. For example, energy security criticalities for installation skills or security issues, such as sabotage, were removed from the list for future consideration as these are not relevant to R&I.

The longlist of R&I challenges for each energy security key criticality was later reviewed by validation workshop participants as part of a pre-workshop exercise (Annex A, Section 8.3).

[9] IEA (2020), Energy Technology RD&D Budgets.

7.2.2. SWOT analysis

SWOT analysis is a management tool that looks at external opportunities and threats and internal strengths and weaknesses to identify key areas for strategic intervention and planning.[10] SWOT analysis is an effective technique to examine the performance, risks and potential of a strategy targeted at a given outcome. It has the added benefit of bringing together different sources of evidence and building in futures analysis, being more forward focused than other management tools[11]. Understanding overlaps and alignment between strengths, opportunities, weaknesses and threats provides a framework to discuss prioritisation of actions and how they interact. For example, where a strength and opportunity align, an intervention could lead to greater energy security with potential for wider benefit such as exports. Considered within the wider SWOT analysis, this intervention may emerge as more fundamental to ensure overall energy security than other interventions, because it builds on an existing strength – and is therefore more likely to be delivered quickly and effectively. The ranking of strengths, weaknesses, threats and opportunities also provides a wider context for the development, discussion and refinement of a strategic plan.

Drawing on the R&I landscape analysis, PESTLE analysis and further desk-based research, SWOT analysis was carried out for the R&I ecosystem of each technology and the specific R&I challenges identified in the previous step. The SWOT analysis was used to assess the internal strengths and weaknesses of EU R&I capability regarding the challenges in question, and existing opportunities for collaboration with external markets, as well as solutions and threats – for example through increased competition from other countries with strong R&I and businesses.

The study team populated a SWOT matrix for each technology with relevant metrics and findings to identify the corresponding SWOT relationships for each R&I challenge. We examined the relationship between the different SWOT groups to identify R&I challenges with potential to deliver on opportunities, mitigate threats, manage risks from weaknesses and maintain strengths – and thus define specific R&I interventions and their timing. Some examples are highlighted below to illustrate the nuances considered in assigning appropriate SWOT categories:

- Lack of planned R&I activities in the EU (internal weakness) and an increased external market were seen as likely to impact research leadership of the EU and result in a brain drain (external threat).

- Existing international (i.e. with non-EU countries) partnerships were classified as opportunities for collaboration. Partnerships between EU countries (i.e. collaborations between EU countries, or with EU-based businesses) would a strength.

- External (non-EU) academic research is included as an opportunity for collaboration. However, research by non-EU businesses poses a threat to EU businesses, exports and R&I activities, as it creates competition – the same is true for non-EU national policies (e.g. US Inflation Reduction Act/IRA).

To support this analysis, we used specific metrics and evidence sources outlined in Table A.7. The SWOT analysis was further reviewed following input from the validation workshop.

[10] Gomer, J. & Hille, J., An essential guide to SWOT analysis. Fertel, C. et al (2013), Canadian energy and climate policies: a SWOT analysis in search of federal/provincial coherence, Energy Policy 63, 1139-1150, Chen, W.-M. et al (2014), Renewable energy in eastern Asia: renewable energy policy review and comparative SWOT analysis for promoting renewable energy in Japan, South Korea and Taiwan, Energy Policy 74, 319-329.

[11] Nazarko J. et al (2017), Application of Enhanced SWOT Analysis in the future-oriented public management of technology. *Procedia Engineering* 182, 482-490.

Table A.7 Metrics for SWOT analysis

Strength/Weakness (internal to EU): • State of EU R&I capability (number of publications and patents, previous relevant R&I programmes, existing R&I infrastructure, workforce, existing/past collaborations, existing R&I investment) • Existing EU regulation, standards and legislative frameworks • Existing networks, relationships and agreements • Existing scientific and technical knowledge
Opportunity/Threat (external): • Relevant R&I programmes in other countries – opportunity for collaboration or threat from competition • Shared challenge with other countries – opportunity for collaboration • PESTLE trends that might impact EU R&I capabilities • Availability of technological solutions or technological trends relevant to the criticality

As the output of the SWOT analysis, each R&I challenge was assigned a 'SWOT category': strength-threat (S-T), strength-opportunity (S-O), weakness-threat (W-T) or weakness-opportunity (W-O). The criteria used to assign a SWOT category are described in Table A.8. R&I challenges categorised as W-T were prioritised for action – as the highest potential risk to energy security – with associated strengths and opportunities used to help define the most appropriate R&I interventions.

R&I challenges categorised as S-T formed the second group for prioritisation, as they represent areas where it is important to maintain energy security. R&I challenges categorised as S-O form the third group for prioritisation, with possible broader potential to benefit the EU beyond mitigating threats or maintaining energy security. Unless the number of R&I challenges is small due to overlapping criticalities in energy technology value chains, challenges categorised as W-T were seen as lower priorities. This is explained in further detail in Annex A, Section 7.2.4.

Table A.8 Criteria for SWOT categorisation

SWOT category	Criteria for assignment
Strength-threat	The EU has a strong R&I ecosystem in the technology area, and is potentially already (though not necessarily directly) addressing the energy security criticality with R&I. The global context of R&I is highly competitive, with significant investment outside the EU, particularly in the private sector where knowledge will not be shared. No technology solution is available or the trends influencing the energy security criticality are a threat (e.g. cyber threats are continuously evolving).
Strength-opportunity	The EU has a strong R&I ecosystem in the technology area, and is potentially already (but not necessarily directly) addressing the energy security criticality with R&I.

	The global context for R&I presents potential for collaboration, with shared challenges and public investment outside the EU. Potential solutions are already in development.
Weakness-threat	The EU R&I ecosystem is less globally competitive, with non-EU countries dominating publications, patents and/or investment. The global context for R&I is highly competitive, with significant investment outside the EU, particularly in the private sector where knowledge will not be shared. No technology solution is available or trends influencing the energy security criticality are a threat (e.g. cyber threats are continuously evolving).
Weakness-opportunity	The EU R&I ecosystem is less globally competitive, with non-EU countries dominating publications, patents and/or investment. The global context for R&I presents potential for collaboration, with shared challenges and public investment, outside the EU. Potential are already in development.

7.2.3. Definition of potential R&I interventions and impact-feasibility analysis

The SWOT analysis provided an evidence base for the initial definition of R&I interventions. With an understanding of the EU R&I landscape and international activities, the study team defined R&I interventions to deliver solutions to the R&I challenges. The type of R&I intervention suggested was based on the state of the R&I ecosystem: whether solutions are already in development, and whether public or private investment is needed. Exemplar categories of R&I interventions and the rationale for suggesting them are presented in Table A.9. R&I challenges already being addressed by EU R&I programmes were identified.

The potential R&I interventions were tested with validation workshop participants. Participants were invited to suggest alternative R&I interventions and discuss the relevance, feasibility and potential impact of the proposed R&I interventions using a feasibility-impact matrix activity (see Annex A, Section 8). Considerations for successful implementation and methods of futureproofing R&I interventions were also discussed.

Following the validation workshop, R&I interventions were refined into R&I actions for inclusion in the R&I action plan, based on feedback from the workshop participants. R&I interventions identified as having low potential impact were automatically discounted or modified to increase the potential impact of the R&I action plan.

The study team and validation workshop participants also considered where R&I might not be the solution to a challenge or criticality, and where policy, regulation or other types of intervention might be more beneficial.

Table A.9 Categories of R&I interventions

R&I intervention	Relevance
Collaborative industry R&I programmes	Typically suitable for medium to high TRL technologies. Industry collaboration develops technologies towards commercialisation and provides support to develop new supply chains and transfer skills across industry and academia.

Research programmes	Typically suitable for lower TRL technologies where discovery research. Research can resolve uncertainty, increase understanding of value chains, and establish proof of concepts.
Missions	Signal strategic interest and favourable policy conditions, and signpost potential future demand for solutions. May be framed as a multidisciplinary challenge and/or in response to a market failure.
Support for start-ups and scale-ups	Enable new innovative companies to develop innovative products and commercialise. Mitigates risk for smaller companies with greater risk exposure.
Networks for knowledge exchange and community building	Ecosystem support to build connections, collaborations, shared knowledge and engagement with policymakers and regulators.
Regulation and standards	Driver for innovation, setting out desirable outcomes and increasing certainty. Level to build public and political trust relating to regulated areas.
International collaboration	Shared challenges and can play to complementary strengths/weaknesses. Multiple actors attempting or replicating R&I can increase chances of success through collective learning from failures and spreading of risks.
Public procurement	Can create and support demand for innovation by establishing a market. Promotes trust in innovations where they have successfully passed due diligence checks.
Incentives and support for innovation adoption	Creates and supports demand for innovation and deployment.

7.2.4. Prioritisation and development of the R&I action plan

R&I challenges were ranked to prioritise inclusion in the R&I action plan.

As a first step, those R&I challenges already addressed in existing or planned EU R&I programmes were deprioritised. Similarly, where no known potential technology solution was in development and a discovery research programme was the proposed R&I intervention, R&I challenges were deprioritised for inclusion in the R&I action plan, as impact from discovery research programmes is uncertain and likely to take significant time to be realised.

R&I challenges and related R&I actions were then prioritised for inclusion in the action plan based on their SWOT category. The highest priority for action were challenges identified as W-T, followed by S-T, S-O and, lastly, W-O. These categories are summarised as follows:

- **First priority for action (W-T):** R&I challenges identified as W-T are prioritised for action, as there are external threats to the system and little to no R&I activity within the EU. Although in some cases regulation and additional policy action was identified as an alternative, or more appropriate, solution to the criticality, potential R&I actions were also included in the final R&I action plan, complementing the technology's development to ensure energy security.

- **Second priority for action (S-T):** R&I challenges identified as S-T are the second category prioritised for action. S-T are prioritised over S-O, as external threats include non-EU competition or no known solution, which need to be mitigated.

- **Third priority for action (S-O):** S-O R&I challenges are the third category, prioritised over W-O as they have greater protentional for immediate impact or activity in the R&I space due to a strong EU R&I ecosystem and opportunities for collaboration with other countries.

- **Fourth priority for action (W-O):** R&I challenges categorised as W-T are the lowest prioritised for action.

A least regrets lens was applied as part of the review of the R&I action plan. Least regrets analysis considers the relevance of an intervention in the context of different scenarios and considerations for futureproofing R&I actions, as well as relevance to multiple R&I challenges and value chains. For example, where two possible R&I interventions may address an R&I challenge, whichever provides least regrets with wider applicability will be prioritised for final selection.

For this study, least regrets analysis was proposed as a complementary method to use alongside SWOT analysis. Least regrets analysis is a valuable tool for looking at interventions in an uncertain context and identifying those needed across multiple scenarios, as well as what further information may be needed, and trigger points for decision making. The definition of regret is adapted to the situation: in the case of investment decisions, regret would be the cost difference between the investment made and the amount saved had the optimal investment decision been made – based on the assumption that decisions have be made with uncertainty, when the optimal timing or decision is impossible to define and not making a decision would have negative consequences. This method is used by the UK National Grid, for example, to make investment and technology roll-out decisions as part of the transition to a clean energy grid several years in advance, and with varying degrees of uncertainty.[12]

Participants in the validation workshop (methodology in Annex A, Section 8, below) provided input on the 'criticality risk – EU preparedness' level for each energy security criticality. This provided a form of ranking for energy security criticalities based on severity and need for mitigation. The action plan was specified to include 30 actions. If more than 30 R&I actions qualified for inclusion, this ranking for energy security criticalities would provide a final filter for prioritisation.

An additional lens for the prioritisation of R&I action was originally proposed as part of this methodology: consideration of clean energy technologies' projected share of EU energy supply. The rationale was to prioritise action for the most important clean energy technologies, or those with the greatest influence in the EU energy system (e.g. PV and wind are expected to have a large market share, while RFNBOs may be less ubiquitous). This lens was removed from the methodology as it was not relevant to all technologies in scope (e.g.

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[12] National Grid, Network Options Assessment Methodology Review, Frerk, M. (2021), Investing for net zero in the face of uncertainty: real option and robust decision-making. Melbourne Energy Institute (2021). Advanced modelling for network planning under uncertainty.

smart energy grid technologies, CCUS, smart cities) and would automatically discount R&I actions that may have high potential impact.

8. Methodology for the validation workshop

The emerging study findings were presented in a validation workshop to expert stakeholders. The workshop aimed to:

- Validate the methodology and findings so far, particularly on energy security criticalities.
- Refine the R&I action plan in consideration of feasibility, potential impact and futureproofing.

Inputs from participants were used to review and refine study findings, for example adding or removing energy security criticalities and refining R&I interventions for the action plan.

8.1. Stakeholder mapping strategy

Stakeholders were identified through relevant trade bodies, EU organisations (e.g. European Commission DGs and Executive Agencies) and partnerships (e.g. European Technology & Innovation Platforms/ETIPs, joint undertakings), research institutes, think tanks and civil society organisations.

Targeted search strings and database searches were used to identify relevant industry stakeholders and academics. For example, industrial representatives were identified through the consortia of EU projects, identified using the CORDIS database[13], and through businesses linked to the trade bodies. Additional EU trade bodies were identified by searching for "[technology] + trade body + europe". Similarly, academic participants across the EU who had studied particular criticalities were identified through targeted search strings based around "[technology] + [criticality] + research + europe".

Care was taken to maintain a diverse and inclusive list of attendees and ensure representation across each technology area in scope of the study. However, not all participants were able or available to attend a full-day workshop, leaving some expertise gaps in the final participant list (e.g. only one participant represented CCUS).

8.2. Pre-workshop activity

Prior to the workshop, participants were sent a materials pack with the agenda, background to the study and brief initial findings, outlining shortlisted energy security criticalities and proposed R&I challenges. Participants were asked to consider the following questions:

- Are these criticalities the main risks to the energy security of the value chains? If not, what is missing?

[13] Search | CORDIS | European Commission (europa.eu)

- In your view, are the corresponding R&I challenges correct?
- What potential solutions to R&I challenges are you aware of?

The feedback received from participants was used to refine the content and activities for the validation workshop, as well as the findings of the study, in particular the assessment of energy security criticalities, SWOT analysis and definitions of R&I interventions.

8.3. Workshop structure

The workshop was run in a hybrid format, with online participants joining through Microsoft Teams and in-person participants joining at the Thon EU Hotel in Brussels. The workshop was divided into a morning and afternoon session covering an introduction to the study and two activities.

- Morning session (9:30–12:00 CET) – study methodology and activities to validate the energy security assessment of clean energy value chains
- Afternoon session (13:30–17:00 CET) – activities refining and validating R&I interventions

The introduction comprised of an overview of the study, highlighting key assumptions and limitations of the project and methodologies used. Participants were then divided into thematic breakout groups (Table A.10) to carry out each activity. In-person breakout groups discussed the activities using a mixture of post-its and whiteboards. Online breakout groups used Mural boards as virtual discursive tools to play back the methods used in the study and validate findings (see Annex E for workshop summary).

Table A.10 Technologies covered in each breakout group

Breakout	Technologies Areas covered
1 (online)	Hydropower, ocean energy, wind energy, energy policy, energy systems and grids, sustainability
2 (online)	bioenergy; advanced biofuels; hydrogen; batteries; sustainability; energy systems and grids; international trade.
3 (online)	Solar energy (PV, concentrated solar energy, renewable and solar fuels), critical raw materials, energy systems and policy
4 (in-person)	CCUS, bioenergy, batteries, hydrogen
5 (in-person)	Solar energy (PV, concentrated solar energy, renewable and solar fuels), heat pumps; ocean energy, geothermal energy

8.4. Activity 1: validation of the shortlist of key energy security criticalities

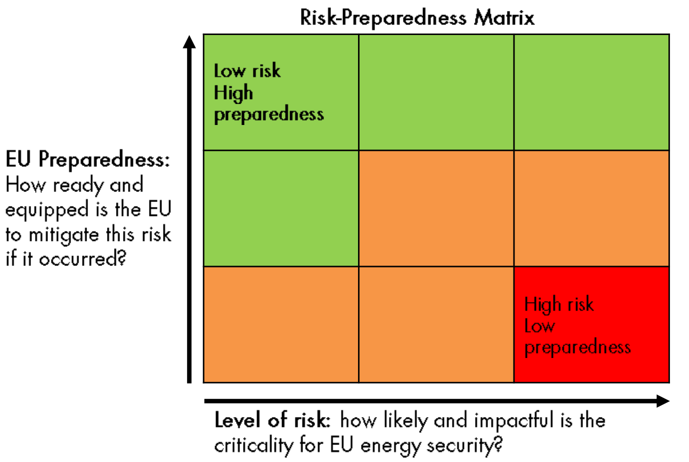
- **Objective:** validate and feedback on the shortlist of key energy security criticalities

The activity involved a discussion to assess the severity/prioritisation of key energy security criticalities, and a discussion of possible future scenarios and implications for energy security criticalities. It was divided into two parts with the follow aims:

- Part 1: To help refine the energy security assessment and understand how important the different criticalities are relative to one another across different energy technologies.

- Part 2: To consider future risks and how the criticalities might evolve, based on the three future scenarios, which challenge EU energy security in different ways.

Figure A.4 Risk-preparedness matrix used to assess criticalities



Each break-out room was provided with a selection of energy security criticalities to discuss, tailored to their expertise. Information was provided on the paper sheets (or Mural board for online participants) for each criticality. Participants were invited to discuss where they would place the criticalities on a risk–preparedness matrix (Figure A.4), by considering the question: *what is the level of risk and how ready is the EU if this risk occurred now?*

Risk was defined as likelihood and impact of the criticality occurring. Preparedness was defined as the extent to which the EU would be able to manage or mitigate the risk occurring. This might be related to the scale of deployment of the technology, how much energy it supplies to the EU, how quickly/easily it could be mitigated, what plans are already in place, or the type of risk. This aimed to prioritise which criticalities need most urgent attention (e.g. because the EU is currently unprepared). The matrix provided a way to compare the severity of different criticalities and consider the wider energy system.

Participants were also encouraged to flag any more important criticalities that had not been shortlisted for the workshop.

In the second part of the activity, participants considered how this assessment would change for each criticality under each of the three scenarios, and provided any comments/key points to consider for the future of EU clean energy security. Each scenario was discussed in turn, with key characteristics of the scenario highlighted in the activity descriptions as follows:

- **Scenario 1**: *It's 2050 and the world is on a similar trajectory to now. The EU has fully decarbonised, but the rest of the world hasn't. This means that the world is on track for 2.7C warming by 2100. Geopolitics are multipolar, with some regional instability. The economy is in recession. EU citizens are concerned about costs and polarised in their views of the clean energy transition.*

- **Scenario 2**: *It's 2050 and we've reached global net zero. The EU pursued a just transition. The race to net zero really intensified and strained global value chains and raw material supply during the 2030s as demand boomed, but collaboration helped resolve these challenges. The EU has relied on digitalisation and global value chains.*

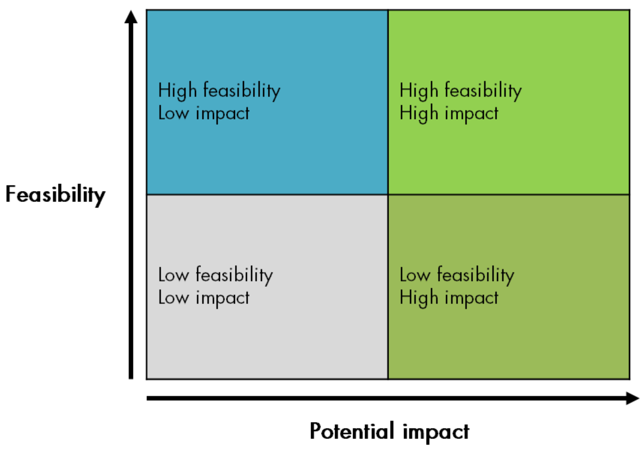
- **Scenario 3**: *It's 2050 and we're in the midst of major power conflict. Geopolitical tensions have increased and cyberattacks are common. Critical raw material supply is severely disrupted. With ongoing trade wars, the EU has on-shored supply chains – but at high cost – and has not managed to achieve net zero despite its best efforts. Global warming is on track for 3C by 2100.*

8.5. Activity 2: validation of R&I interventions

- **Objective:** Develop and refine R&I interventions to address the energy security criticalities

This activity involved a discussion to assess whether R&I interventions are the most effective approach and discussion of impact, feasibility and futureproofing of R&I interventions.

Figure A.5 Feasibility – impact matrix used to assess R&I interventions



To begin, each breakout was provided with a selection of R&I interventions relating to the identified criticalities to discuss. Participants were encouraged to place the R&I interventions on an impact/feasibility matrix (Figure A.5), by considering the question: *how feasible and how impactful is the intervention to solve the corresponding energy security criticality?*

Suggestions of alternatives, and comments and reflections on what might help increase feasibility and impact, were encouraged.

Participants then considered what might change the feasibility or impact of the R&I interventions in future using ‘what if’ provocation statements. For each what-if statement, participants were encouraged to think about what opportunities or challenges there are for the R&I interventions, and any solutions to futureproof them:

i. *What if international knowledge exchange and mobility of talent are limited? (Or, put another way: if there isn’t much international R&I collaboration, or collaboration with some countries becomes challenging, what implications would there be for R&I?)*

ii. *What if clean energy technology R&I is highly competitive between countries? (Or, put another way: what implications would a global race to decarbonise have for R&I?)*

iii. *What if investment in clean energy R&I is limited? (Or, put another way: what if public funding is constrained and energy R&I has to compete with other policy priorities?)*

ANNEX B: PESTLE ANALYSIS

PESTLE (political, economic, social, technological, legislative, environmental) analysis provides a framework to examine trends that might impact or influence the energy security of clean energy technology value chains and related R&I. Evidence was compiled through a literature review and interviews with nine experts across a range of disciplines, with additional interviews to be carried out specifically to capture expert views on technology breakthrough and R&I capabilities. The PESTLE analysis presented here will continue to be iterated and refined as part of the scenario development, with additional expert interviews planned in the coming weeks for validation and additional nuance.

For each PESTLE category, the overarching trend is described in Table B.1, alongside the potential opportunities, risks and uncertainties relevant for consideration in this study. The PESTLE findings will inform the identification of drivers of change and scenario development in Task 1. The PESTLE analysis is technology agnostic.

Table B.1: PESTLE analysis – overview of trends, opportunities, risks and uncertainty for EU energy security of clean energy value chains and R&I

Political trends
Conflict and geopolitical uncertainty Both historically and more recently, geopolitical events have posed a threat to energy security. For example, Russia's invasion of Ukraine resulted in significant gas price rises and supply chain disruption.[1] For fossil fuels, energy security and geopolitics are bound with the geographic location of fossil fuels. Examples include the EU's dependence on imported natural gas from Russia, and fossil fuel prices affected by events in the Middle East. With clean energy technology, energy security and geopolitics are bound by the geographic location of raw materials, manufacturing and the wider supply chain. Russia's invasion of Ukraine, for example, disrupted the supply of CRM including aluminium and nickel, which are both used in electric cars and batteries.[2] Looking ahead to the global green energy transition, demand for critical minerals is expected to rise, and the location of some mineral reserves in countries with high levels of fragility and corruption introduces vulnerability for those value chains.[3] For example, 50% of global cobalt[4] reserves are in the Democratic Republic of Congo, which is the lead producer of cobalt by a significant margin, but also the world's sixth most fragile country, according to Fund for Peace rankings.[5] Geopolitical tensions can also lead to economic conflict, such as trade wars or sanctions that can affect global supply chains. An ongoing example is the trade war between the United States and China, which started in 2015 and focused on technology. As a result, the United States has taken several actions, including to prevent China's access to advanced semiconductor-based technologies and limit knowledge transfer.[6] In February 2023, China also took action restricting exports of solar panel technologies.[7] The impact on EU and global supply chains includes the cumulative and indirect effects of tariffs, and potential risks and opportunities as tensions escalate.[8] The Council on Foreign Relations' Center for Preventive Action surveyed foreign policy experts who identified the following conflicts most likely to occur in 2023: Chinese aggression towards Taiwan, escalation of the conflict in Ukraine, civil unrest in Russia, a highly disruptive cyberattack on the United States, security crisis triggered by North Korean development of nuclear weapons, conflict between Israel and Iran, political unrest in Central America and Mexico, and other, lower likelihood, lower impact potential conflicts, particularly in Africa and Asia.[9] If trends persist, estimated include an additional three countries at war and nine at high risk of war by 2030 compared to 2020.[10] Conflict in Taiwan, explored in a study as a trade blockage, would likely have significant impact on the global economy and global value chains,

as Taiwan is the 16th largest trading economy, near-sole producer of advanced semiconductor chips, and has a significant market share for less advanced chips.[11]

Climate change – which is likely to have a growing impact on the availability of natural resources like water and biomass – is widely viewed as posing an increased risk of conflict.[12]

- **Opportunities**

Ongoing conflicts, in particular Russia's invasion of Ukraine, has brought this risk to the fore and prompted measures to accelerate the transition to clean energies and strengthen energy security. Concerns over geopolitical uncertainty and conflicts may create opportunities, such as investments, with appetite and demand for more energy-secure value chains from politicians, industry and the public, especially where political, economic or social trade-offs may exist.[13]

- **Risks**

Conflict – military or economic – has potential to cause severe disruption to energy technology value chains, in particular where there are only a small number of countries or complex value chains, which introduce vulnerabilities.[14]

Geopolitical instability may contribute to reducing investors' appetite for investments perceived as risky, for example in innovative businesses, start-ups or novel technologies. Geopolitical instability and conflicts may also have an economic impact, as seen in the recent case of increased inflation associated with the energy crisis caused by Russia's invasion of Ukraine, which may affect countries' ability to invest in R&I.

- **Uncertainty**

There is a high level of uncertainty over how geopolitical tensions will evolve over time, with potential for rapid change depending on events or new political leadership. Although future conflicts may be anticipated, the actors involved, duration and scale of impact – especially with risk of secondary or cascading impacts – are uncertain.

EU Member States' policies: convergence and divergence

Domestic policies – including for the green energy transition – can differ in direction, speed and degree of implementation, with variation between renewable energy targets, standards and regulation, trade policy, national R&D funding. Electoral and political cycles across Member States can introduce policy shifts or change of priorities. EU targets for the green transition are viewed to have introduced a degree of convergence between EU members states for the transition. However, Member States' views and priorities on energy security and the green transition vary.[15]

Progress towards green targets is not uniform across EU, and the green transition poses different challenges and opportunities for different states, in terms of economic cost and impact, absorptive capacity for innovative technologies, and environmental and social considerations.[16] Some have argued that convergence will play an important role in achieving the green energy transition.[17]

More generally, political priorities and policy tend to be more driven by short-term electoral cycles than long-term challenges such as energy security and the green transition – other priorities or events may remove the current focus and interest in energy security from the agenda. In Europe, there is political consensus regarding climate change and the need for the clean energy transition, but less consensus on approaches and pathways to decarbonisation.

- **Opportunities**

Domestic interest and priorities can support opportunities for investment, development and deployment of clean energy technologies with policy action. Where Member States' policies align or work constructively together, opportunities could be leveraged on a larger scale than would be possible for an individual country, increasing investment, market size and demand, or supportive innovation ecosystem measures to improve chances of success.

- **Risks**

Diverging or changing political priorities can create uncertainty or complexity, reducing industry and investor confidence. Differing political priorities between Member States can also introduce challenges and slow the pace of development for EU-wide green energy policies. Energy security and the green transition are also longer-term policies than electoral cycles, and there is a risk of focus being losing out to shorter-term policies. The pace of decision-making for collective action is viewed as a risk for EU energy security, although it is important to note that Member States have flexibility to negotiate bilateral agreements that can help support energy security.[14]

- **Uncertainty**

Political cycles inherently introduce a degree of uncertainty regarding long-term policy areas like the green transition and energy security. Changing political priorities will be linked to events and public opinion.

Industrial policy and globalisation

Globalisation is an economic policy that aims to enable free trade and the flow of goods, services, people and capital around the world. Increasing trade around the world has contributed to the globalisation of supply chains, with supply chains across multiple countries benefiting from ease of access to goods and skilled workers and reducing costs. Global value chains represent 70% of international trade.[18] The impact of the COVID-19 pandemic on supply chains highlighted the scale and complexity of global value chains.

Offshoring of manufacturing from the EU has been one of the key outcomes from globalisation. At the company level, offshoring, including of R&D activities, is linked to improved innovation performance.[19] At the country level however, one study linked the location of manufacturing to innovation and R&D investment, raising the question of whether offshoring of manufacturing could reduce national innovation capabilities, and noting that the evidence base is scarce.[20]

In recent years, political parties opposed to globalisation have gained traction and increased success in elections, in both Europe and the United States. Concerns include loss of jobs through offshoring, depressed wages and nationalism.[21] Protectionist or nationalist policies have been introduced, including for clean energy technologies. The Inflation Reduction Act (IRA) in the United States provides incentives for clean energy technology manufacturing located in the United States. The concept of ‘friendshoring’ – setting up supply chains and value chains with partner countries – was introduced into policy discussion in response to geopolitical uncertainty, with reports of companies planning to relocate production accordingly.[22]

The EU pursues a policy of ‘strategic autonomy’, aimed at achieving capacity to act autonomously and independently of other countries in strategically important areas.[23]

- **Opportunities**

Globalisation can provide access to lower-cost products, skills, shared knowledge, and novel technologies. Globalisation and trade-openness have been found to have positive effects on the developments of clean energy innovation due to increased knowledge and material sharing. For example, the increase in developing technologies to offset negative effects on air quality has been attributed to the increase in European globalisation.[24]

The growing trend of protectionism and lessons from the disruption of global supply chains during the COVID-19 pandemic may provide an opportunity for public and political support of R&I interventions that would previously have been considered politically infeasible or too costly to justify.

‘Friendshoring’ may provide opportunities for foreign investment in EU-based clean energy technology value chains.

[14] Interview notes.

- **Risks**

While globalisation increases the openness of markets and supply chains, and enables outsourcing of manufacturing, it also creates a risk of over-reliance on foreign companies and governments, introducing additional vulnerability to the effects of geopolitical unrest.

- **Uncertainty**

Uncertainty surrounding political and geopolitical tensions has negative consequences on the security of value chains in a globalised economy.

The future of globalisation is relatively uncertain. Many European countries are beginning to align with populist and protectionist politics in order to move away from globalised economies.[25]

International relations

International relations define how countries or groups of countries interact with one another politically and economically. International relations can be complex and nuanced, and in the case of the EU, international relations exist at both the EU level and at the Member-State level, with varying impact on energy security, the clean energy transition and R&I.

Following Russia's invasion of Ukraine, the EU and its Member States have imposed sanctions and travel bans on organisations and individuals in Russia, as well as import and export bans.[26] Prior to the invasion, cooperation between the EU and Russia included projects on the environment and climate change, with Russia also being a key exporter of critical materials.

Relations between the EU and China have also been described as deteriorating, and geopolitical competition between the EU, United States and China is increasing.[27] The EU and China are each other's largest trade partners, with China a key exporter of clean energy technologies such as solar panels. The EU has raised concerns over China regarding cybersecurity and the protection of intellectual property, with sanctions adopted against Chinese individuals and legal entities in 2020.[28]

R&I are another sphere in of diplomacy and international relations, which facilitate scientific collaboration through R&D agreements, international exchange programmes and infrastructure, or as a mechanism to support diplomatic processes.[29] As of April 2022, 12 countries were associated for participation in Horizon Europe, with six additional countries in negotiations for association.[30]

- **Opportunities**

R&I can be a mechanism for countries to work together towards shared goals, such as the green energy transition and energy security. Joint ventures with other countries whose R&I strengths complement those of the EU, especially in Asia, would be beneficial. However, geopolitical tensions and international competition may affect the feasibility and success of international collaborations.[31]

Where relations between EU and other countries deteriorate, leading to trade restrictions for example, changing demand and markets can create opportunities for novel technologies or supply chains to respond.

- **Risks**

International relations can change at pace and increase the risk of sudden disruption to supply chains, particularly in energy security where a small number of countries control key elements of the value chain, material supply or manufacturing.

For example, lack of international agreement or cooperation on security related issues may enable proliferation and increase of cyberattacks, with risks from digitalisation further described in the technology trends section.

- **Uncertainty**

How international relations evolve carries uncertainty and can change at pace. Where change or delays are introduced, for example in setting up R&D cooperation and partnerships such as the UK's association to Horizon Europe, uncertainty over timing of decisions can introduce challenges for the R&I community and partnerships at the researcher level.

Politics of the global clean energy transition

The pace of global decarbonisation will be set by the policies of countries across the world. Whereas in Europe, climate change and the need for the clean energy transition is supported by political consensus, this is not the case in all countries. Political priorities in other countries can be more focused on economic growth or poverty reduction, for example, with climate change remaining a contentious issue.

The Paris Agreement was adopted by 196 countries at the UN Climate Change Conference (COP) 21 in 2015 with the goal of keeping the global average temperature increase below 2 °C, compared to pre-industrial levels.[32] Countries have submitted nationally determined contributions to reduce carbon emissions, with the first global stock-take at COP 28 in 2023. By November 2022, 140 countries had announced, or were considering, a net zero carbon emissions target, covering 90% of global emissions. Climate Action Tracker analysis rated the design of net zero targets covering 74% of global emissions as 'insufficient' in terms of scope, architecture and transparency.[33]

As the effects of climate change are increasingly felt – with more frequent extreme weather and impacts on infrastructure and the availability of food and water – policy action may accelerate the pace of decarbonisation.

- **Opportunities**

Acceleration of the pace of global decarbonisation could create opportunities for EU value chains or technology development for commercialisation and export if market demand increases.

A slow pace of decarbonisation across the world may reduce strain on potential bottlenecks in supply – of key materials, for example, or technologies that may be in limited supply or require significant time to ramp up production.

Countries around the world share the goal of achieving net zero carbon emissions, and likely share challenges faced by EU, as well as potential appetite to collaborate or drive innovation themselves, which the EU could also benefit from.

- **Risks**

A sudden acceleration in global decarbonisation could create supply chain challenges, with key resources in high demand and time needed for new mining or production infrastructure to become operational. For example, a cobalt mine in the US state of Idaho, will take five years to be operational.[34] This could lead to a situation where demand for clean energy technologies outstrips supply.[35]

- **Uncertainty**

With limited transparency and a range of broad and shifting priorities around the world, the pace of the global energy transition is uncertain, poses challenges to planning for the different potential impacts of varying levels of global decarbonisation.

Economic trends

Economic growth and the future economic environment

Economic forecasts for 2023 and the next couple years anticipate slower growth, particularly in Europe and developed economies, with a small reduction in the inflation caused by compounding events, including the energy crisis following Russia's invasion of Ukraine and financial instabilities. The risk of stagflation is a concern, with inflation remaining above target for many countries,[36] posing a risk of economic crisis, particularly in developing countries. Levels of debt remain high following the COVID-19 pandemic.[37]

Global growth is estimated at 2.4%–2.6% for 2023 and 2.9%-3% for 2024.[38] Eurozone economic growth is estimated at 0.8% and 1.8% for 2023 and 2024, respectively.[39] A different study forecasts 2010–2100 per capita GDP growth of 2.1% with a standard deviation of 1.1% (global).[40]

Looking ahead to 2050, the top 10 largest economies are expected to change significantly, with China overtaking the United States as the world's largest economy and India and Indonesia moving up the ranks.[41] Europe could represent 10–20% of the global economy by 2050, depending on the forecast, with the Asia-Pacific region dominating with 53% of global GDP.[42]

- **Opportunities**

Faced with economic challenges and low growth, R&I or energy infrastructure projects may be viewed as an opportunity to boost the economy, building on initiatives like the Green New Deal (United States) and the European Grean Deal (EU). The IEA estimates that the energy transition will see the market for clean energy technologies triple by 2030, to USD 650 billion a year,[43] with associated increases in employment and industry growth.

- **Risks**

Low economic growth, high levels of debt and recession can create barriers to investment in R&I, as well as long-term challenges, such as energy security – especially if risks to energy security are not viewed as urgent or acute.

With a falling share of the global economy, Europe may face challenges to maintaining or strengthening its global influence.

Policies introduced to boost growth by increasing productivity may accelerate digitalisation and associated cyber risks.

- **Uncertainty**

Projections and forecasts for economic growth are highly uncertain and can be affected by sudden and unexpected events. Uncertainty in economic trends poses a challenge for other forecasts and projections –- for example, the estimates of global carbon emissions used to inform policy decisions are party based on economic growth projections.

Global trade

Trade tensions are described as high, and the World Trade Organisation has forecast a 1% growth in trade in 2023. In the early 2000s, global trade was growing by 8% a year. The slowdown in trade growth is partly due to disruption from the COVID-19 pandemic and the on-going trade war between the United States and China, as described in the political trends section.[44]

The EU has trade agreements with over 70 countries in the form of free trade, economic partnership or association agreements, and is currently pursuing negotiations with Chile, Mexico, Australia and Indonesia. Trade agreement negotiations for the Transatlantic Trade and Investment Partnership between the EU and United States were unsuccessful, however US interest in 'friendshoring' (discussed in the political trends section above) may provide opportunities for trade.

The EU has historically made use of trade barriers for clean energy technologies, for example imposing tariffs on solar panel imports from China to prevent cheaper technology damaging the EU solar industry from.[45]

- **Opportunities**

Changing global trade relationships may provide opportunities for EU supply chains, particularly regarding export and foreign investment. Competition from imported low cost clean energy technologies, such as solar panels from China, have been found to stimulate innovation in EU companies.[46]

- **Risks**

Trade tensions and current geopolitical uncertainty may result in disruption of global value chains, with potential impacts on clean energy technology value chains, at least temporarily.

- **Uncertainty**

The evolution of trade relations around the world is tied to shifting and uncertain geopolitics, political priorities and doctrine across the world, and particularly in the United States and China.

The global energy technology market, public and private investment

Due to the clean energy transition, the IEA estimates that the market for clean energy technologies will triple by 2030, to USD 650 billion a year,[47] with associated increases in employment and industry growth.

Driven both by the need for an energy transition in response to climate change and associated economic opportunity, public investment – and incentives for investment – in clean energy technologies has increased over the last few years. Since 2016, global investment in clean energy technologies has been greater than investment in fossil fuels, with more than USD 1.7 trillion invested in clean energy in 2023.[48] BloombergNEF estimate that to achieve net zero, annual investment in the energy transition from 2022 to 2025 must be three times what it was 2021.[49]

Spending on clean energy is concentrated in China, the EU and the United States. In 2021, Europe was responsible for roughly USD 10 billion of government investment into energy R&D, with priorities set by net zero targets.[50] In 2019, the 10 biggest investors in clean energy R&D were the United States, Japan, the EU and individual Member States, Canada, Korea and Norway.[51]

Public sector subsidies for renewable energies – including direct (feed-in tariffs) and indirect subsidies (tax breaks) – are increasing across Europe to incentivise clean energy development.[52]

Private sector investment has increased in clean energy technologies, driven by increased market demand for clean energy, attractive return potential and supportive policy. The private sector also has influence beyond purely investing. Companies can exercise 'soft power' along the clean energy value chain, from supplier to consumer, to employee.[53] There are, however, underlying market barriers and a perception of high risk that constrains development and private financing of clean energy projects.[54]

In terms of foreign direct investment (FDI), Europe and Asia attracted the highest number projects between 2003 and 2021. In 2019, near to 40% of all renewable energy power projects globally involved investment from foreign companies.[55] Between 2003 and 2021, global FDI in renewable energy increased from below USD 10 billion a year to around USD 110 billion, with largest share of investment in solar and wind power.

Venture capital funding for clean energy companies increased from USD 1.9 billion in 2019 to GBP 12.3 billion (USD 15.6 billion) in 2022. The majority of investment came from the United States, with USD 3.5 billion investment from European venture capital.[56] It notable that the number energy start-ups globally was relatively stable between 2011 and 2019, before dropping in 2020.[57] In 2020, Europe had the largest share of clean energy start-ups, although this may change following incentives in the Unites States with the Inflation Reduction Act.

- **Opportunities**

Significant investment increases in clean energy technology research, innovation and deployment provide an opportunity for novel technologies and innovative solutions to gain funding and achieve commercialisation, with push and pull factors.

Public investment in clean energy value chains has been shown to play a key role in the pace of capital cost reductions and technological diffusion.[58] The public sector can provide targeted support to address market failures and nurture public-private collaboration, for example on long-term challenges like energy security that may not always align with the market's priorities.

By investing in employees and innovation, the private sector provides opportunities for reskilling and upskilling that strengthen clean energy capacity and capability.[59]

Private sector companies also play a key role in shaping public perception. By adopting and supporting the development of clean energy value chains, companies can promote clean energy principles in the areas where they operate.[60]

Private investment offers opportunities for greater diffusion of clean energy technologies than government and public driven pathways,[61] enabling a higher degree of clean energy adoption and increasing the economic security of the value chain.[62]

- **Risks**

Large scale private investment risks distorting the clean energy market if it is targeted at few technological areas or segments in a value chain, creating dependencies, reducing technological and trade diversity, and increasing the value chain's vulnerability to geopolitical instability.[63] The market opportunities pursued by private sector investments may not align with longer-term considerations or public sector priorities such as energy security and equity.

Increased deployment and development of clean energies can create risk of supply shortages from increased demand, potentially contributing to geopolitical tension and price increases, as well as environmental harm through excessive mining.[64]

Gaps in investment, or inadequate investment, create a risk of missing opportunities to address challenges and falling behind competitors, which may in turn reduce influence over global value chains. A lack of public investment will likely impact the EU's ability to achieve energy transition and climate goals.[65]

FDI carries risks regarding energy, which may be considered critical infrastructure and therefore off limits for some countries and companies in the EU. This could limit involvement and knowledge sharing in some cases.

- **Uncertainties**

Predictions of market behaviour are uncertain, with political/geopolitical conflict, broader macroeconomic trends (such as inflation) and regulation potentially causing volatility and impacting investment.

Investment trends will be linked to the policies, incentives and targets countries set as they develop their respective plans to transition to clean energy.

Cost of energy

The cost of energy is dependent on commodity prices, materials and parts, manufacturing and operation. For some clean energy technologies, such a wind a solar, there is no cost for fuel. Looking across different scenarios, Energy Brainpool highlight commodity and carbon prices as key factors in the cost of energy. The average base load price is expected to fall and then stabilise at 60–100 EUR/MWh from 2030 to 2060.[66]

The European Climate Foundation finds that several different configurations of feasible net zero energy systems in Europe, with potential savings on household energy bills of up to EUR 23 billion, depending on levels of electrification, deployment of smart energy technologies and building efficiency improvements.[67]

- **Opportunities**

Depending on the clean energy technology value chain and resources needed, there may be opportunities to develop technologies and value chains with relatively fixed and stable costs, eliminating the impact of fuel price volatility that has historically affected energy security through affordability.

- **Risks**

The cost of energy technologies for some value chains, particularly those dependent on key materials or components available from a small number of countries, may be highly vulnerable to price volatility linked to geopolitical events.

- **Uncertainties**

The cost of energy, price rises and potential savings for European households will be determined in part by the wider European energy mix and energy system, including efficiency measures and uncertain external events, such a geopolitical or trade tensions.

Social trends

Public perceptions of energy security

EU citizens view energy supply as one of the key issues facing the EU, prioritising it over crime, health and public finances. This is reinforced by significant support for the energy transition (86%), and for reducing dependency on Russian sources of energy (84%). These perceptions have been substantially driven by recent geopolitical events, namely the war in Ukraine, as reflected in the increasing prioritisation of energy security issues.[68] Affordability is a key issue, with 93% of EU citizens highlighting this as a serious problem[69] – though energy independence and reliability have also become areas of growing public concern.[70] Concern over reliability and power outages has risen in EU Member States since 2016 due to the decommissioning of traditional energy generation capacities, and further exacerbated by the war in Ukraine.[71] This is emphasised by energy supply becoming a growing priority across the EU: in 2020–2021 only 3% of EU citizens considered it one of the top two issues facing the EU, in 2022–2023 that figure has risen to 26%.

- **Opportunities**

Increasing concern over energy security, and increased support for energy independence and the clean energy transition, provide an opportunity for increased investment and innovation in this sector. This is currently a salient issue for EU citizens, who are likely to support both EU and Member-State investment in measures to increase energy security and affordability, and to support the green transition. In this context, we also see a high level of acceptance for clean energy approaches. Of three solutions to address the energy crisis – developing renewable energies, reducing energy consumption, or diversifying energy supplies – Europeans have a significant preference for developing renewables.

- **Risks**

Although public perceptions currently place a high level of importance on energy security, affordability is also a significant priority. For example, a March 2022 survey found that 74% respondents supported EU steps to become energy independent, even if it meant higher energy prices. However, this figure gradually fell over the following months as winter approached,[72] suggesting support for clean energy is elastic and may have a strong interaction with affordability. If clean energy technologies cannot deliver affordable energy this may have implications for public perceptions.

- **Uncertainties**

Although public perceptions currently place a high level of importance on energy security, this is a relatively recent phenomenon and may change once the perceived ‘crisis’ is resolved, and if energy affordability improves. Other issues may become more salient as political and economic events unfold.

Public perceptions of clean energy technologies

Overall, people support the green transition and increased investment in renewable energy, with an EU-wide poll indicating that 88% of Europeans think it is important to increase the share of renewable energy in the economy.[73] Russia’s invasion of Ukraine boosted public acceptance for clean energy, with 66% of European respondents agreeing that the war in Ukraine and its impact on energy prices should speed up the green transition.[74]

23% respondents said their perception of renewable energy had become more positive in the previous six months, and most wanted renewable energy to ease climate and affordability concerns.[75] Respondents to a German survey were more supportive of clean energy implementation in their neighbourhoods.[76]

Concerns have been documented over the location of clean energy projects – particularly near people’s homes[77] – as well as privacy, in the case of smart grid deployment.[78] Other concerns include the affordability of clean energy and one survey found that 43% of respondents were concerned about the risk of reduced job opportunities from the green transition.[79] Trade unions have warned that the EU Green Deal will directly affect 11 million jobs in Europe.[80]

Conspiracy theories are also in circulation, with unfounded claims that wind turbines contribute to congenital abnormalities, fatigue and/or cancer. A study in Germany highlighted a strong correlation between conspiracy mentality and non-acceptance of wind turbines.[81]

- **Opportunities**

Positive perceptions of clean energy technology contribute to an environment of opportunity for both investment and wider deployment.

- **Risks**

Public concerns, especially if unaddressed, could contribute to opposition to clean energy technologies, reducing adoption. Affordability, a component of energy security, also has implications for public support, where increasing prices could lead to public opinion and public pressure compounding energy security challenges.

- **Uncertainties**

Although public perceptions currently place a high level of importance on energy security, this is relatively recent phenomenon and may change once the perceived ‘crisis’ is resolved and, in if energy affordability improves. Other issues may become more salient as political and economic events unfold.

Public perceptions and behaviour change with regards to climate change

Within the EU, public awareness of climate change increased following the Paris Agreement and climate action is broadly favoured.[82] A survey found that 74% respondents agreed that the cost of damage resulting for climate change is much higher than the cost of investment needed for a green transition.[83] However, while most Europeans believe that climate change is a real and serious issue, for many it is not the most important issue.[84]

More people are personally taking action to fight climate change – increasing from 53% in 2011 to 64% in 2021. However, actions requiring more effort are far less popular than those, like recycling, that are perceived as less effort. Only 8% of the population have installed solar panels, while 2% had bought an electric car in the previous six months.[85] One in ten Europeans has switched to an energy supplier offering a greater share of renewable energy.[86] With the energy crisis triggered by Russia’s invasion of Ukraine, public information campaigns provided information and encouraged people to reduce their energy consumption. Data suggest that consumers lowered their thermostats by an average of 0.6 °C, though poverty is likely key driver of this efficiency measure.[87]

Public perception of climate change and associated policies have led to public action and protests, both in support of more ambitious climate policies (e.g. Extinction Rebellion) and in opposition to certain policies (e.g. the *Gilets Jaunes* movement) perceived as having an unequal or inequitable impact.

- **Opportunities**

Public interest in, and appetite for, climate action could be an effective recruitment mechanism for clean energy technology value chains or related R&I, with people wanting to make a difference.

- **Risks**

Perceived inequity or inequality of climate policy impacts risks creating public resistance or pressure, which could in turn contribute to policy uncertainty or challenges to the deployment and operation of clean energy technologies.

- **Uncertainties**

Future energy demand will to some extent depend on public behaviour and the extent of behaviour change – such uptake of active travel and adoption of clean energy technologies.

Public pressure on political leaders may also evolve and will likely be influenced by events and potentially inequitable impacts of the green energy transition.

EU skills and workforce for clean energy technologies and related R&I

To achieve net zero, the EU will need an estimated 1.54 million skilled workers in the renewable energy sector, with significant requirements for retraining or upskilling of the existing workforce.[88] Skills shortages are already an issue: nearly 30% of EU businesses involved in electrical equipment manufacturing (which can be a proxy for clean energy technology) experienced labour shortages in 2022.[89] If unaddressed, this bottleneck could tighten rapidly [90]. For example, it is estimated that to meet the REPowerEU goals, 800 000 workers will need to be trained for jobs in the batteries value chain, and 400 000 workers will have to be trained and upskilled in the heat pump value chain.[91] Education and retraining will be key to ensure successful job migration from polluting activities to growing green sectors.[92]

Digital skills also have a key role to play in the green energy transition,[93] and yet only around 44% of Europeans have basic digital skills, and only one in five currently has digital skills above the basic level.[94]

In terms of R&I skills and capability, the EU is the top worldwide patent applicant in the fields of climate & environment (23%) and energy (22%), with Member States like Germany and Denmark performing strongly. In terms of scientific publications, the EU was leading in energy research 10 years ago, but more recently Chinese researchers have taken the lead with a 39% share of most cited publications related to energy. However, the EU is well above the global average and reports higher levels of collaboration between the public and private sectors.[95]

- **Opportunities**

Cedefop predicts 1.2% additional employment growth by 2030 associated with the implementation of the European Green Deal.[96]

The EU has strong energy R&I capability compared to other countries, on metrics such as patents and scientific publications, suggesting strengths to build on and potential comparative advantage.

- **Risks**

Developing a skills pipeline takes time, skills shortages could create bottleneck or pressure on clean energy value chains depending on the parallel pace of training and decarbonisation. Reskilling and upskilling targets for 2025 appear unlikely to be met.[97]

- **Uncertainties**

Demand for clean energy technology related skills is expected to increase globally, however the impact of competing demand across different countries for talent and skills is uncertain.

Just transition

A 'just transition' describe pathways to achieving net zero in a fair way. It was initially developed as a concept to ensure the people working in polluting or high-carbon emissions industries would be protected from the negative impacts of their industries closing or changing as a result of the clean energy transition. The term 'just transition' is often used more broadly to describe an equitable transition that considers the impacts of the energy transition on the population more widely, ensuring negative impacts that might affect different communities are considered and mitigated. The concept of just transition is included in commitments adopted by some countries and draws together the UN Sustainable Development Goals.[98] The EU's Green Deal includes a Just Transition Mechanism.[99]

As exemplified by the Gilets Jaunes movement, perceived or real inequity can result in public unrest or opposition and challenges to climate change policies.

Energy security challenges such as lack of affordability and disruption of energy supply would have varying impacts across different communities. Some solutions to energy security challenges may also have social and local implications: reopening of mines in Europe, for example, is associated with risks and health issues.

- **Opportunities**

Pursuing a just transition can also support energy security objectives, especially with regards to considering and mitigating potential negative impacts of the energy transition on different communities with affordable and continuous availability of energy. R&I can contribute to developing solutions to such challenges.

- **Risks**

Failure to deliver a just transition may result in outcomes that affect energy security, especially if public perceptions change and public opposition affects progress on energy security related action. Perceived lack of transparency in decision making and governance may exacerbate public opposition, especially regarding trade-offs and impacts on local communities.[100]

- **Uncertainties**

The scale of inequitable impacts on communities or success of mitigations is uncertain.

Demographic trends and mobility

The EU has a population of 447.7 million, and is projected to peak in 2026, followed by gradual decline with a similar population size to today's projected for 2050.[101] This demographic trend represents a decline in the EU's share of the global population, from approximately 6%, to 4% in 2100. The EU population is also expected to become older on average, and increasingly concentrated in urban areas.

From 2000 to 2017, immigrants and mobile EU citizens living in the EU increased to 11.1% of the total EU population, with immigrants from outside the EU accounting for approximately 65% of that figure. Most immigration is driven by humanitarian factors. Immigration is likely to make an increasing contribution to the EU workforce. Without migration, the EU would face an estimated deficit of up to 50 million workers by 2050.[102] Currently, skilled migrants often face challenges with regards to recognition of their qualifications and other barriers to entering the workforce.

The impacts of climate change are expected to displace millions of people due to scarcity of resources such as water and crops and increasing frequency and impact of natural disasters such as wildfires and flooding.

- **Opportunities**

Public concern for climate change and energy security may increase the appeal of training and careers in energy and energy security, as well as programmes to support the retraining of workers from emissions heavy industries. Digitalisation and emerging technologies provide opportunities for increased productivity and automation, which could ease the impacts of workforce shortages.

- **Risks**

Workforce shortages or high international competition to attract skilled migrants may exacerbate challenges to accessing the people and skills needed for clean energy value chains.

- **Uncertainties**

The scale of impact of geopolitical events and climate change on the mobility of people is unclear.

Technological trends

Circular economy

The circular economy is a closed loop system through which materials and components are re-used and recycled. Circular economy initiatives are included in net zero strategies across different countries with the objective of reducing carbon emissions, including from materials processing. For clean energy technologies, the circular economy provides an opportunity to improve the sustainability of technology lifecycles through more sustainable end-of-life practices, reducing carbon emissions and pollution related to landfill and disposal of components after use, and an opportunity to reduce resource requirements from mining by recycling and re-using critical materials.[103] For example, under one scenario, IRENA estimates a potential 17.7 million tonnes of raw materials recycled from solar panel waste by 2050, with a corresponding value of USD 8.8 billion.[104]

Progress has been made on embedding circular economy practices in clean energy technologies: for example, Siemens have designed a fully recyclable wind turbine blade using a resin that enables easy separation of materials for recycling.[105] However, for other technologies such as solar photovoltaics, recycling is not yet efficient or widely applied.[106]

- **Opportunities**

The circular economy provides an opportunity to address energy security challenges such as dependencies on certain countries or supply chains for critical materials identified in the Critical Raw Materials Act. R&I can support the development of solutions to enable efficient and cost-effective recycling of clean energy technologies and their components.[107]

- **Risks**

Circular supply chains present risks, including with regards to quality of recycled products[108] and operational delays.[109] There are barriers to adoption of circular economy principles, with businesses found to be more influenced by cultural than technical or economic factors, which may hamper or delay uptake of the circular economy.

- **Uncertainties**

Risks from circular supply chains, especially global ones, are not well understood.

Links to other trends: the scale and pace of adoption of circular economy and sustainable design practice will be partly driven by public support and a culture of sustainability within businesses, as well as policy and regulatory incentives and drivers set through legislation.

Emerging technologies

Artificial intelligence (AI), quantum computing, synthetic and engineered biology, digital twins and distributed ledger technologies are key emerging technologies with potential considerations for clean energy technology value chains.

AI, including machine learning, presents opportunities for energy security regarding efficiency improvement, improved monitoring and forecasting capabilities and automation. AIs can be used to forecast price trends, potential growth areas and weather patterns to help manage energy supply and demand.[110] They can also be used to predict and detect anomalies or security threats to energy grids.[111]

Blockchain can be used to track energy production, consumption and transactions in real time, securely and with complete transparency, for effective supply chain management.[112]

Emerging technologies – in particular digital technologies and AI – also bring new energy demand. Global data centre electricity use in 2021was 220–320 TWh, equivalent to 0.9–1.3% of the global electricity demand, and cryptocurrency mining consumed 100–140 TWh.[113]

- **Opportunities**

Emerging non-energy technologies may provide solutions and opportunities for clean energy technology energy security challenges.

- **Risks**

The application of emerging technologies in clean energy presents the risk of introducing new vulnerabilities, or increasing vulnerability, particularly regarding cybersecurity. Emerging technologies may also be used for malicious purposes, such AI deployed in cyberattacks.

- **Uncertainties**

Emerging technologies may lead to disruptive developments and change, which can be unexpected or difficult to anticipate and plan for. For example, the recent leap in large language model capability, as demonstrated by ChatGPT, has prompted concerns over the risk of easier access to information to develop bioweapons.[114]

Links to other trends: the development of emerging technologies is global and has become a focal point of geopolitical tensions, with AI one recent example. International approaches to the development, application, regulation and governance of emerging technologies may affect the ways in which they are applied, as well as their associated risks and opportunities.

Increasing digitalisation

The deployment of digital technologies is rapidly increasing, including in clean energy technologies, their value chains and energy security. Digitalisation can improve energy systems, but can also introduce risks, including cybersecurity risks. Smart technologies are improving the efficiency of energy systems and reducing energy demand: for example, live monitoring and smart devices have potential to reduce energy use in buildings by 10%.[115]

However, in ever more digitally connected systems, cybersecurity can become a challenge where the weakest link – such as a single leaked password – introduces vulnerability to the system.[116] In Europe in 2020, significant cyberattacks in key sectors doubled, including 33 incidents in the energy sector.[117] In a 2022 World Economic Forum survey, 77% of energy executives identified cybersecurity as a higher priority than two years earlier, making it one of biggest current risks.[118] Cyberattacks are carried out by a range of different actors, from states to criminals and individuals with various goals.

Digital literacy and accessibility of digital technologies could pose energy security challenges for certain communities unable to engage with digital technologies, if support is not provided.

The EU published an action plan for the digitalisation of the energy system in 2022.[119]

- **Opportunities**

Digitalisation can support energy security though the availability of real-time monitoring, efficiency improvements and demand reduction or management through deployment of smart technologies.

- **Risks**

Digitalisation increases cyber risk, with cyberattacks on the rise globally and in some cases targeting energy infrastructure with potential to cause severe disruption to energy supply.

- **Uncertainties**

Understanding the digital connectivity of energy systems and energy technology value chains can be challenging to identify and resolve vulnerabilities.

Clean energy technology innovation

Innovation, and the duration from idea to commercial application, carries risk and uncertainty. Some technologies are developed over decades and the pace of development is not necessarily linear. In recent years, significant cost reductions have been achieved for solar and wind technologies far faster than previously expected, accelerating deployment.[120] The cost of solar power fell by 82% between 2010 and 2019.[121] For wind power, cost reductions are expected to continue, with experts estimating a fall of up to 49% by 2050.[122]

- **Opportunities**

R&I can continue to resolve energy security related challenges, such as affordability and performance for clean energy technologies.

- **Risks**

Innovation contributes to energy security challenges, due to high costs, performance limitations of solutions, or failure to resolve R&I challenges in time. The varying pace of innovation across different technologies may create system-level challenges: for example, intermittent renewable power sources will require energy storage technology to mitigate risks from periods of low wind or solar energy.

- **Uncertainties**

The pace and success of innovation is uncertain, with many factors influencing innovation and adoption of innovative technologies, including the level of technological challenge, existing knowledge and capabilities, public and private investment, policies and other innovation ecosystem considerations.

Links to other trends: innovation can be closely linked to economic trends, due to the availability and scale of public and private investment to support R&I activities, as well as policies that nurture an environment conducive to delivering R&I to application and deployment. Geopolitical tensions may affect international R&I collaborations.

Semiconductors

Semiconductors are a group of materials used to make electronic and photonic devices, with applications across most sectors, including clean energy technology value chains. Semiconductors have become the focus of the US-China trade war, with US restrictions on exports of advanced semiconductor technologies and associated equipment intended to prevent or delay China developing and accessing advanced technologies.

Semiconductor chip supply chains are global and complex, with vulnerabilities in supply due to concentration of certain steps in a small number of countries. Global semiconductor chip shortages have been caused by weather events and drought in Taiwan – one of the key manufacturing countries – and the impact of the COVID-19 pandemic.[123] Most of the world's global chip production is in Taiwan, South Korea and China.

The US Chips Act and EU Chips Act aim to increase competitiveness, resilience and security of supply in their respective economies. The EU currently accounts for 10% of global chip production and aims to double production capacity by 2030.[124] The European Commission has launched a pilot to monitor the semiconductor supply chain so as to enable rapid response to a potential crisis.[125]

- **Opportunities**

Increased investment in European semiconductor R&I and manufacturing includes opportunities for spillover benefits and increased capability with semiconductor technologies that can offer wider benefit to the energy security of clean energy technologies, for example through improved performance or development of a local supply chain.

- **Risks**

Increased demand for semiconductor devices from the green transition and digitalisation is likely to result in shortages similar to those currently resulting from supply chain vulnerabilities and the extensive time needed to increase production.[126] Changing the geographic distribution of the supply chain to reduce vulnerabilities will take years and significant investment.

- **Uncertainties**

Semiconductor supply chains are vulnerable to geopolitical tensions, in particular between Taiwan and China, with the scale of potential conflict and its impact uncertain.

The transition to low carbon transport and implications for supply chains

The transition to a low carbon or net zero carbon system will have implications for clean energy technologies. The scale and pace of the transition will determine the level of energy demand, including the level of active travel and behaviour change, uptake of electric vehicles (EVs) and deployment of solutions for high-carbon emissions transport sectors such as aviation and cargo transport. Current strategies for the EU include electrification of transport and increased use of biofuels.[127]

Decarbonising transport will contribute to wider initiatives to decarbonise supply chains, with opportunities for carbon emissions reduction through, for example, clean transport technologies, reducing the speed of supply chains and closer proximity of supply chains.[128] However, alternative low carbon technologies are not yet available replace fossil fuels in aviation or maritime shipping, for example.[129]

- **Opportunities**

The need to decarbonise transport will create opportunities through push and pull for novel solutions for transport fuels, providing investment and resources for R&I and deployment of innovative solutions.

- **Risks**

Challenges with the transition to low carbon transport could create energy security issues, both in terms of disruption to supply chains if the transition is not well managed, and novel low-carbon transport technologies introducing new vulnerabilities and risks.

- **Uncertainties**

Changes in regulation or other policies intended to incentivise decarbonisation of supply chains could lead to changes or reorganisation of supply chains and their geographic location. Uncertainty over energy demand from transport adds to uncertainty over to energy security and planning for future energy supply to ensure demand is met.

Legislative trends

EU legislation targets for clean energy technology deployment and energy security

EU targets for net zero and renewable energy deployment have become more ambitious over the years, due to ongoing climate change and the pressure on energy security caused by the war in Ukraine.[130] Policy packages have been designed to address individual renewable energy sectors, some of which are already enacted while other are going through the legislative process.

Examples of relevant EU legislation include regulations and directives in the Clean Energy for all Europeans package, the European Green Deal (including revisions to directives and regulation for gas and hydrogen and the Circular economy action plan), the REPowerEU and Fit for 55 packages, and the Net Zero Industry Act.

- **Opportunities**

Significant funds have been dedicated to clean energy technologies, underpinning large legislation packages including the European Green Deal Investment Plan, Industrial Plan and the Just Transition Mechanism. Around EUR 5.8 billion was invested in energy R&I projects in the EU's Horizon Europe programme 2021–2022. There are also catalysts for leveraging funds. InvestEU supports sustainable investment, innovation and job creation in Europe,[131] bringing together the European Fund for Strategic Investments and 13 other EU financial instruments under one roof and aims to trigger more than EUR 372 billion in additional investment over the period 2021–2027.[132] This includes funds, but also an advisory hub and portal that gives projects the opportunity to access technical assistance and network with others.

The legislation is ambitious and targets multiple challenges that underpin the green transition, including financing and administrative barriers to clean tech development. Under the Green Deal Industrial Plan, the commission aims to increase access to funding for clean tech production, streamline processes for approving IPCEI-related projects, create a simpler regulatory framework, enhance skills and open trade for resilient supply chains.

- **Risks**

Rushing the green transition process without solving issues around high energy prices and insufficient supply might negatively affect public perception of the value proposition of green transition legislation, causing opposition and boosting support for actions that allow for short-term reprieves rather than long-term sustainable solutions.

Social, economic and political divisions between western and eastern EU countries may occur, with potential tensions over developing and agreeing on future legislation.[133]

There is a risk of EU legislation 'picking winners' in the clean tech development market, favouring one technology or decarbonisation route over another and potentially overlooking viable or more optimal solutions, or making decisions that lead to technology lock-in. Some legislative actions may suit one pathway over another. More conducive incentive packages and regulatory conditions for technology developers in non-EU countries may draw financing and innovative solutions away from the bloc.

- **Uncertainties**

The latest action plan to speed up deployment is not legally binding, leaving uncertainty over how different Member States will implement it. The action plan is only valid for 18 months and it is not clear whether these measures will be extended or adjusted in the future.[134]

Links to other trends

Legislation is born of political process, to which it is therefore inextricably linked. One example is the legal enforceability of environmental commitments and targets being uncertain without the necessary legal tools.[135]

Critical Raw Materials Act

Some materials, such as minerals and rare earth metals, are crucial to clean technologies. The EU currently only supplies only 1% of the raw materials for many clean technologies,[136] which poses a threat to energy security. To tackle this problem, the EU published the Critical Raw Materials Act in 2020 and pledged to reduce dependency on single third countries.

Under the act, at least 10% of the EU's annual consumption of mined critical raw minerals should be sourced domestically. At least 40% of processed materials and 15% of recycled materials must also be domestically produced. The EU aims to diversify its global supply of minerals so that no more than 65% of its annual consumption any material should come from a single third country.

There are several measures that can mitigate this situation, including diversifying supply, promoting R&I, sustaining long-term extraction within EU, recycling raw materials, and so on. Policy packages have been put in place to address each area. For example, the European Innovation Partnership (EIP) was established as a stakeholder platform to foster actions and secure R&I funding. In addition, strategic partnerships with Norway, Greenland, Ukraine, Canada, Kazakhstan, Namibia, Argentina, Chile, Zambia and the Democratic Republic of Congo have been formed to diversify supply chains.[137] Recycling raw materials is another approach, which is explained in the technological trends section above.

- **Opportunities**

More stable access to raw materials for clean energy technologies may lead to increased investor confidence in the sustainability and potential return of their investments, due to a strong supply chain for raw materials within the EU. Cheaper access to raw materials may also enhance investor confidence, as well as industry actors' ability to participate in the green transition due to lower start-up and continuing costs (e.g. around procuring equipment with more sustainable materials). There may also be less risk around supply chain disruption for raw materials if those supply chains are more numerous and localised within Member States, instead of relying on routes easily disrupted by shocks such as COVID-19 and the war in Ukraine. Production and demand could also be modulated depending on the specific needs of clean energy technologies in specific regions, stockpiling when demand is low to protect against price surges in times of high demand.

- **Risks**

New EU-based supply chains will take time to provide reliable production and may not be competitive with international supply chains. The beginning of this process may suffer from legislative delays in countries such as Sweden and Portugal where the mining would take place, resulting in a long lead-in time before production meets demand.[138] There is also a risk that critical raw material extraction, processing, transport and use may have a net negative contribution to climate goals over and above the benefits associated with the development and deployment of clean energy technologies. However, advancements in efficient use of materials and increased use of sustainable or synthetic materials in place of rare earth metals may ameliorate this risk.

- **Uncertainties**

Political relations with strategic partners such as Canada can affect supply in positive and negative ways. The EU plans to increase bargaining power by forming Critical Raw Materials Clubs with countries such as Canada, which has processing expertise in rare earths. Mining in the EU will continue to be difficult due to environmental concerns, as well as legislation that is not conducive to setting up mines, such as Finland's mining laws which give more power to local residents over decisions for new mines.[139] There is also uncertainty over the EU27's ability to set up these new supply chains and whether it can sustain them with the jobs, skills and people available.

Links to other trends: Political trends may affect the extent to which CRM are mined in certain countries, due to land permissions, environmental lobbying and access to central EU funds. A poor economic climate may depress firms' ability to conduct R&D and produce clean energy products, reducing demand for CRM, or it may stimulate it depending on the overall policy packages countries introduce. There may be social opposition to new mines in Europe. New mining technologies used in fossil-fuel extraction could be repurposed for CRM extraction, or new technology may be needed to extract at the scale required. The environmental implications of new mines will be significant and will count towards the overall economic and GHG cost of extracting materials for green energy technology.

Circular economy action plan

As explained above, recycling one approaches to securing raw materials. The EU has published a new circular economy action plan to boost recycling. The plan contains sector-specific regulations, including for electronics and ICT, and batteries and vehicles. For the former, the EU will revise the current Ecodesign Directive to ensure products are designed to be suitable for recycling and strengthen measures to improve uptake of recycling schemes. For the latter, the EU will propose new regulations to improve the collection and recycling rates of batteries and ensure the recovery of valuable materials.[140]

- **Opportunities**

Recycling could help recover metals from electronic devices and reduce dependence on mining.[141] Recycling mitigates the risks associated with supply (e.g. price volatility, availability and import dependency), especially for raw materials used in clean energy.[142] A key objective of the action plan is to create sustainable growth and jobs in the circular economy: for example, in sourcing and processing as well as in innovating and improving circular economy methods.

- **Risks**

Potential risks from the circular economy are described in the technology trends section below.

- **Uncertainties**

How significantly these new regulations will improve recycling rates remains uncertain. Cultural barriers are ranked as the most important hurdle to businesses transforming for the circular economy.[143]

The rates of implementation across different Member States are also uncertain, with directives not legally binding at this stage. Some Member States, such as the Netherlands, France and Italy, have put regulations in place at a national level.[144]

International legislation, including the United States Inflation Reduction Act

Beyond the EU, other countries are also adopting legislation and targets for the clean energy transition, contributing to setting the pace for the global transition to net zero. By 2021, the EU and Member States, Japan, Canada, the UK, Korea and New Zealand had introduced legally binding targets.[145]

In addition to legislation for net zero targets, industrial policy legislation, standards and regulation may affect the international markets and value chains for clean energy technologies. For example, the US Inflation Reduction Act creates fiscal incentives for clean energy technology manufacturing based in the United States, with the aim of strengthening US-based value chains and US security of supply. This has raised concerns over competition and disadvantage for EU-based clean energy value chains and private investment choosing the United States over the EU.[146]

- **Opportunities**

Industrial policy in the United States is in part driven by concerns over the security of global value chains, creating opportunities for partnerships and 'friendshoring' as described in the political trends section.

- **Risks**

Industrial policy outside the EU may create challenges – from competitive disadvantage, reduced market access and loss of investment opportunities for EU-based energy technology value chains – and affect the geographic distribution of global value channels with potential vulnerabilities.

- **Uncertainties**

With legally binding targets, it is unclear what countries will do if they fail to meet a target and to what extent legislation will incentivise the delivery of these targets in practice.

Environmental trends

Critical materials

Clean energy technologies rely on critical materials, for example copper, nickel, cobalt, lithium[147] and aluminium. The EU is currently reliant on imports of CRM and goods manufacturing with CRM from a small number of countries. For materials with a small number of exporting countries, the supply chain is vulnerable to any shocks or disruption. CRM might also be mined in one country and refined in another, which can add a degree of complexity or concentrate vulnerabilities.

Demand for CRM is expected to increase with the green transition: for example, rare earth demand forecast to increase by a factor of five. Demand for critical materials will depend on the pace of the global transition and the overall energy demand and corresponding demand for clean energy technologies.[148]

Mining practices for CRM also present challenges.[149] Child labour and poor working conditions have been reported in cobalt mines in the Democratic Republic of Congo.[150] Mining can also cause significant environmental damage.[151]

The EU Critical Raw Materials Act includes a non-binding target for EU-based mining to meet 10% of EU needs. Some materials are found in Europe: for example, France and Portugal have large lithium reserves. However, a full assessment of potential for EU mining has not been carried out and new mines take 10 to 15 years to start operations.[152] Public opposition to mining projects in the EU is typically high.

- **Opportunities**

Europe is leading in recycling and circular economy initiatives, which could help reduce the reliance on imported raw materials.[153] According to estimates, and the results from one simulation experiment, circular economies of CRM have potential to reduce total dependence in EU Member States by between 17% and 24%.[154]

- **Risks**

A large portion of materials used in clean energy technologies are currently only available from a small number of countries, introducing vulnerabilities into technology value chains.

Increasing demand due to the acceleration of the green transition or geopolitical tensions could exacerbate vulnerabilities. For example, China is dominant in processing raw materials, and if China's domestic demand increases, leaving less surplus to export, or trade restrictions are introduced (as for rare earths in 2009 and 2012), the EU's supply could be severely disrupted.[155]

Mining can face opposition and disruption by local populations, in the EU and elsewhere, due to ethical, safety and environmental concerns.

- **Uncertainties**

The scale and feasibility of mining in the EU is uncertain, as is the scale and pace of potential demand for critical materials.

Climate change

Global temperatures are rising, with anthropogenic emissions estimated to contribute to a 0.2-°C increase every decade.[156] In 2022, the global mean temperature rise was 1.24 °C, compared to pre-industrial levels.[157] The Paris Agreement set the goal of keeping global warming well below 2 °C and ideally below 1.5 °C. However, with policies currently in place, the world is on track for 2.6–2.9 degrees Celsius of warming by 2100[158] and 1.5 °C of warming may be reached in the next five years.[159]

Climate change is already affecting weather patterns, including by increasing the frequency and severity of extreme weather events. Renewable energy technologies like hydropower, wind and solar power are affected by weather conditions such as *Dunkelflaute* events (wind-solar drought) and droughts caused by lack of rainfall. Under a 2 °C scenario, extreme events like the 2003 heatwave in Europe would occur most years.[160] The changing frequency and potential impact of climate change on renewable energy production is not well understood, with experts noting that further study is required to consider climate adaptation for the energy system. Currently, such weather events are managed through system flexibility, with provision of energy from another source, such as fossil fuels, nuclear power or energy storage technologies.

Changing weather patterns are likely to affect energy demand, by increased demand for cooling during heatwaves, for example.[161] As described in the social trends section, climate change is also expected to displace populations.

- **Opportunities**

With increasing risk to energy security from weather events, demand for energy storage and grid technologies that allow for more flexibility may provide a pull factor for the development and deployment of innovative solutions.

- **Risks**

The level of global warming reached in the coming decades is uncertain, and dependent on policy action and technology development and deployment. This creates a challenge for climate adaptation planning in the energy system, especially in where decisions taken now may have long-term consequences – for example if specifications for technology performance become inadequate over time and introduce climate related vulnerabilities in the energy system.

Climate change impacts will vary across countries. Depending on the geographic location of global value chains, climate adaptation in non-EU countries may also become a critical issue for European energy security.

- **Uncertainties**

The level of global warming that will be reached is uncertain, as policies and climate action evolve over the coming decades. Impacts of changing weather patterns on clean energy technologies or their wider value chain and energy security are not well understood.[162]

Environmental impact of clean energy technologies

As an alternative to fossil-fuel-based energy, clean energy technologies provide a mechanism to reduce global carbon emissions. Clean energy technology value chains generate some carbon emissions through steps such as manufacturing and transport and may be subject to regulation or standards as part of wider net zero policies. Lifecycle assessments of emission from clean energy value chains allow for comparison and evaluation.

The energy and transport systems are both sources of air pollution that contribute to negative health impacts around the world. Renewable energy technologies and EVs have potential to improve air quality.[163]

Concerns have been raised over the environmental, health and biodiversity impacts of clean energy technologies. Depending on the technology, assessing potential impact may be challenging due to the range of possible locations – for example, a solar panel installation in a valley versus a solar panel on a roof. Overall, renewable energy technologies are found to have lower impact than fossil fuels.[164] Materials and mining are a key factor in the environmental impact of these technologies.

Renewable energy installations are now reaching end-of-life, creating opportunities to learn and develop best practices for recycling and sustainable end-of-life. For example, 94% of a wind turbine is recyclable, but components commonly go into landfill rather than being recycled.[165] Reducing the environmental impact of clean energy technologies would contribute towards additional benefits from investment in clean energy and progress towards energy and environmental targets.

- **Opportunities**

Initiatives to reduce the environmental impact of energy technologies may provide an additional driver for R&I in re-use and recycling of key materials for clean energy technology value chains.

- **Risks**

Local environmental impacts, especially if negative, may affect public and political support for clean energy technologies.

- **Uncertainties**

The potential environmental impact of clean energy technologies is not fully understood, and there are still technical challenges to the development of sustainable practices such as sustainable mining and recycling some materials.

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[1] Jakob Feveile Adolfsen et al., "The Impact of the War in Ukraine on Euro Area Energy Markets," June 21, 2022, https://www.ecb.europa.eu/pub/economic-bulletin/focus/2022/html/ecb.ebbox202204_01~68ef3c3dc6.en.html; Yuru Guan et al., "Burden of the Global Energy Price Crisis on Households," Nature Energy 8, no. 3 (February 16, 2023): 304–16, https://doi.org/10.1038/s41560-023-01209-8; KPMG, "Russia-Ukraine War Impact on Supply Chains and Inflation," accessed June 8, 2023, https://www.kpmg.us/insights/2022/russia-ukraine-war-impact-supply-chains-inflation.html; Deloitte, "Supply Chain Implications of the Russia-Ukraine Conflict," Deloitte Insights, 2022, https://www2.deloitte.com/uk/en/insights/focus/supply-chain/supply-chain-war-russia-ukraine.html; Rene Wagner and Nadine Schimroszik, "Ukraine Conflict Adds to European Supply Chain Snags," Reuters, March 9, 2022, sec. European Markets, https://www.reuters.com/markets/europe/ukraine-conflict-adds-european-supply-chain-snags-2022-03-09/.

[2] OECD, "The Supply of Critical Raw Materials Endangered by Russia's War on Ukraine," OECD, 2022, https://www.oecd.org/ukraine-hub/policy-responses/the-supply-of-critical-raw-materials-endangered-by-russia-s-war-on-ukraine-e01ac7be/.

[3] IISD, "Green Conflict Minerals: The Fuels of Conflict in the Transition to a Low-Carbon Economy," 2018, https://www.iisd.org/system/files/publications/green-conflict-minerals.pdf.

[4] Cobalt is used clean energy technologies including electric vehicles and energy storage.

[5] IISD, "Green Conflict Minerals: The Fuels of Conflict in the Transition to a Low-Carbon Economy."

[6] Jennifer Lee, “Beauty and the Beast: Implications of the US-China Tech War on Climate and Energy,” Atlantic Council (blog), March 6, 2023, https://www.atlanticcouncil.org/blogs/energysource/beauty-and-the-beast-implications-of-the-us-china-tech-war-on-climate-and-energy/.
[7] Jeff Pao, “China Bans Export of Core Solar Panel Technologies,” Asia Times, February 1, 2023, https://asiatimes.com/2023/02/china-bans-export-of-core-solar-panel-technologies/.
[8] Jie Wu et al., “Evaluating the Cumulative Impact of the US–China Trade War along Global Value Chains,” The World Economy 44, no. 12 (2021): 3516–33, https://doi.org/10.1111/twec.13125; Haiou Mao and Holger Görg, “Friends like This: The Impact of the US–China Trade War on Global Value Chains,” The World Economy 43, no. 7 (2020): 1776–91, https://doi.org/10.1111/twec.12967.
[9] Carnegie Corporation of New York, “Seven Global Conflicts to Watch in 2023,” Carnegie Corporation of New York, 2023, https://www.carnegie.org/our-work/article/seven-global-conflicts-watch-2023/.
[10] Gary Milante, Hannes Mueller, and Robert Muggah, “Estimating Future Conflict Risks and Conflict Prevention Implications by 2030” (UN Peacekeeping, n.d.), https://peacekeeping.un.org/sites/default/files/estimating_future_conflict_risks_and_conflict_prevention_implications_by_2030.pdf.
[11] Charlie Vest, Agatha Kratz, and Reva Goujon, “The Global Economic Disruptions from a Taiwan Conflict,” Rhodium Group (blog), 2022, https://rhg.com/research/taiwan-economic-disruptions/.
[12] Devin C Bowles, Colin D Butler, and Neil Morisetti, “Climate Change, Conflict and Health,” Journal of the Royal Society of Medicine 108, no. 10 (October 1, 2015): 390–95, https://doi.org/10.1177/0141076815603234.
[13] John A. Paravantis et al., “Energy Security and Renewable Energy: A Geopolitical Perspective,” in *Renewable Energy - Resources, Challenges and Applications* (IntechOpen, 2020), https://doi.org/10.5772/intechopen.91848.; REN21, “Renewables 2019 Global Status Report,” 2019, https://www.ren21.net/gsr-2019/; World Economic Forum, “Accelerating the Energy Transition Through Innovation,” 2021, https://www.irena.org/publications/2017/Jun/Accelerating-the-Energy-Transition-through-Innovation.
[14] Aad Correljé and Coby van der Linde, “Energy Supply Security and Geopolitics: A European Perspective,” Energy Policy, Hong Kong Editorial Board meeting presentations, 34, no. 5 (March 1, 2006): 532–43, https://doi.org/10.1016/j.enpol.2005.11.008; Roman Vakulchuk, Indra Overland, and Daniel Scholten, “Renewable Energy and Geopolitics: A Review,” Renewable and Sustainable Energy Reviews 122 (April 1, 2020): 109547, https://doi.org/10.1016/j.rser.2019.109547.
[15] M.D.L.E. Mata Perez and Daniel Scholten, “Divergent Energy Paths within the European Union: ECPR General Conference,” in Divergent Energy Paths within the European Union (ECPR General Conference, ECPR Conference, 2018), https://pure.tudelft.nl/ws/portalfiles/portal/57399740/Mata_Perez_and_Scholten_2018_ECPR_Divergent_Energy_Paths_within_the_European_Union.pdf.
[16] María de la Esperanza Mata Pérez, Daniel Scholten, and Karen Smith Stegen, “The Multi-Speed Energy Transition in Europe: Opportunities and Challenges for EU Energy Security,” Energy Strategy Reviews 26 (November 1, 2019): 100415, https://doi.org/10.1016/j.esr.2019.100415.
[17] Richard Youngs, “The Divisive Politics of the Green Transition: Europe’s Unmet Challenge,” Carnegie Europe, 2021, https://carnegieeurope.eu/2021/12/15/divisive-politics-of-green-transition-europe-s-unmet-challenge-pub-85978; Jonas Grafström, “Divergence of Renewable Energy Invention Efforts in Europe: An Econometric Analysis Based on Patent Counts,” Environmental Economics and Policy Studies 20, no. 4 (October 1, 2018): 829–59, https://doi.org/10.1007/s10018-018-0216-y; Eulalia Rubio, “Financing the Energy Transition in Europe: Towards a More Holistic and Integrated Approach,” in Making the Energy Transition a European Success (Jacques Delors Institute, 2018), https://institutdelors.eu/wp-content/uploads/2018/01/ch3-makingtheenergytransitionaeuropeansuccess-study-pellerincarlinfernandesrubio-june2017.pdf; Grażyna Wojtkowska-Łodej and Honorata Nyga Lukaszewska, “Convergence or Divergence of the European Union’s Energy Strategy in the Central European Countries?,” CES Working Papers 11 (August 21, 2019): 91–110.
[18] OECD, “Global Value Chains and Trade,” accessed June 8, 2023, https://www.oecd.org/trade/topics/global-value-chains-and-trade/.
[19] Christopher F Baum et al., “Offshoring and Innovation Capabilities: Evidence from Swedish Manufacturing$,” CESIS, 2018, https://static.sys.kth.se/itm/wp/cesis/cesiswp469.pdf.
[20] Alex Coad and Antonio Vezzani, “Manufacturing the Future: Is the Manufacturing Sector a Driver of R&D, Exports and Productivity Growth?” (European Commission, 2017), https://joint-research-centre.ec.europa.eu/system/files/2017-09/jrc107579.pdf.
[21] Philipp Manow, “The Political Economy of Populism in Europe” (Chatham House, 2021), https://www.chathamhouse.org/sites/default/files/2021-12/2021-12-15-political-economy-populism-europe-manow.pdf.
[22] World Economic Forum, “What’s the Difference between ‘Friendshoring’ and Other Global Trade Buzzwords?,” World Economic Forum, February 17, 2023, https://www.weforum.org/agenda/2023/02/friendshoring-global-trade-buzzwords/.
[23] European Parliament, “EU Strategic Autonomy 2013-2023: From Concept to Capacity,” 2022, https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)733589.

[24] Mohammad Mafizur Rahman and Khosrul Alam, “The Roles of Globalization, Renewable Energy and Technological Innovation in Improving Air Quality: Evidence from the World’s 60 Most Open Countries,” Energy Reports 8 (November 1, 2022): 9889–98, https://doi.org/10.1016/j.egyr.2022.07.165; Torsten Henzelmann and Dieter Billen, “Clean Energy and the Reshaping of Global Value Chains” (Roland Berger, 2021), https://www.rolandberger.com/en/Insights/Publications/Clean-energy-and-the-reshaping-of-global-value-chains.html.
[25] Manow, “The Political Economy of Populism in Europe.”
[26] European Council, “EU Sanctions against Russia Explained,” June 8, 2023, https://www.consilium.europa.eu/en/policies/sanctions/restrictive-measures-against-russia-over-ukraine/sanctions-against-russia-explained/.
[27] Interview notes
[28] EEAS, “EU CHINA RELATIONS,” 2022, https://www.eeas.europa.eu/sites/default/files/documents/EU-China_Factsheet_01Apr2022.pdf.
[29] EEAS, “What Is Science Diplomacy? | EEAS,” 2022, https://www.eeas.europa.eu/eeas/what-science-diplomacy_en.
[30] European Union, “List of Participating Countries in Horizon Europe,” April 15, 2022, https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/common/guidance/list-3rd-country-participation_horizon-euratom_v2.0_en.pdf.
[31] Interview notes
[32] UNFCCC, “The Paris Agreement,” accessed June 9, 2023, https://unfccc.int/process-and-meetings/the-paris-agreement.
[33] CAT, “CAT Net Zero Target Evaluations,” accessed June 9, 2023, https://climateactiontracker.org/global/cat-net-zero-target-evaluations/.
[34] Michael Holtz, “Idaho Is Sitting on One of the Most Important Elements on Earth,” The Atlantic, January 24, 2022, https://www.theatlantic.com/science/archive/2022/01/cobalt-clean-energy-climate-change-idaho/621321/.
[35] Interview notes
[36] World Bank, “Stagflation Risk Rises Amid Sharp Slowdown in Growth,” June 7, 2022, https://www.worldbank.org/en/news/press-release/2022/06/07/stagflation-risk-rises-amid-sharp-slowdown-in-growth-energy-markets.
[37] IMF, “World Economic Outlook, April 2023: A Rocky Recovery,” April 2023, https://www.imf.org/en/Publications/WEO/Issues/2023/04/11/world-economic-outlook-april-2023.
[38] PwC, “Global Economy Watch - Projections,” PwC, accessed June 9, 2023, https://www.pwc.com/gx/en/research-insights/economy/global-economy-watch/projections.html; World Bank, “GLOBAL OUTLOOK,” in Global Economic Prospects (World Bank, 2023), https://openknowledge.worldbank.org/server/api/core/bitstreams/2106db86-a217-4f8f-81f2-7397feb83c1f/content; OECD, “OECD Economic Outlook, Interim Report March 2023: A Fragile Recovery” (OECD, March 17, 2023), https://doi.org/10.1787/d14d49eb-en.
[39] European Central Bank, “ECB Staff Macroeconomic Projections for the Euro Area, March 2023,” March 16, 2023, https://doi.org/10.2866/478445.
[40] P. Christensen, K. Gillingham, and W. Nordhaus, “Uncertainty in Forecasts of Long-Run Economic Growth,” Proceedings of the National Academy of Sciences 115, no. 21 (May 22, 2018): 5409–14, https://doi.org/10.1073/pnas.1713628115.
[41] PwC, “The World in 2050,” PwC, February 2017, https://www.pwc.com/gx/en/research-insights/economy/the-world-in-2050.html.
[42] The Economist, “Long-Term Macroeconomic Forecasts: Key Trends to 2050,” 2015, https://espas.secure.europarl.europa.eu/orbis/sites/default/files/generated/document/en/Long-termMacroeconomicForecasts_KeyTrends.pdf; PwC, “The World in 2050.”
[43] IEA, “Energy Technology Perspectives 2023 –Executive Summary,” IEA, January 2023, https://www.iea.org/reports/energy-technology-perspectives-2023/executive-summary.
[44] Claudia Schmucker, “The World Trade Crisis,” Internationale Politik Quarterly, January 2023, https://ip-quarterly.com/en/world-trade-crisis.
[45] Pia Andres, “Was the Trade War Justified? Solar PV Innovation in Europe and the Impact of the ‘China Shock,’” Grantham Research Institute on climate change and the environment, October 6, 2022, https://www.lse.ac.uk/granthaminstitute/publication/was-the-trade-war-justified-solar-pv-innovation-in-europe-and-the-impact-of-the-china-shock/.
[46] Pia Andres, “Was the Trade War Justified? Solar PV Innovation in Europe and the Impact of the ‘China Shock,’” Grantham Research Institute on climate change and the environment, October 6, 2022, https://www.lse.ac.uk/granthaminstitute/publication/was-the-trade-war-justified-solar-pv-innovation-in-europe-and-the-impact-of-the-china-shock/.
[47] IEA, “Energy Technology Perspectives 2023 –Executive Summary.”
[48] IEA, “World Energy Investment 2023,” 2023, https://iea.blob.core.windows.net/assets/8834d3af-af60-4df0-9643-72e2684f7221/WorldEnergyInvestment2023.pdf.
[49] BloombergNEF, “Energy Transition Investment Trends 2022” (BloombergNEF, January 2022), https://assets.bbhub.io/professional/sites/24/Energy-Transition-Investment-Trends-Exec-Summary-2022.pdf.

[50] IEA, “World Energy Investment 2023.”
[51] IEA, “Energy Technology RD&D Budgets” (IEA, 2020), 2023-06-09, https://iea.blob.core.windows.net/assets/b6e2d46e-9808-4118-9dae-6cf3f589bb7c/Energy_Technology_RDD_2020_Overview1.pdf.
[52] European Commission, “2022 Report on Energy Subsidies in the EU,” 2022, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022DC0642.
[53] World Economic Forum, “Why Europe’s ‘Climate Moon-Shot’ Needs the Private Sector as Co-Pilot,” 2021, https://www.weforum.org/agenda/2021/11/why-europe-s-climate-moon-shot-needs-the-private-sector-as-co-pilot-european-green-deal/.
[54] IRENA, “‘Unlocking Renewable Energy Investment: The Role of Risk Mitigation and Structured Finance,” 2016, https://www.irena.org/publications/2016/Jun/Unlocking-Renewable-Energy-Investment-The-role-of-risk-mitigation-and-structured-finance.
[55] World Bank, “Enabling Foreign Direct Investment in the Renewable Energy Sector” (World Bank, 2023), https://www.energycharter.org/fileadmin/DocumentsMedia/Occasional/Renewable_Energy_FDI_Final__032923.pdf.
[56] Reuters, “Venture Capital Investment in Clean Energy Startups Soars,” May 19, 2023, https://www.reuters.com/sustainability/venture-capital-investment-clean-energy-startups-soars-2023-05-18/.
[57] IEA, “Innovative Energy Start-Ups,” IEA, June 29, 2021, https://www.iea.org/articles/innovative-energy-start-ups.
[58] Omar Castrejon-Campos et al., “Economic and Environmental Impacts of Public Investment in Clean Energy RD&D,” Energy Policy 168 (September 1, 2022): 113134, https://doi.org/10.1016/j.enpol.2022.113134.
[59] World Economic Forum, “Why Europe’s ‘Climate Moon-Shot’ Needs the Private Sector as Co-Pilot.”
[60] World Economic Forum.
[61] P. Balachandra, Hippu Salk Kristle Nathan, and B. Sudhakara Reddy, “Commercialization of Sustainable Energy Technologies,” Renewable Energy 35, no. 8 (August 1, 2010): 1842–51, https://doi.org/10.1016/j.renene.2009.12.020.
[62] Flavio Calvino and Chiara Criscuolo, “Gone Digital: Technology Diffusion in the Digital Era” (Brookings, 2022), https://www.brookings.edu/blog/up-front/2022/01/20/gone-digital-technology-diffusion-in-the-digital-era/.
[63] J. P Painuly, “Barriers to Renewable Energy Penetration; a Framework for Analysis,” Renewable Energy 24, no. 1 (September 1, 2001): 73–89, https://doi.org/10.1016/S0960-1481(00)00186-5.
[64] Baolu Zhou et al., “Rare Earth Elements supply vs. clean energy technologies: new problems to be solve,” Gospodarka Surowcami Mineralnymi 32, no. 4 (2016): 29–44, https://doi.org/10.1515/gospo-2016-0039.
[65] European Economic and Social Committee. “The EU Needs More Public Investment in Energy Infrastructure to Fight Climate Change,” 2022. https://www.eesc.europa.eu/en/news-media/news/eu-needs-more-public-investment-energy-infrastructure-fight-climate-change#:~:text=The%20EU%20needs%20more%20public%20investment%20in%20energy%20infrastructure%20to%20fight%20climate%20change,-This%20page%20is&text=In%20an%20opinion%20adopted%20at,massive%20public%20investment%20is%20needed
[66] Alex Schmitt and Huangluolun Zhou, “EU Energy Outlook to 2060: How Will Power Prices and Revenues Develop for Wind, Solar, Gas, Hydrogen + More,” Energy Post (blog), December 6, 2022, https://energypost.eu/eu-energy-outlook-to-2060-how-will-power-prices-and-revenues-develop-for-wind-solar-gas-hydrogen-more/.
[67] European Climate, “TOWARDS FOSSIL-FREE ENERGY IN 2050” (European Climate, March 2019), https://europeanclimate.org/wp-content/uploads/2019/11/14-03-2019-towards-fossil-free-energy-in-2050-executive-summary.pdf.
[68] Eurobarometer, “Standard Eurobarometer 98 - Winter 2022-2023,” February 2023, https://europa.eu/eurobarometer/surveys/detail/2872.
[69] European Union, “Fairness Perceptions of the Green Transition - Eurobarometer Survey,” 2022, https://europa.eu/eurobarometer/surveys/detail/2672.
[70] Isabell Hoffmann and Catherine de Vries, “End of Summer, End of Solidarity?” (Bertelsmann Stiftung, 2022), https://www.bertelsmann-stiftung.de/fileadmin/files/BSt/Publikationen/GrauePublikationen/EZ_eupinions_slides_update_Ukraine_2022.pdf.
[71] Századvég, “Hungarians Are the Least Afraid of Blackouts in Europe,” January 16, 2023, http://szazadveg.hu/en/2023/01/16/hungarians-are-the-least-afraid-of-blackouts-in-europe~n3476.
[72] Hoffmann and de Vries, “End of Summer, End of Solidarity?”
[73] European Commission. Directorate General for Climate Action. “Special Eurobarometer 513. Climate Change.” LU: Publications Office, 2021. https://data.europa.eu/doi/10.2834/437.
[74] EIB.org. “2022-2023 EIB Climate Survey, Part 1 of 2: Majority of Europeans Say the War in Ukraine and High Energy Prices Should Accelerate the Green Transition.” Accessed April 4, 2024. https://www.eib.org/en/surveys/climate-survey/5th-climate-survey/eu-usa-china.htm.

[75] "Energy Perception Report." Accessed April 4, 2024. https://www.statkraft.com/newsroom/multimedia-and-publications/energy-perception-report/.
[76] Agentur Fur Erneuerbare Energien. "AEE Acceptance Request 2022," 2022. https://www.unendlich-viel-energie.de/mediathek/grafiken/aee-akzeptanzumfrage-2022.
[77] Jason Harold et al., "Drivers of People's Preferences for Spatial Proximity to Energy Infrastructure Technologies: A Cross-Country Analysis," *The Energy Journal* 42, no. 4 (July 1, 2021): 47–90, https://doi.org/10.5547/01956574.42.4.jhar.
[78] Reyes, Joseph Anthony L. "Willingness to Share Information for Energy Efficiency: Exploring Differences and Drivers across the Nordic Countries." Energy, Sustainability and Society 12, no. 1 (September 16, 2022): 38. https://doi.org/10.1186/s13705-022-00363-3.
[79] European Commission. "Special Eurobarometer 527: Fairness Perceptions of the Green Transition," October 2022. https://europa.eu/eurobarometer/surveys/detail/2672.
[80] EURACTIV, "Eleven Million Jobs at Risk from EU Green Deal, Trade Unions Warn," www.euractiv.com, March 9, 2020, https://www.euractiv.com/section/energy-environment/news/eleven-million-jobs-at-risk-from-eu-green-deal-trade-unions-warn/
[81] Kevin Winter et al., "Anticipating and Defusing the Role of Conspiracy Beliefs in Shaping Opposition to Wind Farms," *Nature Energy* 7, no. 12 (December 2022): 1200–1207, https://doi.org/10.1038/s41560-022-01164-w.
[82] Patricia Nayna Schwerdtle et al., "Interlinkages between Climate Change Impacts, Public Attitudes, and Climate Action—Exploring Trends before and after the Paris Agreement in the EU," Sustainability 15, no. 9 (January 2023): 7542, https://doi.org/10.3390/su15097542.
[83] European Commission, "Climate Change: Report." (Publications Office, 2021), https://data.europa.eu/doi/10.2834/437.
[84] Sam Crawley, Hilde Coffé, and Ralph Chapman, "Climate Belief and Issue Salience: Comparing Two Dimensions of Public Opinion on Climate Change in the EU," Social Indicators Research 162, no. 1 (July 1, 2022): 307–25, https://doi.org/10.1007/s11205-021-02842-0.
[85] European Commission, "Climate Change."
[86] Kantar Public, "European Attitudes to Climate Change," European attitudes to climate change, 2021, https://www.kantarpublic.com/inspiration/thought-leadership/european-attitudes-to-climate-change.
[87] IEA, "Europe's Energy Crisis: What Factors Drove the Record Fall in Natural Gas Demand in 2022?," IEA, March 14, 2023, https://www.iea.org/commentaries/europe-s-energy-crisis-what-factors-drove-the-record-fall-in-natural-gas-demand-in-2022.
[88] McKinsey, "Europe's Path to Decarbonization | McKinsey," 2020, https://www.mckinsey.com/capabilities/sustainability/our-insights/how-the-european-union-could-achieve-net-zero-emissions-at-net-zero-cost.
[89] European Commission, "Progress on Competitiveness of Clean Energy Technologies," 2022.
[90] European Commission, "EU Solar Energy Strategy," 2022, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A221%3AFIN.
[91] European Commission, "Progress on Competitiveness of Clean Energy Technologies."
[92] EURACTIV, "Green Jobs and the Green Transition: A Long, Bumpy but Exciting Journey," 2021, https://www.euractiv.com/section/energy-environment/opinion/green-jobs-and-the-energy-transition-a-long-bumpy-but-exciting-journey/.
[93] CEDEFOP, "An Ally in the Green Transition: VET, Especially Apprenticeship, Can Provide the Skills Needed for Greening Jobs– and in Turn Help Shape Them." (Publications Office, 2022), https://data.europa.eu/doi/10.2801/712651.
[94] EESC, "Just Transition: Targeted Training of Workers Can Turn Challenges into Opportunities," EESC, December 7, 2021, https://www.eesc.europa.eu/en/news-media/news/just-transition-targeted-training-workers-can-turn-challenges-opportunities.
[95] European Commission, "Progress on Competitiveness of Clean Energy Technologies."
[96] Cedefop (2021). "The Green Employment and Skills Transformation." Luxembourg: Publications Office. http://data.europa.eu/doi/10.2801/112540
[97] EESC, "Just Transition."
[98] Climate Justice Alliance, "JUST TRANSITION: A Framework for Change," Climate Justice Alliance, accessed June 9, 2023, https://climatejusticealliance.org/just-transition/; Greenpeace, "The Just Transition," Greenpeace, accessed June 9, 2023, https://www.greenpeace.org.uk/challenges/environmental-justice/just-transition/.
99 EBRD, "What Is a Just Transition?," EBRD, accessed June 9, 2023, https://www.ebrd.com/what-we-do/just-transition.
[100] Interview notes
[101] Eurostat, "Population Projections in the EU," Eurostat, March 2023, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Population_projections_in_the_EU.
[102] ESPAS, "Global Trends to 2030: The Future of Migration and Integration" (ESPAS, 2018), https://espas.secure.europarl.europa.eu/orbis/sites/default/files/generated/document/en/Ideas%20Paper%20Future%20Migration%20Integration_V04.pdf.

[103] Alejandro Gallego-Schmid and Joan Manuel F. Mendoza, “Circular Economy and the Clean Energy Transition,” Future Earth (blog), December 16, 2022, https://futureearth.org/2022/12/16/circular-economy-and-the-clean-energy-transition/.
[104] IRENA, “Circular Economy,” IRENA, accessed June 9, 2023, https://www.irena.org/Energy-Transition/Policy/Circular-economy.
[105] James Pennington, “3 Ways the Circular Economy Is Vital for the Energy Transition,” World Economic Forum, February 23, 2022, https://www.weforum.org/agenda/2022/02/3-ways-circular-economy-renewables-energy-transition/.
[106] Mark Peplow, “Solar Panels Face Recycling Challenge,” ACS Central Science 8, no. 3 (March 23, 2022): 299–302, https://doi.org/10.1021/acscentsci.2c00214.
[107] M. Massoud et al., “Review on Recycling Energy Resources and Sustainability,” Heliyon 9, no. 4 (April 1, 2023): e15107, https://doi.org/10.1016/j.heliyon.2023.e15107.
[108] Esrat Farhana Dulia et al., “Admitting Risks towards Circular Economy Practices and Strategies: An Empirical Test from Supply Chain Perspective,” Journal of Cleaner Production 317 (October 1, 2021): 128420, https://doi.org/10.1016/j.jclepro.2021.128420.
[109] Manavalan Ethirajan et al., “Analysing the Risks of Adopting Circular Economy Initiatives in Manufacturing Supply Chains,” Business Strategy and the Environment 30, no. 1 (2021): 204–36, https://doi.org/10.1002/bse.2617.
[110] Oleh Boiko, “Artificial Intelligence in Energy: Use Cases, Solutions, Best Practices” (N-iX, 2022), https://www.n-ix.com/artificial-intelligence-in-energy/.
[111] Jia-Hao Syu et al., “Energy Grid Management System with Anomaly Detection and Q-Learning Decision Modules,” Computers and Electrical Engineering 107 (April 1, 2023): 108639, https://doi.org/10.1016/j.compeleceng.2023.108639.
[112] Khalid Almutairi et al., “Blockchain Technology Application Challenges in Renewable Energy Supply Chain Management,” Environmental Science and Pollution Research, January 6, 2022, https://doi.org/10.1007/s11356-021-18311-7.
[113] IEA, “Data Centres and Data Transmission Networks” (IEA, 2022), https://www.iea.org/reports/data-centres-and-data-transmission-networks.
[114] Sean Ekins et al., “There’s a ‘ChatGPT’ for Biology. What Could Go Wrong?,” Bulletin of the Atomic Scientists (blog), March 24, 2023, https://thebulletin.org/2023/03/chat-gpt-for-biology/.
[115] IEA, “Digitalization and Energy” (IEA, 2017), https://iea.blob.core.windows.net/assets/b1e6600c-4e40-4d9c-809d-1d1724c763d5/DigitalizationandEnergy3.pdf.
[116] Alejandro Romero and Jonathan Nelson, “Why Europe’s Energy Industry Is Vulnerable to Cyber-Attacks,” ECFR, March 7, 2022, https://ecfr.eu/article/why-europes-energy-industry-is-vulnerable-to-cyber-attacks/.
[117] Álvaro Merino, “Cyber attacks are growing in the European Union,” OBC Transeuropa, March 15, 2022, https://www.balcanicaucaso.org/eng/Areas/Europe/Cyber-attacks-are-growing-in-the-European-Union-216529.
[118] Akshay Joshi, “Europe Is Bolstering Energy Sector Resilience. But Cyberattack Risk Remains a Major Vulnerability for Europe’s Energy Sector,” World Economic Forum, October 31, 2022, https://www.weforum.org/agenda/2022/10/europe-is-energy-sector-resilience-cyber-risk/.
[119] European Commission, “Digitalisation of the Energy System,” European Commission, accessed June 9, 2023, https://energy.ec.europa.eu/topics/energy-systems-integration/digitalisation-energy-system_en.
[120] A. Elia et al., “Wind Turbine Cost Reduction: A Detailed Bottom-up Analysis of Innovation Drivers,” Energy Policy 147 (December 1, 2020): 111912, https://doi.org/10.1016/j.enpol.2020.111912; Josh Gabbatiss, “Record Clean-Power Growth in 2023 to Spark ‘New Era’ of Fossil Fuel Decline,” Carbon Brief, April 11, 2023, https://www.carbonbrief.org/record-clean-power-growth-in-2023-to-spark-new-era-of-fossil-fuel-decline/.
[121] lempriere, “Solar PV Costs Fall 82% over the Last Decade, Says IRENA,” Solar Power Portal, June 3, 2020, https://www.solarpowerportal.co.uk/news/solar_pv_costs_fall_82_over_the_last_decade_says_irena.
[122] Ryan Wiser et al., “Expert Elicitation Survey Predicts 37% to 49% Declines in Wind Energy Costs by 2050,” Nature Energy 6, no. 5 (May 2021): 555–65, https://doi.org/10.1038/s41560-021-00810-z.
[123] Julian Kamasa, “Chip Shortages in the Light of Geopolitics and Climate Change,” CSIS, February 9, 2022, https://www.csis.org/blogs/strategic-technologies-blog/chip-shortages-light-geopolitics-and-climate-change.
[124] European Commission, “European Chips Act,” accessed June 9, 2023, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-chips-act_en.
[125] European Commission, “European Chips Act: Commission Launches Pilot System to Monitor Semiconductor Supply Chain | Shaping Europe’s Digital Future,” May 10, 2023, https://digital-strategy.ec.europa.eu/en/news/european-chips-act-commission-launches-pilot-system-monitor-semiconductor-supply-chain.
[126] Kamasa, “Chip Shortages in the Light of Geopolitics and Climate Change.”
[127] Romeo Danielis, Mariangela Scorrano, and Marco Giansoldati, “Decarbonising Transport in Europe: Trends, Goals, Policies and Passenger Car Scenarios,” Research in Transportation Economics, Decarbonising transport, 91 (March 1, 2022): 101068, https://doi.org/10.1016/j.retrec.2021.101068.

[128] World Economic Forum, "SUPPLY CHAIN DECARBONIZATION" (World Economic Forum, 2009), https://www3.weforum.org/docs/WEF_LT_SupplyChainDecarbonization_Report_2009.pdf.
[129] Christian Brand, "7 Reasons Why Global Transport Is so Hard to Decarbonize," World Economic Forum, November 22, 2021, https://www.weforum.org/agenda/2021/11/global-transport-carbon-emissions-decarbonise/.
[130] European Commission, "Renewable Energy Targets," 2023, https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-targets_en.
[131] European Union, "Invest EU," Invest EU, accessed June 9, 2023, https://investeu.europa.eu/index_en.
[132] European Commission, "EU Funding Possibilities in the Energy Sector," 2023, https://energy.ec.europa.eu/topics/funding-and-financing/eu-funding-possibilities-energy-sector_en.
[133] EURACTIV, "Eleven Million Jobs at Risk from EU Green Deal, Trade Unions Warn," www.euractiv.com, March 9, 2020, https://www.euractiv.com/section/energy-environment/news/eleven-million-jobs-at-risk-from-eu-green-deal-trade-unions-warn/.
[134] Pinsent Masons, "EU Adopts Regulation to Fast Track Permits for Renewable Energy Projects," Pinsent Masons, 2023, https://www.pinsentmasons.com/out-law/news/eu-adopts-regulation-to-fast-track-permits-for-renewable-energy-projects.
[135] Alicja Sikora, "European Green Deal – Legal and Financial Challenges of the Climate Change," ERA Forum 21, no. 4 (January 1, 2021): 681–97, https://doi.org/10.1007/s12027-020-00637-3.
[136] Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (European Commission) et al., *Critical Raw Materials for Strategic Technologies and Sectors in the EU: A Foresight Study* (Publications Office of the European Union, 2020), https://data.europa.eu/doi/10.2873/58081.
[137] "EU and Norway Sign Strategic Partnership," Text, European Commission - European Commission, accessed April 4, 2024, https://ec.europa.eu/commission/presscorner/detail/en/ip_24_1654; European Commission, "EU and Greenland Sign Strategic Partnership," Text, European Commission - European Commission, accessed April 4, 2024, https://ec.europa.eu/commission/presscorner/detail/en/ip_23_6166.
[138] Economist Intelligence Unit, "EU Acts to Secure Access to Critical Raw Materials," Economist Intelligence Unit, aoril 2023, https://www.eiu.com/n/eu-acts-to-secure-access-to-critical-raw-materials/.
[139] Finnish Government, "Amended Mining Act Will Strengthen Citizen Influence, Economic Prospects and Environmental Aspects," Valtioneuvosto, March 23, 2023, https://valtioneuvosto.fi/en/-/1410877/amended-mining-act-will-strengthen-citizen-influence-economic-prospects-and-environmental-aspects.
[140] European Commission, "A New Circular Economy Action Plan For a Cleaner and More Competitive Europe," 2020, https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN.
[141] Pennington, "3 Ways the Circular Economy Is Vital for the Energy Transition."
[142] EU Monitor, "Circular Economy: Definition, Importance and Benefits - EU Monitor," 2023, https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vknegugz7hwu?ctx=vjxzjv7ta8z1.
[143] Julian Kirchherr et al., "Barriers to the Circular Economy: Evidence From the European Union (EU)," *Ecological Economics* 150 (August 1, 2018): 264–72, https://doi.org/10.1016/j.ecolecon.2018.04.028.
[144] Blaise Hope, "How Countries Are Striving to Build Their Circular Economy," March 25, 2022, https://sustainabilitymag.com/sustainability/how-countries-are-leading-build-a-circular-economy-eu-sustainability-regenerative; Ewa Mazur-Wierzbicka, "Circular Economy: Advancement of European Union Countries," *Environmental Sciences Europe* 33, no. 1 (September 27, 2021): 111, https://doi.org/10.1186/s12302-021-00549-0.
[145] Dominic Carver, "Global Net Zero Commitments," November 12, 2021, https://commonslibrary.parliament.uk/global-net-zero-commitments/.
[146] Pau Ruiz Guix, "Key Transatlantic Implications of the Inflation Reduction Act," Elcano Royal Institute, April 11, 2023, https://www.realinstitutoelcano.org/en/analyses/key-transatlantic-implications-of-the-inflation-reduction-act/.
[147] Marie Le Mouel and Niclas Poitiers, "Why Europe's Critical Raw Materials Strategy Has to Be International" (Bruegel, April 5, 2023), https://www.bruegel.org/analysis/why-europes-critical-raw-materials-strategy-has-be-international.
[148] Patrick Schröder, Pepijn Bergsen, and Jack Barrie, "Europe's Pursuit of Securing Critical Raw Materials for the Green Transition," Chatham House, April 4, 2023, https://www.chathamhouse.org/2023/04/europes-pursuit-securing-critical-raw-materials-green-transition-0.
[149] IEA, "Encouraging Sustainable and Responsible Practices," in Critical Minerals Policy Tracker (IEA, 2022), https://www.iea.org/reports/critical-minerals-policy-tracker/encouraging-sustainable-and-responsible-practices; George Barakos, "Sustainable Mining of Critical Minerals and Metals around the World: Bottlenecks and Opportunities," International Journal of Mining, Reclamation and Environment 36, no. 9 (October 21, 2022): 605–6, https://doi.org/10.1080/17480930.2022.2143790.
[150] Allison Seyler, "Cobalt in the Democratic Republic of Congo: The Cost of Innovative Technology and Historical Lessons in Global Economics for a More Ethical Future," May 2021, https://soar.suny.edu/handle/20.500.12648/1905.

[151] Stefania Massari and Marcello Ruberti, “Rare Earth Elements as Critical Raw Materials: Focus on International Markets and Future Strategies,” Resources Policy 38, no. 1 (March 1, 2013): 36–43, https://doi.org/10.1016/j.resourpol.2012.07.001.
[152] Edoardo Righetti and Vasileios Rizos, “The EU’s Quest for Strategic Raw Materials: What Role for Mining and Recycling?,” Intereconomics 2023, no. 2 (2023): 69–73.
153 EU Monitor, “Circular Economy: Definition, Importance and Benefits - EU Monitor.”
[154] Rainer Lütkehus, “How Europe Can Become Less Dependent on Raw Materials Imports,” European View 13, no. 2 (December 1, 2014): 295–302, https://doi.org/10.1007/s12290-014-0334-2.
[155] Interview notes
[156] IPCC, “Global Warming of 1.5 oC: Summary for Policymakers” (IPCC, 2018), https://www.ipcc.ch/sr15/chapter/spm/.
[157] Robert Rohde, “Global Temperature Report for 2022,” Berkeley Earth (blog), January 12, 2023, https://berkeleyearth.org/global-temperature-report-for-2022/.
[158] CAT, “Temperatures,” CAT, accessed June 9, 2023, https://climateactiontracker.org/global/temperatures/.
[159] World Meteorological Organization, “Global Temperatures Set to Reach New Records in next Five Years,” World Meteorological Organization, May 15, 2023, https://public.wmo.int/en/media/press-release/global-temperatures-set-reach-new-records-next-five-years.
[160] Andrew D. King and David J. Karoly, “Climate Extremes in Europe at 1.5 and 2 Degrees of Global Warming,” Environmental Research Letters 12, no. 11 (November 2017): 114031, https://doi.org/10.1088/1748-9326/aa8e2c.
[161] Faith Birol, “The World’s Electricity Systems Must Be Ready to Counter the Growing Climate Threat,” IEA, July 12, 2021, https://www.iea.org/commentaries/the-world-s-electricity-systems-must-be-ready-to-counter-the-growing-climate-threat.
[162] Interview notes
[163] IEA, “Air Quality,” in Multiply Impact for a Better Tomorrow with Sustainable Industries (IEA, 2019), https://www.iea.org/reports/multiple-benefits-of-energy-efficiency/air-quality.
[164] UNEP, “Green Energy Choices: The Benefits, Risks and Trade-Offs of Low-Carbon Technologies for Electricity Production” (International Resource Panel, 2016), https://www.resourcepanel.org/reports/green-energy-choices-benefits-risks-and-trade-offs-low-carbon-technologies-electricity.
[165] Su Mei Woo and Jonathan Whale, “A Mini-Review of End-of-Life Management of Wind Turbines: Current Practices and Closing the Circular Economy Gap,” Waste Management & Research 40, no. 12 (December 1, 2022): 1730–44, https://doi.org/10.1177/0734242X221105434.

ANNEX C: FACTSHEETS

9. Introduction

This Annex presents the energy security assessments (factsheets) for all value chains analysed in this study (see Section 7.2 in the main report for the value chains that were selected for each clean energy technology category).

The first part of the factsheet, covering 'characteristics', provides a brief description of the technology, including the value chain's role in the energy system and some technical information such as its primary energy source (if applicable), technology readiness level (TRL), and a description of its life cycle phases (construction, use, end-of-life). In the second part of the factsheets, the 10 energy security indicators were evaluated and scored. For each indicator, a qualitative assessment was given, followed by a score based on this assessment. Three different scores could be assigned: 1 (low risk), 2 (moderate risk) or 3 (high risk). The assessment reflects a time-independent risk level – i.e. the extent to which each value chain is intrinsically vulnerable to the energy security risks associated with the indicators. The scores are intended as relative to risk levels for the other value chains, to enable conclusions on which risks are most pronounced across the technologies in scope.

9.1. Advanced biofuels

9.1.1. Algae-based advanced biofuels

Algae-based biofuels have a very significant feedstock potential, but still face technical, biological and financial obstacles to making the production process viable.

There are two types of algae: macroalgae (also called seaweed) and microalgae. Microalgae are microscopic unicellular algae and can be cultivated in open ponds or land-based bioreactors. As larger aquatic organisms, macroalgae and can be cultivated in the sea, using lines and nets for the algae to grow on. The bioenergy yield per unit of mass from macroalgae is lower than from microalgae, but the production costs are also lower.

Macroalgae contain less lignin and might be better suited to production of biomethane than to other applications. Furthermore, algae are in principle restricted to nutrient-rich waters and artificial fertilisation or pumps to bring nutrients to the surface may be required.[1]

9.1.1.1. Characteristics

Role in EU energy system: Algae based advanced biofuels would play a role as an energy carrier in transport.

Algae biofuels are in the research phase, so co algae biofuels are currently used in the EU energy system. Algae derived biofuels are, however, classified under Annex IXa of the RED II (if cultivated on land in ponds or photobioreactors) and therefore eligible for double counting towards the target.

Primary energy source: for macroalgae, sunlight, CO_2 and nutrients from the water. If cultivated in a closed system, moderate levels of energy are needed to sustain the system. For microalgae – cultivated in a controlled environment – much more energy is required. This includes artificial light, yeast, glycerol and other chemicals, thereby exceeding the environmental footprint of conventional diesel.[2]

TRL: Major biological challenges to extracting the necessary level of lipids from wild algae remain. Uncontrolled lagoons or ponds often entail contamination from unproductive algae and organisms that feed on the algae, which affects availability for harvest. Closed cultivation systems have significantly higher capital and operating costs. Genetic modification may result in a species more suitable for biofuel feedstock, but this is still in the research phase. ExxonMobil, which had a 12-year research project on algae, pulled out of it in 2022. Another two more decades and many billions of euros in funding may be needed to reach commercialisation.[3]

In Europe, there are currently a few hundred algae production units, which are mainly used for food, cosmetics, food supplements and feed.[4] TRLs range from 4 to 5.[5]

9.1.1.2. Life cycle: construction phase

Demonstration projects use photobioreactors, coolers, compressors, pumps, fermenters and centrifuges (mainly steel). For large-scale production these systems must become commercially viable. The catalysts used may be made from a range of materials. Natural catalysts (dolomite, olivine, zeolite) are inexpensive and not critical. Better performing catalysts from stable metals (Ni, Ru, Pd, Pt, Rh, Zn, Cu, Al, Co, Cr, Fe based catalysts etc.) are more costly but can also suffer from fouling or poisoning.

As described in the characterisation of the technique, a wide range of different processes might be applied for conversion of algae into fuel.

9.1.1.3. Life cycle: use phase

The aim of the ongoing research track is to create a cultivation process for algae without any continuous or significant maintenance inputs (except naturally available sources, like sunlight and nutrients available in the water).

The production of algae-based biofuels does need a continuous supply of algae.

9.1.1.4. Life cycle: end-of-life

We have no information on waste flows, but they are unlikely to have an impact on energy security. At the end-of-life of a facility, it may be used for recycling.

Table C.1 Energy security indicators for algae-based advanced biofuels

Geopolitical availability (score: 1)
No geopolitical issues are yet known, since no commercial producers exist.
Abundance (score: 1)

No significant volumes of critical materials needed, therefore no challenges regarding availability.

Circularity (score: 1)

No information on waste flows of algae. The facilities needed to produce biofuels from feedstock may be subject to circularity objectives.

Supply chain complexity (score: 3)

Multiple processes are possible to obtain advanced biofuels, including hydrolysis, pyrolysis (CFP), gasification and further hydroprocessing. For algae biofuels, no optimal supply chain exists yet. CFP employs various catalysts that promote cracking, dehydration and deoxygenation reactions to produce a bio-oil with lower oxygen levels, increased heating value and higher hydrocarbon content (mostly aromatics and olefins). Catalysts may be deactivated via coking and condensation of poly-aromatics. Hydrolysis processes need acid resistant steel reactors, Teflon or ceramics-coated materials. Gasification needs a reactor with catalysts.[5] The supply chains for these processes are moderately complex.

Also, feedstock needs to be transported from the location of cultivation to the biofuel production facility. Complexity increases if large volumes must be imported from outside the EU. TRL 4–6 of the production process for algae biofuel[6] justifies a score of 3.

Supply chain location (score: 1)

Potentially in all aquatic areas (both fresh and saltwater). Production of biofuels can also in principle be located anywhere. No significant flows of resources.

Digital vulnerability (score: 1)

No significant digital instruments/infrastructure needed; digital vulnerability is not concern in terms of energy security.

Physical vulnerability (score: 2)

Cultivation of algae in open water might entail physical treats from predatory organisms, and tidal or climatological risks that could jeopardise harvest.

Broader sustainability (score: 2)

Algae cultivation could extract too many nutrients from the water, which might affect other organisms or ecosystems. On other hand, harvesting delays could result in an oversupply of nutrients (eutrophication).[1]

Affordability (score: 2)

No commercial algae derived biofuel is available yet, therefore no comparison with alternatives is possible. Affordability of the commercial product is subject of the research stage. Currently, production costs might be in the range of 0.50–0.80 EUR/litre biodiesel, which is 55–90 EUR/MWh.[3]

Skills (score: 1)

No special skills needed. Furthermore, research is aimed at establishing a supply chain that requires little human labour.

9.1.1.5. Bibliography

[1] CE Delft (2020), Availability and costs of liquified bio and synthetic methane, Delft: CE Delft, https://ce.nl/wp-content/uploads/2021/03/CE_Delft_190236_Availability_and_costs_of_liquefied_bio-_and_synthetic_methane_Def.pdf

[2] T. Bradley et al. (2023), Life cycle assessment of microalgae-derived biodiesel, New York: Springer, https://link.springer.com/article/10.1007/s11367-023-02140-6

[3] El-Sheekh et al. (2021), Handbook of algal biofuels, Amsterdam: Elsevier, (PDF) HANDBOOK OF ALGAL BIOFUELS Aspects of Cultivation, Conversion, and Biorefinery (researchgate.net)

[4] R. Araujo et al. (2021), Current status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy, Lausanne: Frontiers, https://www.frontiersin.org/articles/10.3389/fmars.2020.626389/full#F9

[5] CETO (2022), Advanced biofuels in the European Union, Luxembourg: Publications Office of the European Union, https://setis.ec.europa.eu/advanced-biofuels-european-union_en

[6] T. Mahmood et al. (2023), Sustainable production of biofuels from the algae-derived biomass, New York: Springer, https://link.springer.com/article/10.1007/s00449-022-02796-8

9.1.2. Primary crop-based advanced biofuels

Primary crop-based advanced biofuels within the RED II context may be classified in two categories of Annex IXa: other non-food cellulosic material and other lignocellulosic material.

Non-food cellulosic material refers to feedstock mainly composed of cellulose and hemicellulose, and with a lower lignin content than lignocellulosic material, including food and feed crop residues such as straw, stover, husks and shells; grassy energy crops with a low starch content such as ryegrass, switchgrass, miscanthus and giant cane; cover crops before and after main crops; ley crops; industrial residues, including from food and feed crops after vegetable oils, sugars, starches and protein have been extracted; and material from biowaste, where ley and cover crops are understood to be temporary, short-term sown pastures comprising a grass-legume mixture with a low starch content to obtain fodder for livestock and improve soil fertility to obtain higher yields of arable main crops.

Lignocellulosic material refers to material composed of lignin, cellulose and hemicellulose, such as biomass sourced from forests, woody energy crops and forest-based industries' residues and wastes.[1]

9.1.2.1. Characteristics

Role in EU energy system: Energy carrier. No precise outlook for primary crop-based advanced biofuels is known. Production capacity of all biofuels across the EU was around 35 million tons in 2021.[2]

Primary energy source: sun, minerals.

TRL: 8–9

9.1.2.2. Life cycle: construction phase

Different pathways are possible to convert feedstock into biofuel. Biofuel refineries do not need CRM for their construction or operation.

The catalysts used may be made of a range of materials. Natural catalysts (dolomite, olivine, zeolite) are inexpensive and not critical. Better-performing catalysts from stable metals (Ni, Ru, Pd, Pt, Rh, Zn, Cu, Al, Co, Cr, Fe based catalysts etc.) are more costly but can also suffer from fouling or poisoning.[3]

9.1.2.3. Life cycle: use phase

Feedstock must be supplied continuously for the production of biofuels.

9.1.2.4. Life cycle: end-of-Life

No information about significant waste streams, but they are unlikely have an impact on energy security.

Table C.2 Energy security indicators for primary crop-based advanced biofuels

Geopolitical availability (score: 1)
Crops can be diverse and, can be grown within the EU but also imported from outside the EU. No particular geopolitical complexity.
Abundance (score: 1)
Dependent on cultivation and availability of land without creating (indirect) land use change.
Circularity (score: 1)
No information on significant waste flows, no energy security issues related to circularity of primary crop-based advanced biofuels. The facilities needed to produce biofuel from feedstock may be subject to circularity objectives.
Supply chain complexity (score: 2)
Multiple processes are possible to obtain advanced biofuels, including hydrolysis, CFP, gasification and further hydroprocessing. For algae biofuels, no optimal supply chain exists yet. CFP employs various catalysts that promote cracking, dehydration and deoxygenation reactions to produce a bio-oil with lower oxygen levels, increased heating value and higher hydrocarbon content (mostly aromatics and olefins). Catalysts may be deactivated via coking and condensation of poly-aromatics. Hydrolysis processes need acid resistant steel reactors, Teflon or ceramics-coated materials. Gasification needs a reactor with catalysts.[4] The supply chains for these processes are moderately complex. Furthermore, feedstock must be transported from the location of cultivation to the biofuel production facility. Complexity increases if large volumes must be imported from outside the EU.
Supply chain location (score: 1)

Cultivation takes place on arable land. Production can take place anywhere, but preferably where industrial conditions are met (energy supply, transport facilities).

Digital vulnerability (score: 1)
No significant digital instruments/infrastructure needed; digital vulnerability is not a concern in terms of energy security.
Physical vulnerability (score: 1)
General weather conditions might be perceived as a threat (e.g. droughts, heavy rains, etc.).
Broader sustainability (score: 1)
Indirect land use change might be a risk factor, but this is regulated by the Land Use, Land-Use Change and Forestry (LULUCF) directive, and RED sustainability criteria. Land can only be used for primary crop-based biomass if these sustainability criteria are met. If demand for primary crop based advanced biofuels exceeds supply possible from the degraded agricultural land available in the EU, it must be imported. This could entail raised sustainability risks, although imported biomass must also fulfil RED and LULUCF sustainability criteria. We consider the sustainability measures in place sufficient to assess the score as 1.
Affordability (score: 1)
Unlikely to have an impact on energy security. Costs are largely dependent on feedstock, but estimates point to a range of 65–158 EUR/MWh for biomass based advanced fuels.[5]
Skills (score: 1)
Agricultural skills needed for cultivation. No highly specific skills are needed to produce biofuels.

9.1.2.5. Bibliography

[1] EC (2023), Regulation (EU) 2018/841 of the European Parliament and of the Council, Luxembourg: Publications Office of the European Union, CL2018R0841EN0020010.0001.3bi_cp 1..1 (europa.eu)

[2] Eurostat (2023), Liquid biofuels production capacities, Luxembourg: Publications Office of the European Union, https://ec.europa.eu/eurostat/databrowser/view/NRG_INF_LBPC__custom_7235282/default/table?lang=en

[3] CETO (2022), Advanced biofuels in the European Union, Luxembourg: Publications Office of the European Union, https://setis.ec.europa.eu/advanced-biofuels-european-union_en

[4] Santos, Santa Margarida, Ana Carolina Assis, Leandro Gomes, Catarina Nobre, and Paulo Brito. “Waste Gasification Technologies: A Brief Overview.” Waste 1, no. 1 (March 2023): 140–65. https://doi.org/10.3390/waste1010011.

[5] IEA Bioenergy (2019), Advanced biofuels, potential for cost reduction, https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf

9.1.3. Waste-based advanced biofuels

Waste-based advanced biofuels are listed in Annex IXa of the RED II and are eligible for double counting towards the directive’s renewable energy transport target. Waste as category is specifically mentioned for:

- Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets.

- Biowaste from private households subject to separate collection.

- Biomass fraction of industrial waste unfit for use in the food or feed chain, including material from retail and wholesale and the agro-food, fish and aquaculture industry, excluding used cooking oil or animal fat.

- Biomass fraction of wastes and residues from forestry and forest-based industries, namely, bark, branches, pre-commercial thinnings, leaves, needles, treetops, sawdust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil.

Other categories might be considered 'waste' are listed in Annex IXa:

- Straw
- Animal manure and sewage sludge
- Palm oil mill effluent and empty palm fruit bunches
- Tall oil pitch
- Crude glycerine
- Bagasse
- Grape marcs and wine lees
- Nut shells
- Husks
- Cobs cleaned corn kernels

9.1.3.1. Characteristics

Role in EU energy system: Energy carrier.

The share of Annex IXa in renewable transport is supposed to grow towards 2030. In all climate neutral EU scenarios, waste (not further specified) will grow from 60 Mtoe (2015) to almost 100 Mtoe in 2050 (approximately 116 million tons of biodiesel).

Production capacity of all biofuels in the EU was around 35 million tons in 2021.[1]

Primary energy source: waste can have different primary energy sources.

TRL: 6–9.[2] The use of waste as feedstock for biofuels is already commercially applied. Some pathways are still being optimised or are the subject of research.

Hydrotreatment has a TRL of 9. Gasification combined with Fischer Tropsch to produce biodiesel/kerosene/gasoline has a TRL of 7–8. Gasification combined with synthesis to produce methanol has a TRL of 8. Hydrolysis fermentation has a TRL of 5–8. Alcohol catalysis has a TRL of 6–7. Anaerobic digestion to produce methane (from manure) has a TRL of 9.[3]

9.1.3.2. Life cycle: construction phase

Many different industrial processes are used to transform biowaste into fuel – depending on the nature of the feedstock – including pyrolysis, gasification, hydroprocessing and fermentation.

Materials include stainless steel, nickel-chromium alloys, and catalysts that can be made of a range of materials. Natural catalysts (dolomite, olivine, zeolite) are inexpensive and not critical. Better performing catalysts from stable metals (Ni, Ru, Pd, Pt, Rh, Zn, Cu, Al, Co, Cr, Fe based catalysts etc.) are more costly and can suffer from fouling or poisoning.[2]

9.1.3.3. Life cycle: use phase

A continuous supply of feedstock is needed for production.

9.1.3.4. Life cycle: end-of-Life

No information on significant waste streams.

Table C.3 Energy security indicators for waste-based advanced biofuels

Geopolitical availability (score: 1)
Waste can be supplied mainly by EU countries. Large import streams of waste from outside the EU are unlikely, because collection is decentralised and therefore expensive, meaning local application might be more attractive and for EU biofuel production it might be more economically reasonable to have dedicated, nearby supply.
Abundance (score: 2)
Continuous but moderate supply. Once all recycling and recovering measures are implemented, availability is not flexible: supply of waste cannot be increased in response to demand from production processes.
Circularity (score: 1)
No information on significant waste streams or circularity. The feedstock (waste) is itself a waste stream. The facilities needed to produce biofuel from feedstock may be subject to circularity objectives.
Supply chain complexity (score: 2)
Complexity relates to the process of recovering waste from the economy and securing valuable waste streams from non-usable waste but cannot be assessed as a security risk. Having supply from nearby sources is economically more attractive.

Multiple processes are possible to obtain advanced biofuels, including hydrolysis, CFP, gasification and further hydroprocessing. For algae biofuels, no optimal supply chain exists yet. CFP employs various catalysts that promote cracking, dehydration and deoxygenation reactions to produce a bio-oil with lower oxygen levels, increased heating value and higher hydrocarbon content (mostly aromatics and olefins). Catalysts may be deactivated via coking and condensation of poly-aromatics. Hydrolysis processes need acid resistant steel reactors, Teflon or ceramics-coated materials. Gasification needs a reactor with catalysts.[2] The supply chains for these processes are moderately complex.

Supply chain location (score: 1)

Waste is generated everywhere, which contributes to the complexity of gathering it in a cost-effective way. Although complex and cumbersome, this cannot be perceived as an energy security issue.

Digital vulnerability (score: 1)

No significant digital instruments/infrastructure needed; digital vulnerability is not a concern in terms of energy security.

Physical vulnerability (score: 1)

Waste cold ignite during collection or storage.

Broader sustainability (score: 1)

If the economic value of waste becomes high, it may be attractive to present cheap non-waste biomass as waste. This could have adverse effects on land use, carbon emissions or the food supply chain. A new database on biofuels is being established under the RED III to ensure better control of sustainability and possible fraud risks.

Affordability (score: 2)

Gasification + FT: 270–620 EUR/tonne

Gasification + synthesis: 270–620 EUR/tonne (for methanol blend)

Pyrolysis: 800–1410 EUR/tonne

Hydrolysis fermentation: 700–1 270 EUR/tonne

Alcohol catalysis: 1100–4 800 EUR/tonne

Anaerobic digestion[3]: 500–1 600 EUR/tonne

Costs are also largely dependent on the feedstock, but estimates point to costs in the range of 48–104 EUR/MWh for waste-based biofuels.[4]

Skills (score: 1)

No specific skills required. A relatively large volume of human labour may be required to collect or separate waste.

9.1.3.5. Bibliography

[1] Eurostat (2023), Liquid biofuels production capacities, Luxembourg: Publications Office of the European Union. https://ec.europa.eu/eurostat/databrowser/view/NRG_INF_LBPC__custom_7235282/default/table?lang=en
[2] CETO (2022), Advanced biofuels in the European Union, Luxembourg: Publications Office of the European Union. https://setis.ec.europa.eu/advanced-biofuels-european-union_en
[3] Energy Community (2020), Modalities to foster use of renewable energy sources in the transport sector by the Energy Community Contracting Parties, Modalities to foster use of renewable energy sources in the transport sector by the Energy Community Contracting Parties – EU NEIGHBOURS east. https://euneighbourseast.eu/news/publications/modalities-to-foster-use-of-renewable-energy-sources-in-the-transport-sector-by-the-energy-community-contracting-parties/
[4] IEA Bioenergy (2019), Advanced biofuels, potential for cost reduction. https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf

9.2. Bioenergy

9.2.1. Primary crop-based and forest-based bioenergy

Primary crop-based and forest-based bioenergy refers to solid non-food or feed biomass feedstock that is used for bioenergy (excluding liquid or gaseous biofuels). It is woody biomass that is primarily cultivated for bioenergy, or woody biomass as secondary product from the forest industry or maintenance of forests (e.g. sawdust, pruning waste, residual wood).

Woody biomass can be directly used for bioenergy in a stove, boiler or fireplace – mostly by households, but it can also be compressed into pellets, briquettes or chips for use in industrial applications including electricity generation (as well as in households).

RED II and LULUCF sustainability criteria restrict the supply of woody biomass that can be used for bioenergy in installations above 20MW. This means primary forest, highly biodiverse forests or grasslands, nature protected areas and land with high carbon stocks including wetlands, are excluded. As woody biomass entails potential threats to biodiversity or carbon stock, it may be further restricted in future. Individual use of woody biomass might continue to be used in rural areas as a flexible energy source without any value chain risks. In combination with CCS, bioenergy might offer a way to achieve negative emissions.[1]

9.2.1.1. Characteristics

Role in EU energy system: Storage/energy carrier

EU scenarios for 2050 foresee forest stemwood use similar to 2015 levels (around 30 Mtoe). Forest residue as feedstock for bioenergy could double (to 30 Mtoe in 2050). Use is mainly anticipated in power generation and industry. Total biomass (including all other biomass applications) will cover a maximum of 20% of final energy demand in 2050.[2]

If bioenergy with carbon capture and storage (BECCS) increases – not accounted for in current scenarios – bioenergy could become much more important.

Primary energy source: biomass.

TRL: 9

9.2.1.2. Life cycle: construction phase

Significant land area is needed to produce biomass, but it can be produced anywhere on condition that sustainability criteria are met. Facilities to produce pellets are not technically complex and mainly made of steel. Applications to burn bioenergy do not contain critical materials, but limited amounts of steel, bricks or concrete.

9.2.1.3. Life cycle: use phase

A continuous supply of feedstock is needed for production.

9.2.1.4. Life cycle: end-of-fife

No information on waste streams. The end-of-life stage of primary crop-based and forest-based bioenergy is energy extraction. The end-of-life stage of facilities used to produce pellets or extract energy may be subject to circularity objectives.

Table C.4 Energy security indicators for primary crop-based and forest-based bioenergy

Geopolitical availability (score: 1)
In principle, there is no complexity regarding geopolitical availability. Primary crop-based and forest-based bioenergy is not dependent on geopolitical factors and can be cultivated anywhere arable land is available at relatively cheaply. Currently, the United States, Canada, Scandinavia, the Baltics and Russia are important producers of woody biomass. Future geopolitical availability depends mainly on the availability of cheap land in those countries. Therefore, small and densely populated countries are unlikely to become large producers.
Abundance (score: 2)
Although woody biomass is abundant, sustainable woody biomass is much less so. Moreover, the strict sustainability measures that must be taken – including monitoring and certification – mean sustainable woody biomass is not very abundant. Important producers are currently countries with a large forest area and large areas of cheap land to produce (woody) biomass – such as Sweden, the Baltics, Russia, Canada and the United States.
Circularity (score: 1)
To ensure sustainability, land used to produce feedstock may have circular cultivation. The facilities needed to produce biofuel from feedstock may be subject to circularity objectives.
Supply chain complexity (score: 2)
Supply chain complexity for biomass is linked to administrative complexity. Monitoring, verification and certification of biomass feedstock is complex and cumbersome, with risks of irregularity and fraud, especially when the biomass is imported from non-EU countries.[1]
Supply chain location (score: 1)
Not complex, but feedstock must be transported from location of cultivation to biofuel production facility. Complexity increases if a large amount must be imported from outside the EU.

Digital vulnerability (score: 1)
Digital vulnerability may be related to any installation connected to the internet or, for example, certificates exchanged in the digital environment.
Physical vulnerability (score: 1)
General vulnerabilities, like droughts, fires or effects of climate change could threaten crops.
Broader sustainability (score: 2)
Sustainability risks, such as minimum carbon savings criteria and land use change risks, are the most important risk in the value chain, but these are currently covered by the RED and LULUCF. This must be monitored strictly and continuously. Since forest grows almost everywhere around the world, there is a risk exists of high value forest countries supplying forest-based bioenergy to the EU if the price becomes too attractive.[1]
Affordability (score: 1)
Boiler on secondary wood: 0.038 EUR/kWh. Wood pellets in industrial applications[3]: 0.0635 EUR/kWh
Skills (score: 1)
Agricultural skills are needed for cultivation. No special skills are needed for conversion of biomass.

9.2.1.5. Bibliography

[1] JRC (2021), The use of woody biomass for energy production in the EU, Luxembourg: Publications Office of the European Union, JRC Publications Repository - The use of woody biomass for energy production in the EU (europa.eu). https://publications.jrc.ec.europa.eu/repository/handle/JRC122719

[2] European Commission (2018), A Clean Planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, Luxembourg: Publications Office of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52018DC0773

[3] PBL (2023), Model SDE++, Den Haag: Planbureau voor de Leefomgeving. https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.pbl.nl%2Fsites%2Fdefault%2Ffiles%2Fdownloads%2Fpbl-2023-ot-model-sde-plus-plus-2023-4815_1.xlsx&wdOrigin=BROWSELINK

9.2.2. Waste-based bioenergy

Waste-based biomass consists of waste from households, agriculture residues, paper and pulp residues, and sewage treatment residues. This waste is a direct result of consumption patterns and has a more or less fixed supply, if all measures for recycling are optimised, i.e. the most (environmentally) valuable materials allocated to the most economically valuable activities. Waste-based bioenergy can be used for power supply, road transport, industry, heating and air transport.

Although waste-based bioenergy might also be used for BECCS, the limited supply and lack of significant scalability of waste-based biomass implies that BECCS will probably use other forms of biomass (such as primary crop or forest-based biomass).

9.2.2.1. Characteristics

Role in EU energy system: Energy carrier/storage

Bioenergy feedstock supply in the EU was around 150 Mtoe in 2015 but should increase to 250–300 Mtoe in 2050, depending on the scenario. This increase can be realised by increasing separation and recycling. Use in 2050 is mainly foreseen in power generation and industry. Total biomass (including all other biomass applications) will cover a maximum of 20% of final energy demand in 2050.[1,2]

Primary energy source: biomass.

TRL: 9 – bioenergy is already widely used in a number of applications.

9.2.2.2. Life cycle: construction phase

Facilities are needed to convert the biomass into a useable energy carrier. These facilities are mainly made of steel and concrete and do not require advanced materials.

9.2.2.3. Life cycle: use phase

Waste-based bioenergy needs a continuous supply of waste. Waste needs to be collected, stored and treated (dried).

9.2.2.4. Life cycle: end-of-life

Facilities will need to be decommissioned at end-of-life and might be recycled.

Table C.5 Energy security indicators for waste-based bioenergy

Geopolitical availability (score: 1)
Waste-based biomass is supplied by the EU economy but can also be imported. However, considering its relatively small role in the future energy system and present supply in Europe, as well as the possibility of cultivating other biomass on a more economically feasible scale, it is unlikely that large import flows will be organised.
Abundance (score: 2)
Waste is a direct result of consumption patterns and not scalable. Import of waste is possible, but unlikely considering the alternatives. Higher demand could create problems in the supply chain.
Circularity (score: 1)
Circular application of waste-based bioenergy is not applicable, but circularity issues do play a role for waste before it is selected for use as bioenergy. Circularity issues are also relevant for facilities converting waste into a usable energy feedstock.

Supply chain complexity (score: 1)
Waste is often geographically diffuse, which complicates collection in economic terms, but does not pose a risk.
Supply chain location (score: 1)
Throughout the EU, on condition that waste is collected separately or separated post-collection.
Digital vulnerability (score: 1)
No significant digital instruments/infrastructure needed; digital vulnerability is not a concern in terms of energy security, although there are general digital risks (e.g. hacks, crashes).
Physical vulnerability (score: 1)
Waste can ignite during collection or treatment.
Broader sustainability (score: 1)
If the economic value of waste becomes high, it becomes attractive to turn cheap non-waste biomass into waste. Furthermore, waste may have more valuable applications than bioenergy. However, this last point is currently regulated by the RED and LULUCF waste directives.
Affordability (score: 1)
Depending on the feedstock and precise application, approximately 0.04 EUR/kWh.[3]
Skills (score: 1)
Collection of waste may be labour intensive, but requires no specific skills, and nor are special skills needed for the application of waste-based bioenergy.

9.2.2.5. Bibliography

[1] European Commission (2018), A Clean Planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, Luxembourg: Publications Office of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52018DC0773

[2] JRC (2021), The use of woody biomass for energy production in the EU, Luxembourg: Publications Office of the European Union, JRC Publications Repository - The use of woody biomass for energy production in the EU (europa.eu). https://publications.jrc.ec.europa.eu/repository/handle/JRC122719

[3] PBL (2023), Model SDE++, Den Haag: Planbureau voor de Leefomgeving. https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.pbl.nl%2Fsites%2Fdefault%2Ffiles%2Fdownloads%2Fpbl-2023-ot-model-sde-plus-plus-2023-4815_1.xlsx&wdOrigin=BROWSELINK

9.3. Concentrated solar energy

9.3.1. Concentrated solar energy

Concentrated solar power (CSP) and heat uses mirrors to reflect and concentrate solar energy onto a specific point (receiver). In this way, solar energy in the form of sunlight is converted to thermal energy (heat), which is then transferred to a working liquid, travels through a sealed heat exchanger, finally heating water to boiling point. Steam from the boiling water spins a turbine to generate electricity.

The same working principle can also be applied to concentrating solar energy for district heating (or cooling) and industrial processes (SHIP). A temperature of 100–400 °C required for SHIP.

Note, concentrated solar energy (CSE) also covers solar heating: thermal collector, which utilises similar technology to concentrated solar energy, but off-grid and on a smaller scale, being directly placed on roofs to provide domestic and residential heating.

9.3.1.1. Characteristics

Role in EU energy system: Intermittent energy generation. Currently plays a small role in the EU but has potential.

- CSP: EU capacity is 2.4 GW – almost all in Spain[1]
- SHIP: data not available

Primary energy source: the sun

TRL: 9

9.3.1.2. Life cycle: construction phase

Main elements of CSP system:[2]

- Steam generators/steam turbines
- Heat transfer materials/corrosion-resistant materials
- Mirrors (made of silver)
- Frames, supports and trackers
- Receivers (+ absorptive material)
- Solar field (reflectors and receivers)

Infrastructure:[2]

- CSP can be combined with thermal energy storage (TES)
- Access to electricity grid

9.3.1.3. Life cycle: use phase

- Working liquid for heat transfer (synthetic oil or molten salt)
- Maintenance

9.3.1.4. Life cycle: end-of-life

CSP systems are made to last 20 to 30 years.[3]

Table C.6 Energy security indicators for concentrated solar energy

Geopolitical availability (score: 1)
Since almost all technologies contain permanent magnets (as part of generators) and copper (as part of the connection to the grid) these materials are considered a background risk (score 1). Besides this, CSP does not use materials from the EU's CRM list[2] and therefore the score given is 1.
Abundance (score: 1)
Since almost all technologies contain permanent magnets (as part of generators) and copper (as part of electronics) these materials are a considered background risk (score 1).
Circularity (score: 2)
In several lifecycle assessment (LCA) studies covering CSP, the following end-of-life scenarios are sketched: 40% recycling; 30% landfill; 30% materials recovery.[4] The corrosive nature of heat transfer fluids may cause damage and shorten the lifetime of the technology.[5] Recycling of these fluids is also difficult, and they can damage the environment if not handled properly.[5] Because of these issues, this indicator is assigned a score of 2.
Supply chain complexity (score: 1)
Over the past 10 years, CSP manufacture has become more standardised. However, to become even more competitive further standardisation should occur.[6] Compared to other technologies, the components of CSP are not highly specialised. During operations, only maintenance takes place. Therefore, this indicator is assigned a score of 1.
Supply chain location (score: 2)
In terms of manufacturing, there is a very strong Spanish presence.[1,2] Chinese companies are emerging. Only some geographical locations are suitable, as direct, year-around sunlight is needed (more so than for PV, which also works with ambient daylight). To summarise, there is no significant risk in terms of manufacturing components, but there is risk terms of operation. Therefore, a score of 2 is given.
Digital vulnerability (score: 1)

Although cyberattacks can never be excluded, there is no particular digital risk for this technology compared to other value chains, and the damage resulting from a cyberattack could probably be limited. Therefore, a score of 1 is assigned.

Physical vulnerability (score: 2)

- High temperatures can impact efficiency[7]
- All circuit elements of central receiver towers are subject to freezing and corrosion[8]
- Working fluid is toxic and flammable[8]
- Excessive concentration on a single element (receiver) is a risk[8]
- Substantial back-up energy required to avoid freezing of salt fluid

To summarise, physical risks are mostly linked to the technology's materials and components. Since there are some risks, a score of 2 is given.

Broader sustainability (score: 2)

Ecosystem and biodiversity: For central receiver plants, some US environmental groups raised concerns over the potential impact of concentrated light beams on wildlife.

Water use: 3.5 m3/Mwh (in operation, wet cooling);[2] the steam generators and turbines in particular have high water use[8]

Land use:[2] 2.4–3.2 ha/MW (direct area)

Compared to other technologies, there is a high land and water requirement, but the risks to ecosystems are limited. Therefore, a score of 2 is given.

Affordability (score: 2)

CSP: The levelised cost of energy (LCOE) is 0.182 USD/kWh (2019);[6,10] therefore, this indicator is assigned a score of 2.

SHIP:[2] Less data, CAPEX of EU SHIP systems 541 USD/kW (2019)

Skills (score: 1)

No specific data available. There is no evidence that skills availability poses a significantly higher risk than for comparable value chains, even accounting for the relatively small scale of application of CSP. Therefore, this indicator is assigned a score of 1.

9.3.1.5. *Bibliography*

[1] Statista. 'EU: Concentrated Solar Power Capacity 2030.'; Pihl et al. (2012). 'Material constraints for concentrating solar thermal power'. *Energy*. Volume 44 (944-954). https://doi.org/10.1016/j.energy.2012.04.057

[2] JRC (2022), Concentrated Solar Power and Heat in the European Union, Luxembourg: Publications Office of the European Union. https://setis.ec.europa.eu/concentrated-solar-power-and-heat-european-union_en

[3] Ejaz et al. (2021). 'Concentrated photovoltaics as light harvesters: Outlook, recent progress, and challenges'. *Sustainable Energy Technologies and Assessments.* Volume 46. Concentrated photovoltaics as light harvesters: Outlook, recent progress, and challenges – ScienceDirect. https://www.sciencedirect.com/science/article/abs/pii/S2213138821002095

[4] Corona et al. (2014). 'Life cycle assessment of concentrated solar power (CSP) and the influence of hybridising with natural gas'. *The International Journal of Life Cycle Assessment*. Volume 19 (1264-1275). Life cycle assessment of concentrated solar power (CSP) and the influence of hybridising with natural gas | The International Journal of Life Cycle Assessment (springer.com)

[5] Alami et al. (2023). 'Concentrating solar power (CSP) technologies: Status and analysis'. *International Journal of Thermofluids*. Volume 18. Concentrating solar power (CSP) technologies: Status and analysis - ScienceDirect

[6] IRENA (2019). IRENA Power Generation Costs 2019. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019.pdf?rev=77ebbae10ca34ef98909a59e39470906

[7] Gernaat et al. (2021). 'Climate change impacts on renewable energy supply'. *Nature Climate Change*. Volume 11 (119-125). https://www.nature.com/articles/s41558-020-00949-9

[8] The World Bank (2021). Concentrating Solar Power on Demand 24/7, Washington, DC: World Bank. WorldBank-CSP-Report-Concentrating-Solar-Power-Clean-Power-on-Demand-24-7-FINAL.pdf

[10] Kiefer and del Río (2020). 'Analysing the barriers and drivers to concentrating solar power in the European Union. Policy implications'. *Journal of Cleaner Production*. Volume 251. Analysing the barriers and drivers to concentrating solar power in the European Union. Policy implications. https://doi.org/10.1016/j.jclepro.2019.119400

9.4. Geothermal energy

9.4.1. Geothermal plant for heat and electricity generation

Geothermal energy uses the earth's thermal energy, which can be used to generate electricity, or used directly – to heat buildings, for example. Geothermal energy potentials depend on geographical location, the depth of geothermal wells, and which application the geothermal energy is used for (e.g. heating, agriculture, industry etc.).[1] There are several types of geothermal power plant, with suitability dependent on the quality of geothermal resources and their geographical location.[2]

9.4.1.1. Characteristics

Role in EU energy system: In 2021, 877 MWe of geothermal energy was installed in the EU.[2] Combined heat and power (CHP) plants account for around 20–25% of installed geothermal electricity generation capacity, and about 20% is geothermal district heating and cooling (DHC) capacity.[2] In 2021, total installed geothermal district heating and cooling capacity was 5.6 GWth in Europe for 364 DHC systems, of which 262 (2.2 GWth) are located in the EU.[2]

Geothermal heat production is expected to grow from 870.5 ktoe in 2020 to 1 000 ktoe in 2030.[2] The geothermal district heating and cooling sector grows slowly, with a 3% growth rate in installed capacity in Europe overall, and 6% in the EU.[2]

Primary energy source: geothermal energy

TRL: Geothermal power/heat plants have reached a mature technological level.[2] However, several developments with lower TRL are being investigated – such as geothermal heating and cooling for urban areas (TRL 7),[2] closed-loop geothermal systems (TRL 3–4) and improved/novel drilling techniques (TRL 3–5).[2,3]

9.4.1.2. Life cycle: construction phase

A geothermal plant is composed of the following elements and materials:[4]

- Wells casing and cementing: steel, cement, bentonite, silica sand, lignosulfonates, perlite, NaOH, HCl, oil and lubricants

- Drilling platform: steel, cement, aluminium, sand, plastic

- Steam adduction pipeline: steel, cement, aluminium, rock wool insulation

- Condensate pipeline: plastic

- Turbine and alternator: cast iron, copper, iron-nickel-chromium alloy, rock wool, Chromium steel 18/8, steel (low-alloyed), steel (unalloyed)

- Compressors: aluminium, cast iron, steel (unalloyed), copper

- Condenser: chromium steel 18/8

- Intercooler: chromium steel 18/8

- Cooling towers: steel piping, plastic piping, fiberglass, copper, cast iron

- Gas treatment system: sorbent (selenium for Hg), catalyst (titanium for H_2S), aluminium, chromium steel 18/8

- Building: cement, diesel for construction works, plastic pipes, aluminium, steel (low-alloyed).

- Accessories: copper, plastic pipes, chromium steel 18/8, steel (low-alloyed)

Summary of materials

We summarise the materials in the following categories: crucial raw materials, non-critical raw material and other:

- Critical raw material: copper, aluminium, nickel

- Non-critical raw material: chromium, iron

- Other: rock wool, plastic, fiberglass, cement, sand, steel, cast iron, sorbent (selenium for Hg), catalyst (titanium for H_2S), bentonite, silica, lignosulfonates, perlite, NaOH, HCl, oil and lubricants

Construction equipment

The construction of a geothermal plant roughly requires the following:[5]

- Drilling machines are to drill wells

- Machinery/equipment to build underground pipes, which are used to inject water and extract steam

- Machinery/equipment to build the infrastructure to transport heat

- Machinery/equipment to build the grid infrastructure to transport electricity

9.4.1.3. Life cycle: use phase

During the operational phase, various maintenance tasks are required, depending on the type of the geothermal plant. For geothermal electricity plants, the construction of additional (make-up) wells may be required to maintain productivity.[5] Additionally, removal of silica deposits from the heat exchangers may be required.[5] Geothermal plants suffer from corrosion and require inspection and replacement of materials to prevent operational problems.[6]

9.4.1.4. Life cycle: end-of-life

The operation phase for a geothermal plant lasts 20 to 40 years.[2] Steel and copper equipment can be recycled, with a recycling percentage of 70% for steel and 50% for copper.[7]

Table C.7 Energy security indicators for geothermal plant for heat and electricity generation

Geopolitical availability (score: 1)
Geothermal installations require relatively few CRM.[2] The critical materials used in a geothermal plant and their relative geopolitical availability are listed here: • Copper: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Aluminium: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Nickel: four EU suppliers. Top suppliers are of low political risk. Supply not concentrated in one country. Relatively low supply risk (score: 1). • Titanium: available in one EU country and multiple global countries. Supply risk relatively low. Supply not concentrated in one country, but the top suppliers (China and Russia) are politically risky (score: 2). The average of all materials is a score of 1.
Abundance (score: 2)
Since almost all technologies contain permanent magnets (as part of generators) and copper (as part of the connection to the grid) these materials are considered a background risk (score 1). The critical materials in the technology's core and their abundance risk are: • Copper, which has a medium abundance risk (1 to 100 ppm, score 2). • Aluminium, which has a low abundance risk (>10 000 ppm, score 1). • Titanium, which has a low abundance risk (>10 000 ppm, score 1). • Nickel, which has a medium abundance risk (1 to 100 ppm, score 2). Since the average score for all materials is 2, this is the overall score assigned to this indicator.
Circularity (score: 1)

Whenever possible, components and equipment from decommissioned geothermal plants can be repurposed or relocated to new projects. Materials mostly used for geothermal plants such as steel and metals can often be recycled, as is already done nowadays, therefore the score of 1 is assigned.

Supply chain complexity (score: 1)

Geothermal installations require fewer CRM than other technologies,[2] which makes the total supply chain less vulnerable to disruption. The overall complexity of the technology we consider relatively low, and therefore we assign a score of 1 for this energy security indicator.

Supply chain location (score: 2)

In 2016, around 80% of globally installed geothermal power capacity was dominated by four major manufacturers: Toshiba (Japan), Mitsubishi (Japan), Ormat (United States) and Fuji (Japan).[8] In 2016, Ansaldo-Tosi (Italy) led the European market with about 30% of installed capacity.[8] The oil and gas industry is the main supplier of most of the equipment used for the underground geothermal installations.[8]

Since most manufacturers are located outside the EU, we assign a score of 2 for this energy security indicator.

Digital vulnerability (score: 1)

While geothermal plants could be potential targets of cyberattacks, we estimate that the digital vulnerability is relatively low compared to other energy technologies such as wind turbines, where cyberattacks may cause substantial damage. Therefore, a score of 1 is assigned.

Physical vulnerability (score: 1)

Erosion-corrosion

Geothermal systems can contain several aggressive constituents, such as salt brines, hydrogen chloride, hydrogen sulphide and carbon dioxide gas from volcanic systems.[6] These constituents can lead to (increased) corrosion and erosion-corrosion of materials used in the geothermal plant. The rate of erosion-corrosion also depends on pressure, temperature, flow rate, chloride content and pH.[6]

We expect sufficient monitoring and maintenance to lower the risks associated with erosion-corrosion. Therefore, we assign a score of 1 to this energy security indicator.

Broader sustainability (score: 2)

Pollutants and greenhouse gases

Geothermal plants may emit pollutants in case of inadequate containment and treatment.[2] In general, potential emissions into the air include CO_2, H_2S, hydrogen, NH_3 (ammonia) and CH_4 (methane), radon, volatile metals, silicates, carbonates, metal sulphides and sulphates and traces of mercury, arsenic, antimony, selenium and chromium.[2] H_2S emissions contribute to acidification, and NH_4^+ emissions contribute to marine and terrestrial eutrophication.[7]

The majority of GHG emissions from geothermal operations are CO_2 from geothermal fluids.[2] Geological conditions are the main factor determining levels of GHG emissions, which are overall higher for volcanic areas.[2] CH_4 emissions also contribute to global warming. These emissions might be mitigated by reinjecting these gasses in the geothermal well.[9]

Public acceptance

Several concerns have been reported with respect to geothermal plants.[2,7] The drilling phase contributes to natural land transformation and noise pollution.[2,7] During operation, fluid injections may induce seismic activities and may cause groundwater contamination (see Environmental impact[2]).

The emission of pollutants and GHGs linked to geothermal power plants may pose a challenge to operations, due to environmental regulations and public acceptance concerns. For these reasons, a score of 2 is assigned.

Affordability (score: 1)

Geothermal energy has a global weighted average LCOE of 0.068 USD/kWh.[10]

Geothermal energy potential is unequally distributed. In areas with high geothermal potential, geothermal energy is affordable. Therefore, we assign a score of 1.

Skills (score: 2)

Around 40 000 persons are directly employed in the European geothermal sector, and employment numbers rose slowly in 2021.[2] Since the geothermal sector operates locally, most of its economic value is created locally.[2]

The geothermal sector does face supply difficulties. For example, in the period 2020–2021 increased demand for ground-source heat pump systems could not be met due to several factors: components were not delivered in time, skilled workers were not available and public administrations and licensing authorities were often overwhelmed by the increasing demand.[2] Therefore, a score of 2 is assigned.

9.4.1.5. Bibliography

1 Dalla Longa et al. (2020), 'Scenarios for geothermal energy deployment in Europe'. https://www.sciencedirect.com/science/article/pii/S0360544220311671

2 JRC (2022), 'Deep Geothermal Energy in the European Union'. https://setis.ec.europa.eu/deep-geothermal-energy-european-union_en

3 Aposteanu et al. (2014), 'Geothermal Technology Roadmap'. https://www.rhc-platform.org/content/uploads/2020/02/Geothermal_Roadmap-WEB.pdf

4 Basosi et al. (2020), 'Life Cycle Analysis of a Geothermal Power Plant: Comparison of the Environmental Performance with Other Renewable Energy Systems'. https://www.mdpi.com/2071-1050/12/7/2786

5 Karlsdóttir et al. (2015), 'Life cycle inventory of a flash geothermal combined heat and power plant located in Iceland'. https://link.springer.com/article/10.1007/s11367-014-0842-y

6 Brownlie et al. (2021), 'A study on the erosion-corrosion behaviour of engineering materials used in the geothermal industry'. https://www.sciencedirect.com/science/article/abs/pii/S0043164821002106

7 Marchand et al. (2015), 'Life Cycle Assessment of High Temperature Geothermal Energy Systems'. http://minesparis-psl.hal.science/hal-01146355/

8 Magagna et al. (2017), 'Supply chain of renewable energy technologies in Europe, An analysis for wind, geothermal and ocean energy'. https://op.europa.eu/en/publication-detail/-/publication/772bf71b-d8a6-11e7-a506-01aa75ed71a1/language-en

9 Bonafin et al. (2019), 'CO_2 emissions from geothermal power plants: evaluation of technical solutions for CO_2 reinjection'. https://www.semanticscholar.org/paper/CO2-emissions-from-geothermal-power-plants%3A-of-for-Bonafin-Pietra/e852324058c56191c124a9e1e360c23f06b34232

10 IRENA (2021), 'Renewable Power Generation Costs in 2021'. https://www.irena.org/Publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021

9.5. Hydropower

9.5.1. Hydropower plant for electricity generation

Water flows from higher altitudes to lower ones. This difference is called gross hydraulic head. This altitude difference generates the power of water, which can take the form of potential power (pressure and water level) and kinetic power (water flow velocity). Traditional hydropower is a renewable energy source that converts hydraulic (water) power into mechanical power by means of a rotating turbine, and into electricity through the connection to an electric generator.[1]

Overall efficiency is >80%, five times higher than photovoltaics and three times higher than wind energy.[1]

9.5.1.1. Characteristics

Role in EU energy system: Continuous energy generation

- There is currently 151 GW of installed hydropower capacity in the EU.[1]
- Most suitable locations for large reservoirs in the central and northern EU have already been exploited.[1]
- There is substantial potential for increased pumped hydropower, modernisation of hydropower, and in water network infrastructures.[1]

Primary energy source: rainwater and melting glaciers.

TRL:[1] 9

9.5.1.2. Life cycle: construction phase

Components:

- Hydraulic/mechanical equipment for hydropower: typically made of materials such as steel, concrete and copper
- Manufacture of mechanical components: typically steel
- Permanent magnets

Infrastructure: dams, reservoirs, control gates, penstocks, turbines, powerlines, powerhouses, transformers, generators

Critical materials: copper and aluminium.[2]

9.5.1.3. Life cycle: use phase

Maintenance.

9.5.1.4. Life cycle: end-of-life

- Lifespan of civil structures is 80 years, after which retrofitting activity is required.
- Electromechanical equipment has a lifespan of 20 to 30 years.
- According to a UN University study, dams reach the end of their useful life 50 to 100 years after construction. From as early as 25 to 35 years, measures must be taken to maintain a dam.[3]
- Dams in Europe are on average very old. This means there is a significant trend of decommissioning dams in the next years.[3]

Table C.8 Energy security indicators for hydropower plants for electricity generation

Geopolitical availability (score: 2)
The critical materials for a hydropower plant and their relative geopolitical availability are as follows: • Aluminium: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Copper: available in more than three EU and global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Permanent magnets: materials not available in EU and mostly concentrated in China, supply risk relatively high (score: 3). Since the average score of all materials is 2, this is the score given to the indicator.
Abundance (score: 2)
The critical materials in this technology[4] and their abundance risk are: • Copper, which has a medium abundance risk (1 to 100 ppm, score 2). • Aluminium, which has a low abundance risk (>10 000 ppm, score 1). • Permanent magnets, which have a medium abundance risk (1 to 100 ppm, score 2). Since the average score for all materials is 2, this is the overall score assigned to this indicator.
Circularity (score: 2)
Lifetime of most components is relatively long and many of the materials (e.g. steel) can be recovered. However, the decommissioning of dams once they have reached end-of-life is highly complex compared to other technologies. In Europe, most dams are reaching old age and there are strong arguments in favour of decommissioning these dams, including protection of public safety, growing maintenance costs, progressing sedimentation of reservoirs and environmental restoration.[3] Therefore a score of 2 is given.
Supply chain complexity (score: 2)
Hydropower is one of the oldest renewable technologies and manufacture of its components has therefore become standardised. Many hydropower components are also found in other

technologies and are therefore not highly complex. Building and decommissioning a hydropower plant is complex and takes many years of planning, design and building.[5] Therefore, a score of 2 is given.

Supply chain location (score: 1)

The EU is a leader in scientific research, technological innovation, export and market development.[1] For the extraction phase, only some critical materials come from outside the EU. For the manufacturing and operations phase, a large number are found in the EU. Therefore, a score of 1 is given. It should be noted that more dams are currently being decommissioned for environmental reasons leaving ever fewer suitable locations for hydropower plants in the EU.

Digital vulnerability (score: 1)

Since the EU is a lead exporter, hydropower is a secure market for the EU and there is no dependency from foreign countries.[1] Therefore, a score of 1 is assigned to this indicator.

Physical vulnerability (score: 3)

- Disruptive weather (i.e. droughts and heavy rain) and climate change can disrupt hydropower electricity generation.[1] For flood risk, 75% of existing dams and 83% of projected dams are within river basins with medium to very high risk.[6,7]
- Damage can be done by wars – the Russian attack on critical dam in Ukraine, for example – with very large negative consequences.[8]

Because of the severity of the effects of the physical vulnerability of hydropower plants, a score of 3 is assigned to this indicator.

Broader sustainability (score: 3)

In many cases, dams serve multiple functions beyond energy generation, such as irrigation, water supply, flood control and recreation, benefiting local communities and serving broader purposes. However, there is a very high ecological impact from dam and reservoir installation, including modification of hydrological regimes and aquatic habitats, water quality, barriers to fish migration, introduction of pest species and impact on sedimentation, impoundment and methane emissions. Further, there is a negative social impact because building of dams may involve resettlement of local communities, impact the few remaining pristine waterways in Europe, increase the risk of waterborne diseases, and affect cultural heritage sites. Lastly, there is also a public safety risk as dams become older.[1,3,9]

Due to the combination of these issues, a score of 3 is assigned to this indicator.

Affordability (score: 1)

- LCOE is 0.048 USD/kWh (2021).[10] Therefore, this indicator is assigned a score of 1.
- Costs increased from 0.039 to 0.048 from 2010 to 2021.

Skills (score: 1)

In general, there is a loss of knowledge around the hydropower sector due to low attraction of traditional engineering fields for young professionals.[1] However, viewed globally, most parts of the renewable energy sector are still in the early stages of development and, proportionate to the current low base, are growing rapidly. Hydropower is something of an exception, with a relatively large installed base.[11] Therefore, compared to other energy technologies, the skills required for hydropower are more developed worldwide and this indicator is assigned a score of 1.

9.5.1.5. Bibliography

[1] JRC (2022). Hydropower and pumped hydropower storage in the European Union. Luxembourg, Publication Office of the European Union. https://setis.ec.europa.eu/hydropower-and-pumped-hydropower-storage-european-union_en

[2] IEA (2022). 'The role of critical materials in clean energy transitions'. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/mineral-requirements-for-clean-energy-transitions

[3] Perera, D. et al. (2021). 'Ageing water storage infrastructure: An emerging global risk'. United Nations University, Institute for Water, Environment and Health. https://inweh.unu.edu/wp-content/uploads/2021/01/Ageing-Water-Storage-Infrastructure-An-Emerging-Global-Risk_web-version.pdf

[4] EC (2023). 'Study on the Critical Raw Materials for the EU 2023'. Final Report. Luxembourg: Publications Office of the European Union. https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

[5] IEA (2023). 'Energy Technology Perspectives 2023'. https://www.iea.org/reports/energy-technology-perspectives-2023

[6] Opperman, J.J. et al (2022). 'Using the WWF water risk filter to screen existing and projected hydropower projects for climate and biodiversity risks'. *Water 2022*. Volume 14(5). https://www.mdpi.com/2073-4441/14/5/721

[7] WWF (2022). 'New Study: US Hydropower Threatened by Increasing Droughts Due to Climate Change'. World Wildlife Fund (WWF). https://www.worldwildlife.org/press-releases/new-study-us-hydropower-threatened-by-increasing-droughts-due-to-climate-change

[8] Schmidt, S.; Koshiw, I.; Abbakumova, N.; Korolchuk, S. (2023). 'Damage to Russian-held hydroelectric plant floods south Ukraine battlefield'. The Washington Post 6 June 2023. https://www.washingtonpost.com/world/2023/06/06/ukraine-russia-kakhovka-dam-hydroelectric-war/

[9] Xu, R. et al. (2023). 'A global-scale framework for hydropower development incorporating strict environmental constraints'. *Nature Water*. Volume 1(113-122). https://www.nature.com/articles/s44221-022-00004-1

[10] IRENA (2021). Renewable Energy Statistics 2021. Renewable Energy Statistics 2021 (irena.org)

[11] ILO (nd). Research Brief: 'Investment in renewable energy generates jobs. Supply of skilled workforce needs to catch up'. https://www.ilo.org/wcmsp5/groups/public/@ed_emp/@ifp_skills/documents/publication/wcms_168354.pdf

9.6. Ocean energy

9.6.1. Tidal energy technologies

Kinetic energy can be obtained from tidal currents, created by water flow derived from the tidal filling and emptying of coastal areas. This can take place at flood defences as well as in the open sea. There are two main types of tidal energy technology: tidal stream systems and tidal range systems. Tidal stream systems operate similarly to underwater wind turbines. Tidal range systems utilise the difference between water levels at high tide and low tide and operate similarly to dam-like structures. Tidal range systems, such as barrage technologies, have a relatively low resource potential at a high environmental and economic cost.[1] The focus of this factsheet is therefore on tidal stream systems.

9.6.1.1. Characteristics

Role in EU energy system: Intermittent energy generation

- Current capacity:[1] 11.5 MW for EU in 2021

- Potential capacity:[2] 10 GW

Primary energy source: tidal

TRL:[1] 7–9

9.6.1.2. Life cycle: construction phase

- Infrastructure:[3] subsea cables, O&M vessels
- Structural components: N/A
- Floating systems: moorings, anchors, nacelles, device access
- Fixed bottom systems:[3] pile, cross-arm, nacelles, device access
- Power conversion system:[3] generator, gearbox and driveshaft, hydraulic system, frequency converter, set-up transformer, riser cable, control systems bearing and linear guides, rotors
- Critical:[4,5] copper, aluminium, permanent magnets (boron, dysprosium, neodymium and praseodymium)
- Non-critical:[5] steel, plastic, composites, water, electronics, lead, PVC, PE pipe, tin, platinum, nickel, concrete

Note: materials used have a major effect on the performance of converters due to high risk of corrosion in the marine environment.

9.6.1.3. Life cycle: use phase

Maintenance (can be costly and difficult, leading to higher operational costs).[4]

9.6.1.4. Life cycle: end-of-life

Lifetime of between 20 and 25 years.[1] The metal components of turbines and support structures can be recycled relatively easy, as with wind turbines. However, since these metal parts are exposed to harsh conditions, they have a higher chance of corrosion and wear over time, and thus overall, the recyclability is assumed to be lower than for wind power.

Table C.9 Energy security indicators for tidal energy technologies

Geopolitical availability (score: 2)
The critical materials of tidal energy technology and their relative geopolitical availability are as follows: • Copper: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Aluminium: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1).

- Permanent magnets: materials not available in EU and mostly concentrated in China. Supply risk relatively high (score: 3).

Since the average score for all materials is 2, this is the overall score assigned to this indicator.

Abundance (score: 2)

This technology relies on several critical materials with the abundance risk level of each given in brackets: copper (2), aluminium (1) and permanent magnets (3).

Since the average score for all materials is 2, this is the overall score assigned to this indicator.

The critical materials in the technology and their abundance are:

- Copper, which has a medium abundance risk (1 to 100 ppm, score 2)
- Aluminium, which has a low abundance risk (>10 000 ppm, score 1)
- Permanent magnets, which has a medium abundance risk (1 to 100 ppm, score 2)

Since the average score for all materials is 2, this is the overall score assigned to this indicator.

Circularity (score: 2)

Primary materials (steel and other metals) can be easily recycled. Recycling rates are similar to onshore wind turbines (see Annex C, 9.12) but expected to be lower due to corrosion. This, together with the fact deep-water infrastructure is harder to recycle, means a score of 2 is given.

Supply chain complexity (score: 2)

For manufacturing, the components of tidal energy technology are similar to wind energy, and therefore the supply chain is not highly specialised. In terms of operations, turbines can be placed at flood defences (easier to access and making use of existing infrastructure) or open sea (harder to access). Another challenge is limited grid accessibility due to the remote location of tidal energy resources. Because the supply chain is somewhat complex, but not unusually so, we assign this indicator a score of 2.

Supply chain location (score: 2)

- Extraction: apart from CRM, most materials can be sourced within the EU.
- Building/manufacturing: most companies active in developing tidal stream devices with TLR >5 identified in Europe (41%).[1]
- Operations: operating tidal energy systems deployed in areas of high flow, in channels, river mouths, or deep-sea floors; suitable locations in EU.

As part, but not all, of the supply chain is, or can be, located in the EU, we assign this indicator a score of 2.

Digital vulnerability (score: 2)

There are digital devices in wave energy that are integral to the operation, control and monitoring of wave energy systems. Therefore, there is a cybersecurity threat. We can assume similar characteristics to wind turbines: Most wind turbines are controlled and monitored using remote communication systems.[6] A ‘zero-dynamics attack’ is a cyberattack that cannot be detected by the monitoring output and exploits the internal dynamics of a system to cause damage.[6] In case of a wind turbine, this may involve an attack that causes uncontrolled/unstable rotational speed.

Therefore, we assign this indicator a score of 2.

Physical vulnerability (score: 1)

Weather

Regulated by the moon, tidal streams are predictable. Strong tidal currents are not required for operation. Only extreme weather (such as storms or hurricanes) can impact tidal stream energy – potentially breaking the system, with a risk of local marine life impacted by falling debris.

Physical attacks

Unlikely, since technology is underwater, but not impossible.

As the physical vulnerability of this value chain is rather low, we assign this indicator a score of 1.

Broader sustainability (score: 2)

Ecological effects

- Impacts of underwater noise pollution on marine animals are the biggest potential risk for tidal energy converters. No significant impacts have been established, but uncertainties remain.[7]
- There is also potential risk from electromagnetic fields, changes to habitat and oceanographic systems, and entanglement of marine animals in cables.
- According to Organic Electronics Saxony (OES), there is still a lot of uncertainty over the ecological impacts of tidal energy and more research is needed. Moreover, most insights are based on small installations and large-scale implementation is not yet researched.

Because of the uncertainty around the broader sustainability of tidal energy, we assign this indicator a score of 2.

Affordability (score: 3)

Currently LCOE is 0.20 EUR/kWh. In future, this could be reduced to 0.1 EUR/kWh (according to the EU Strategic Energy Technology/SET Plan).[1] Therefore, we assign this indicator a score of 3.

Largest cost attributed to structural components and power conversion system of device, followed by moorings to keep the device in place.

Since procedures, materials and manufacturing of ocean energy devices are not streamlined, both CAPEX and OPEX are currently high, but expected to decrease with the commercialisation of more projects and increase of installed capacity.[1]

Skills (score: 2)

Technical skills are required for areas including engineering, mechanics and control systems, as are divers for subsea inspections. The necessary skills require relatively long, university-level education – compared to more decentralised technologies (such as heat pumps and PV) fewer skilled installers are needed overall. To summarise, tidal energy technology requires complex and specialised skills, but a relatively small workforce, resulting in a score of 2.

9.6.1.5. Bibliography

[1] JRC (2022). Ocean Energy in the European Union. Luxembourg: Publication Office of the European Union. https://setis.ec.europa.eu/ocean-energy-european-union_en

[2] EC (nd). 'Fast-tracking Offshore Renewable energy With Advanced Research to Deploy 2030MW of tidal energy before 2030'. The European Maritime Spatial Planning Platform. https://maritime-spatial-planning.ec.europa.eu/projects/fast-tracking-offshore-renewable-energy-advanced-research-deploy-2030mw-tidal-energy

[3] Pennock, S., A. Garcia-Teruel, D.R. Noble, O. Roberts, A. de Andres, C. Cochrane, and H. Jeffrey (2022), 'Deriving Current Cost Requirements from Future Targets: Case Studies for Emerging Offshore Renewable Energy Technologies'. *Energies*, Vol. 15(5)

[4] Brink, R. Van den, Lamoo, S. (2021). Factsheet Energy from water – tidal stream. TNO. energy-from-water-factsheet-tidal-stream-9.pdf

[5] Uihlein, A. (2016). 'Life cycle assessment of ocean energy technologies'. *The International Journal of Life Cycle Assessment*. Volume 21, 1425-1437. https://link.springer.com/article/10.1007/s11367-016-1120-y

[6] Kim, D., Ryu, K. and Back, J. (2021), 'Zero-Dynamics Attack on Wind Turbines and Countermeasures Using Generalized Hold and Generalized Sampler'. *Applied Sciences*. Volume 11(3), 1257. https://www.mdpi.com/2076-3417/11/3/1257

[7] Copping & Hemery, editors (2020) - OES-Environmental 2020 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. https://tethys.pnnl.gov/sites/default/files/publications/OES-Environmental-2020-State-of-the-Science-Report_final.pdf

9.7. Wave energy technologies

Kinetic energy, created by wind passing over the surface of the ocean, can be obtained from waves.

9.7.1.1. Characteristics

Role in EU energy system: Intermittent energy generation.

- 1.4 MW for EU in 2021[1]

- 10% of electricity production will come from wave energy by 2050 (350 000 GWh per year)[2]

Primary energy source: kinetic energy of waves, driven by wind.

TRL: 7–9[1]

9.7.1.2. Life cycle: construction phase

- Floating systems: moorings, anchors, device, device access

- Fixed bottom systems: structure, device access[3]

- Structural components: surface floaters, vertical columns, reaction plates[3]

- Power take-off: generator, hydraulic components, hydraulic energy storage, frequency converter, set-up transformer, riser cable, control systems bearing and linear guides[3]

- Infrastructure: construction of elements of the farm and their connection and deployment to the electrical grid, subsea cables, O&M vessels, terminations and connectors[4]

- Critical materials: copper, aluminium permanent magnets (boron, dysprosium, neodymium and praseodymium)
- Non-critical materials: steel, plastic, composites, water, electronics, lead, PVC, PE pipe, tin, platinum, nickel, concrete[4]

Materials used have a major effect on the performance of converters due to high possibly of getting corroded in the marine environment.

9.7.1.3. Life cycle: use phase

Maintenance.

9.7.1.4. Life cycle: end-of-life

- Lifetime 20–30 years[1]
- No one has real experience of disposal of ocean energy devices, but same assumptions made as for wind energy converters.[4]

Table C.10 Energy security indicators for wave energy technologies

Geopolitical availability (score: 2)
The critical materials for tidal energy technology and their relative geopolitical availability are as follows: • Copper: available in more than three EU and global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Aluminium: available in more than three EU and global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Permanent magnets: materials not available in EU and mostly concentrated in China. Supply risk relatively high (score: 3). Since the average score for all materials is 2, this is the overall score assigned to this indicator.
Abundance (score: 2)
This technology relies on several critical materials, with the abundance risk level of each given in brackets: copper (2), aluminium (1) and permanent magnets (3). Since the average score for all materials is 2, this is the overall score assigned to this indicator. The critical materials in the technology and their abundance are: • Copper, which has a medium abundance risk (1 to 100 ppm, score 2). • Aluminium, which has a low abundance risk (>10 000 ppm, score 1). • Permanent magnets, which have a medium abundance risk (1 to 100 ppm, score 2). Since the average score for all materials is 2, this is the overall score assigned to this indicator.
Circularity (score: 2)

There is limited data on lifetime duration. As for other technologies, primary materials (steel and titanium) can be recycled, but since corrosion and challenging sea conditions are expected to make this more difficult, a score of 2 is given.

Supply chain complexity (score: 3)

For manufacturing, lack of design convergence has been highlighted as one of the drawbacks of wave energy development thus far.[5] This means production is highly specialised, and harsh conditions at sea make it even more complex.

In terms of operations, complexity depends on the location of the technology, which can be categorised as shoreline, offshore or near-shore. For offshore placed at seabed (depth of 25 m-200 m), strong commercialisation has not commenced and is therefore highly complex. Closer to shore, the supply chain is less complex because the technology is closer to the grid and maintenance is easier. Moving further from the shore, materials must withstand rough conditions and salt water.[6] Because the supply chain is very complex, we assign this indicator a score of 3.

Supply chain location (score: 2)

- Extraction: apart from CRM, most materials can be sourced within the EU.
- Manufacturing: most (55%) companies developing devices are in the EU.[1]
- Operations: high potential in the EU.[1]

As part, but not all, of the supply chain, is, or can be, located in the EU, we assign this indicator a score of 2.

Digital vulnerability (score: 2)

There are digital devices in wave energy that are integral to the operation, control and monitoring of wave energy systems. Therefore, there is a cybersecurity threat. We can assume similar characteristics to wind turbines: Most wind turbines are controlled and monitored using remote communication systems.[7] A ‘zero-dynamics attack’ is a cyberattack that cannot be detected by the monitoring output and exploits the internal dynamics of a system to cause damage.[7] In case of a wind turbine, this may involve an attack that causes uncontrolled/unstable rotational speed.

Therefore, we assign this indicator a score of 2.

Physical vulnerability (score: 1)

Onshore and near-shore wave energy are more susceptible to storm burns.[6]

Offshore wave energy is more susceptible to corrosion.[6]

As the physical vulnerability of this value chain is quite low, we assign this indicator a score of 1.

Broader sustainability (score: 2)

Ecological effects

- Impacts of underwater noise pollution on marine animals are a potential risk for wave energy converters. Although no significant impacts have been identified so far, uncertainties remain, partly due to the limited number of devices deployed so far, especially at larger scale.[8]

- There is also a potential risk due to electromagnetic fields, changes to habitat and oceanographic systems, and entanglement of marine animals in cables.
- According to OES, there is still a lot of uncertainty over the ecological impacts of wave energy and more research is needed. Moreover, most insights are based on small installations and large-scale implementation is not yet researched.

Wave energy can also cause disturbances to the shipping industry, affecting human lives.[6]

Because of the uncertainty over negative environmental side-effects, especially for larger-scale devices, we assign this indicator a score of 2.

Affordability (score: 3)

- Currently LCOE is 0.27 EUR/kWh. In future this could be reduced to 0.15 EUR/kWh (according to the SET Plan).[1] Therefore, we assign this indicator a score of 3.
- The largest cost is attributed to structural components and PTO of a device, followed by moorings to keep it in place.[9]

Skills (score: 2)

Technical skills are required for areas including engineering, mechanics and control systems, as are divers for subsea inspections. The necessary skills require relatively long, university-level education – compared to more decentralised technologies (such as heat pumps and PV) fewer skilled installers are needed overall. To summarise, tidal energy technology requires complex and specialised skills, but a relatively small workforce, resulting in a score of 2.

9.7.1.5. Bibliography

[1] JRC (2022). Ocean Energy in the European Union. Luxembourg: Publication Office of the European Union. https://setis.ec.europa.eu/ocean-energy-european-union_en

[2] Dutch Wave Power (nd). Wave energy potential. https://dutchwavepower.com/news/20201001-wave-energy-potential/

[3] EC (2023). Study on the Critical Raw Materials for the EU 2023. Final Report. Luxembourg: Publications Office of the European Union. https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

[4] Uihlein, A. (2016). 'Life cycle assessment of ocean energy technologies'. *The International Journal of Life Cycle Assessment*. Volume 21, 1425-1437. https://link.springer.com/article/10.1007/s11367-016-1120-y

[5] Brink, R. Van den, Lamoo, S. (2021). Factsheet Energy from water – wave energy. TNO. https://energy.nl/media/data/Energy-from-water-factsheet-Wave-energy.pdf

[6] Satriawan, M. et al. (2021). 'Unlimited energy source: a review of ocean energy utilization and its impact on the environment'. *Indonesian Journal of Science & Technology*. Volume 6(1). https://doi.org/10.17509/ijost.v6i1.31473

[7] Kim, D., Ryu, K. and Back, J. (2021), 'Zero-Dynamics Attack on Wind Turbines and Countermeasures Using Generalized Hold and Generalized Sampler'. *Applied Sciences*. Volume 11(3), 1257. https://www.mdpi.com/2076-3417/11/3/1257

[8] Copping & Hemery, editors (2020) - OES-Environmental 2020 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. https://tethys.pnnl.gov/sites/default/files/publications/OES-Environmental-2020-State-of-the-Science-Report_final.pdf

[9] IRENA (2023). Scaling up investments in ocean energy technologies. https://www.irena.org/-/media/files/irena/agency/publication/2023/mar/irena_oee_scaling_up_investment_ocean_energy_2023.pdf?rev=8743c0e4f40f443fa8f4d1d0aebc1184

9.7.2. Ocean Thermal Energy Conversion (OTEC)

Ocean energy thermal conversion uses temperature differences between warm surface water and cold deep ocean water to generate electricity. Warm surface water evaporates a working fluid, which drives a turbine to generate electricity, after which the working fluid is condensed again by the cold water. The process exploits temperature differences of around 20 °C, for which a sea-depth of approximately 1 km is needed and a surface temp of approximately 25 °C. OTEC can be onshore or offshore. For onshore plants, water intake occurs via a tunnel from the shoreline. For offshore plants, water intake occurs via a vertical cold seawater intake pipeline. So far, the only pilot plants are onshore.[1]

9.7.2.1. Characteristics

Role in EU energy system

- Continuous energy generation
- Only deployable in tropical seas (in EU overseas islands)
- Energy efficiency considerably low (3%)[2]
- Theoretical output worldwide: 8 000 GW[2]

Primary energy source: thermal gradient of water.

TRL: 5–7; only pilot plants exist[3]

9.7.2.2. Life cycle: construction phase

Infrastructure for offshore OTEC: Large shipyards, mooring systems and interfaces between cold water pipes and ships, long dabbles for power transmission (>10km), power generation platform. For onshore OTEC this infrastructure is not required.

Components: Ejectors; Heat exchangers; Seawater pumps.

Materials: Most of the materials for OTEC installations are for seawater inlet pipes and heat exchangers. Multiple materials may be suitable for seawater inlet pipes, such as concrete, steel, composite and polyethylene (HDPE). Heat exchangers are usually made of titanium, of which relatively little is available in the desired thickness. All-seas is investigating the possibility of using plastics as material for the heat exchangers.[4]

Summarised:

- Critical: titanium
- Non-critical: concrete, steel, composite and HDPE

9.7.2.3. Life cycle: use phase

Maintenance and working fluid (e.g. ammonia).

9.7.2.4. Life cycle: end-of-life

Expected lifetime between 15–30 years.[5]

Titanium can be recycled but corrosion can make it less suitable than onshore applications of titanium. Other parts, such as steel and concrete, can often be recycled.

Offshore infrastructure is harder to recycle but can sometimes be reused for other purposes.

Table C.11 Energy security indicators for ocean thermal technologies

Geopolitical availability (score: 1)
The critical material for OTEC is titanium, which is available in one EU country and multiple global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1).
Abundance (score: 1)
The only critical material in the technology is titanium, which has a low abundance risk (100 to 10 000 ppm). Therefore, a score of 1 is assigned.
Circularity (score: 2)
Expected lifetime between 15–30 years.[5] Titanium can be recycled but corrosion can make it less suitable than onshore applications of titanium. Other parts, such as steel and concrete, can often be recycled. However, since all materials are susceptible to corrosion the materials are harder to recycle than other technologies, and so this technology is given a score of 2.
Supply chain complexity (score: 3)
For manufacturing, several parts are complex from an engineering point of view, as the materials must withstand corrosion and challenging sea conditions. For example, the cold-water inlet pipe (CWP) is difficult to engineer as it is affected by a variety of forces.[6] For operations, the supply chain is complex as offshore OTEC locations are far out to sea, requiring deep sea divers. Because the supply chain is highly complex, we assign this indicator a score of 3.
Supply chain location (score: 3)
Titanium extraction: available in one European country, but most reserves are found outside Europe. Operations: only suitable in tropical regions, because the temperature difference must always be around 25 °C. Only deployable in tropical seas in EU overseas islands (Caribbean, Pacific Islands, India, west and southeast coasts of the American continent, and Africa). As almost all the supply chain is located outside the EU and only very limited geographic locations are suitable for OTEC, we assign this indicator a score of 3.
Digital vulnerability (score: 2)
There are digital devices that integral to the operation of OTEC energy and control and monitoring of OTEC energy systems. Therefore, there is cybersecurity threat. No records of cyberthreats to date because the technology is not yet widely adopted. Due to cybersecurity risk,

and because much is still unknown and the technology is decentrally operated, a score of 2 is given.

Physical vulnerability (score: 3)

Damage

The materials of the technology can corrode in the deep water. This is an issue with all marine structures but more but prominent in OTEC plants due to the size of piping required.[6]

Climate change

The possible rise in surface seawater temperatures increases the available temperature difference, which may improve OTEC performance. However, temperature difference is not uniform across the northern and southern hemispheres, with the former estimated to be undergoing a larger temperature rise. Thermohaline circulation will be reserved or altered, meaning that the altitude difference required to reach 20 °C temperature difference will be 2100–2300 metres, making this technology highly impractical in the future.[2,7]

In addition, cyanobacteria disasters in spring can alter the functioning of OTEC power stations.[8] Lastly, small islands may disappear due to rising sea levels, reducing availability of onshore OTEC sites.[9] Because of the severity of the physical vulnerability of OTEC plants, a score of 3 is assigned to this indicator.

Broader sustainability (score: 2)

Potential environmental risks are linked to the size of the infrastructure, which can pose risks to marine life flows. In addition, the infrastructure generates noise and electromagnetic fields that could pose a risk to marine life. Currently, the ecological effects of OTEC are not fully understood, and additional local research is needed. Due to the high level of uncertainty around risks for marine wildlife that must be considered in the design of OTEC, a score of 2 is given.

Affordability (score: 3)

The technology is not in commercial phase yet. Costs are based on estimations:

Estimated LCOE with original interest rate is 0.15 USD /kWh for a 10-Mwe OTEC plant and 0.03–0.22 USD/kWh (2018) for a 100-Mwe OTECT plant.[5]

Estimated LCOE with adjusted interest rate is 0.20–0.67 USD/kWh for a 10-Mwe OTEC plant and 0.04–0.29 USD/kWh (2018) for 100-Mwe OTECT plant.[5]

Capital investment costs range from 2 500 USD/kW to 8 000 USD/kW. This is considerably higher than other technologies.[2]

Heat exchanger accounts for 30–50% of total cost.[2]

With an increase in capacity, a predicted 0.029 USD/kWh can be achieved for a 100-MW offshore OTEC plant.[5]

Skills (score: 2)

Technical skills are required for areas such as engineering, mechanics and control systems, as are divers for subsea inspections. The necessary skills require relatively long, university-level education. However, compared to technologies that are more decentralised such as heat pumps and PV, fewer installers are needed overall. To summarise, the skills required are complex and specialised, but a relatively smaller workforce is needed, giving a score of 2.

9.7.2.5. Bibliography

[1] Makai Ocean Engineering (nd). https://www.makai.com/faq/

[2] Dhanak, M.R.; Xiros, N.I. (2016). Springer Handbook of Ocean Engineering. https://link.springer.com/book/10.1007/978-3-319-16649-0

[3] JRC (2022). Ocean Energy in the European Union. Luxembourg: Publication Office of the European Union. https://setis.ec.europa.eu/ocean-energy-european-union_en

[4] Brink, R. Van den, Lamoo, S. (2021). Factsheet Energy from water – Ocean Thermal Energy Conversion (OTEC). TNO. https://energy.nl/wp-content/uploads/energy-from-water-factsheet-otec-9.pdf

[5] Langer, J.; Quist, J.; Blok, K. (2020) 'Recent progress in the economics of ocean thermal energy conversion: Critical review and research agenda'. *Renewable and Sustainable Energy Reviews.* Volume 130(109960). https://www.sciencedirect.com/science/article/pii/S1364032120302513?via%3Dihub

[6] Farhan, M. et al. (2018). 'Ocean Thermal Energy Conversion: a Techno-economic Analysis for Coastal Area of Pakistan'. *2018 International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET)*. https://link.springer.com/book/10.1007/978-3-319-16649-0

[7] Tianshi D. et al. (2022). 'Growth of ocean thermal energy conversion resources under greenhouse warming regulated by oceanic eddies'. *Nature Communications*. Volume 13(7249). https://www.nature.com/articles/s41467-022-34835-z

[8] Zhang, M.; Yang, Z.; Shi, X.; Yu, Y. (2022). 'The synergistic effect of rising temperature and declining light boosts the dominance of bloom-forming cyano-bacteria in spring'. *National Library of Medicine*. Volume 116(102252). https://pubmed.ncbi.nlm.nih.gov/35710204/

[9] Hall, K.; Kelly, S.; Henry, L. (2022). 'Site selection of Ocean Thermal Energy Conversion (OTEC) plants for Barbados'. *Renewable Energy*. Volume 201-2. 60-69. https://linkinghub.elsevier.com/retrieve/pii/S0960148122016883

9.7.3. Salinity gradient power generation

Salinity gradient energy is harnessed from the chemical potential energy difference between two kinds of water with different salt concentrations. Energy from the difference in salinity can be extracted by placing membranes between a fresh and a saltwater stream. There are two main techniques for generating electricity from fresh-saltwater differences: 1) reverse electrodialysis (RED) and 2) pressure retarded osmosis (PRO).[1]

- RED: two types of ion-selective membranes allow positive sodium and negative chloride ions to pass through. Several of these membranes are stacked together. The compartments between the membranes are alternately filled with sea water and freshwater. The salinity gradient transports ions, resulting in an electric potential which can be converted into electricity.[1,2]

- PRO: a membrane is used to separate freshwater and dissolved salt. Equilibrium drives freshwater to flow through to seawater, increasing the pressure within the seawater chamber. The pressure moves a turbine that generates electricity.[1,2]

These technologies are mostly dependent on the development of membranes. They are still only in the conceptual stage and less mature than other types of ocean energy. RED technology has more practical examples, so this will be the focus of this datasheet.

9.7.3.1. Characteristics

Role in EU energy system: Continuous energy generation, with a technical potential in the EU of 49 GW).[2]

Primary energy source: salinity gradient.

TRL: 7 – several companies are in the test-phase of RED technology.[1]

9.7.3.2. Life cycle: construction phase

RED installations take up a comparable space as coal-fired power stations.[1] They consist of the following key components:[3]

- Ion exchange membranes:
  - Cation exchange membrane (CEM): stretched titanium mesh substrates with ruthenium/iridium metal oxides
  - Anion exchange membrane (AEM): stretched titanium mesh substrates with ruthenium/iridium metal oxides
- Electrodes:
  - Usually made of platinum[3]
- Spacer: polyethersulfone (PES)
- Channels and stacks: endplate/frame made of polypropylene (PP)
  - Pumps, pipes and other components usually made of stainless steel
  - Power conversion system and electronic components

9.7.3.3. Life cycle: use phase

During the use phase, only maintenance is needed.

9.7.3.4. Life cycle: end-of-life

- RED membranes: lifetime 5–7 years
- Stacks: lifetime 15–20 years
- High degree of reuse is possible[1]

Table C.12 Energy security indicators for salinity gradient power generation

Geopolitical availability (score: 2)
Membranes are the heart of salinity gradient power generation technologies. They contain the following critical materials: • Titanium: available in one EU country and multiple global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Ruthenium/iridium: materials not available in EU. Higher degree of concentration. Supply risk moderate (score: 2). Since the average score for all materials is 2, this is the overall score assigned to this indicator.

Abundance (score: 2)

The critical materials in the technology are:

- Titanium, which has a low abundance risk (100 to 10 000 ppm, score 1)
- Ruthenium/iridium, which has a high abundance risk (<0.01 ppm, score 3).

Since the average score for all materials is 2, this is the overall score assigned to this indicator.

Circularity (score: 1)

- RED membranes: lifetime 5–7 years
- Stacks: lifetime 15–20 years

A high degree of reuse of RED stacks is possible.[1]

Supply chain complexity (score: 2)

One of the sector's main challenges is development of specific and dedicated components. Currently, there are only a limited number of companies producing dedicated membranes and other parts of the installations (e.g. stacks or modules).[2] Because the supply chain is quite complex, but not unusually so, we assign this indicator a score of 2.

Supply chain location (score: 2)

- Raw materials: some are sourced from the EU but not all.
- Manufacturing: RED pilots and manufacturing in EU locations (Netherlands and Italy).[4]
- Operations: locations where freshwater streams flow into the sea, such as rivers, discharge sluices or pumping stations that discharge surface water or purified wastewater.

As part, but not all of the supply chain is, or can be, located in the EU, we assign this indicator a score of 2.

Digital vulnerability (score: 1)

Salinity-gradient power generation technologies are expected to be connected to the internet, making them vulnerable to cyberattacks. The membrane cells themselves are not vulnerable to digital attacks. Although cyberattacks can never be excluded, there is no particular digital risk for this technology compared to other value chains, and the damage resulting from a cyberattack could probably be limited. Therefore, a score of 1 is assigned.

Physical vulnerability (score: 2)

Corrosion

As with other ocean energy, there is a higher risk of corrosion causing components to malfunction.

Climate change

River runoff and melting glaciers, as well as heavy or lack of precipitation, impact salinity.[5]

Damage and dirt

Membranes are susceptible to dirt which can originate in seawater and interfere with the functioning of this technology.

As there are some risks to this technology, though less severe than for other technologies, a score of 2 is given.

Broader sustainability (score: 2)

Environmental

Inlet volumes can pose a risk to the environment of fish and other organisms.[1]

Societal resistance is not expected because installations will be in suitable locations.[6]

Because there are some ecological concerns, a score of 2 is given.

Affordability (score: 3)

0.41 EUR/kWh based on investment and operational costs from the SDE.[6]

Mainly driven by cost of membranes (50–80% of total capital costs).[2]

Therefore, we assign this indicator a score of 3.

Skills (score: 3)

R&D is needed to bring salinity gradient power technology to maturity so it can be broadly implemented. This requires a highly skilled labour force. Acquiring the necessary skills requires relatively long, university-level education. The relative level of R&D still required, as well as specialised skills, gives this criterium a high score of 3.

9.7.3.5. Bibliography

[1] Brink, R. Van den, Lamoo, S. (2020). Factsheet Energy from water – Salinity Gradient Power. TNO. https://energy.nl/wp-content/uploads/energy-from-water-factsheet-salinity-gradient-power-9.pdf

[2] IRENA (2014). Salinity Gradient Energy Technology Brief. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/Jun/Salinity_Energy_v4_WEB.pdf

[3] Tristán, C., Rumayor, M., Dominguez-Ramos, A., Fallanza, M., Ibáñez, R., & Ortiz, I. (2020). 'Life cycle assessment of salinity gradient energy recovery by reverse electrodialysis in a seawater reverse osmosis desalination plant'. *Sustainable Energy & Fuels.* Issue 8. https://pubs.rsc.org/en/content/articlelanding/2020/se/d0se00372g

[4] Essalhi, M. et al. (2023). 'The potential of salinity gradient energy based on natural and anthropogenic resources in Sweden'. *Renewable Energy*. Volume 215(118984). https://www.sciencedirect.com/science/article/pii/S096014812300890X

[5] IRENA (2020). Innovation Outlook Ocean Energy Technologies. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Innovation_Outlook_Ocean_Energy_2020.pdf

[6] Witteveen+Bos & CE Delft (2019) - Perspectieven energie uit water: Nationaal potentieel voor 2030 en 2050 (in Dutch).

9.8. Photovoltaics

Photovoltaics (PV) covert light into electricity using specialised semiconducting materials. Depending on the material, we distinguish between crystalline silicon technologies, thin-film technologies (CIGS, CdTe, perovskites) and multi-junction technologies. The latter are not discussed here. Crystalline silicon solar panels are the dominant technology accounting for around 95% of global installed PV capacity. Thin-film technologies have advantages such as lower weight and higher flexibility. They can be made with simple and scalable methods, and are therefore more cost-effective than crystalline silicon technologies. However, thin-film technologies are not widely commercially available yet because further technical development – on operational lifetime, degradation and manufacturing processes, for example – is needed.

REPowerEU aims to bring over 320 GW of newly installed solar PV online by 2025 – more than twice current capacity – and almost 600 GW by 2030. According to SolarPower Europe, the EU's total solar fleet is projected to reach 920 GW under a medium scenario and 1 184 GW under a high scenario, both surpassing the REPowerEU goal of 600 GW by 2030.[1]

As solar PV works in ambient daylight and is not dependent on direct sunlight, its area of application includes most of Europe, in contrast to concentrated solar energy (see Section 9.3). In general, application of solar PV is strongly localised, in the sense that it is applied to many different small-scale locations (mostly roofs of houses and other buildings). In the EU, almost all generation capacity is connected to the main electricity grid. Larger scale applications – such as car park roofs, solar farms in fields and floating solar farms – are becoming more widely used. Floating solar panels, especially at sea, are more complex and expensive to connect to land. However, as the efficiency of solar PV decreases at higher temperatures, the natural cooling provided at sea is a specific advantage.[2]

9.8.1. Silicon-based photovoltaics

Silicon-based photovoltaics are primarily made from silicon (Si), which is refined from one of the most common materials on earth, silicon dioxide (SiO_2). There are different types of silicon-based PV, of which two – monocrystalline (mono c-Si) and polycrystalline (poly c-Si) – are most commonly used. Amorphous silicon is also used on a small scale to make thin-film solar cells but is not further discussed here due to its limited applications. Crystalline silicon technologies account for 95% (143.9 GWp) of global PV module production. Of these, 80% are monocrystalline modules, the remaining are polycrystalline.[3]

9.8.1.1. Characteristics

Role in EU energy system: Silicon-based PV is used for sustainable energy generation by converting solar energy into electricity with efficiencies ranging from 15% to 26% (the latter a laboratory record).[4]

Primary energy source: solar energy.

TRL: the TRL of crystalline silicon-based PV is 9.

9.8.1.2. Life cycle: construction phase

Silicon-based solar cell modules use the following materials (those in **bold** are classified by the EU as CRM):[5] **aluminium**, iron, lead in alloys with tin as solder for electric circuits and interconnectors, **nickel**, zinc, **copper**, **boron**, **silicon**, silver, phosphorus, molybdenum, glass, plastic, per- and polyfluoroalkyl substances/PFAS (in back-sheet layer of PV – however, there are already many alternatives on the market, so this does not apply for every silicon-based solar cell). Also, several chemicals and solvents are used throughout the manufacturing processes of different PV technologies.

Silicon-based solar cells are used in solar panels. The panel requires the following materials:

- Concrete: system support structures
- Steel: system support structures
- Plastic: environmental protection
- Glass: substrates, module encapsulation
- Aluminium: module frames, racking, supports
- Copper: wiring, cabling, earthing, inverters, transformers, PV cell ribbons

The total infrastructure of a solar PV installation requires:

- Inverter, including electronics
- Cables (copper)
- Connection to the grid

For the long-term grid, reinforcement is needed.

9.8.1.3. Life cycle: use phase

During the use phase only maintenance and cleaning of PV technology is needed.

9.8.1.4. Life cycle: end-of-life

In general, silicon-based photovoltaics have a life expectancy of around 25–30 years. Suppliers of solar panels are obliged by a European directive to collect and recycle solar panels at the end of their useful life. Recycling and reuse of solar panels are only beginning since the volume of end-of-life products is still low. In practice, scarce or valuable materials, such as high-purity silicon, silver and copper, are barely recovered in this process. The valuable high-purity silicon is currently not yet recovered for high-grade reuse in solar cells. Since producing silicon requires a lot of energy, there is room for improvement from a sustainability point of view. Recovering high-quality silicon from the waste stream is a technical and economic challenge, but a lot of development is expected over the coming years through R&D efforts.

From the solar panel itself, glass, wafers, aluminium and silver can easily be reused.[6] Another challenge for the end-of-life stage of silicon-based PV is the back-sheet layer of the PV panel, which may contain halogenated plastic (PFAS) that pose potential waste management problems because they are not biodegradable. After disposal, the back-sheet layer is not recyclable, and incineration can release toxic fluorine compounds.[7,8] However, there are alternatives on the market that do not contain PFAS, which are expected to become dominant in new solar panels.[6]

Table C.13 Energy security indicators for silicon-based photovoltaics

Geopolitical availability (score: 3)
The critical materials used in silicon-based PV and their relative geopolitical availability are as follows: • Silicon: available in three EU countries and global countries. Worldwide supply is not concentrated in one country and the EU supply risk is low (score: 3). • Copper: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Aluminium: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Nickel: four EU suppliers. The top suppliers carry low political risk. Supply not concentrated in one country. Relatively low supply risk (score: 1). • Boron: not available in EU countries, worldwide supply is concentrated in three countries. Overall there is a relatively high supply risk (score: 2). Since silicon is the main component of silicon-based PV, the overall score assigned to this indicator is 3.
Abundance (score: 2)
The critical materials for PV and their abundance risk are: • Silicon, which has a low abundance risk (>10 000 ppm, score 1). • Copper, which has a medium abundance risk (1 to 100 ppm, score 2). • Aluminium, which has a low abundance risk (>10 000 ppm, score 1). • Nickel, which has a medium abundance risk (1 to 100 ppm, score 2). • Boron, which has a medium abundance risk (1 to 100 ppm, score 2). Since the average score for all materials is 2, this is the overall score assigned to this indicator.
Circularity (score: 2)
End-of-life is described above, under characteristics. Due to improved efficiency and a focus on cost reduction, the use of material per Wp has reduced over time, particularly for silver and silicon. The recovery of secondary materials from PV modules is still in the early stage, due to the low volume of end-of-life products. In the EU, treatment of end-of-life PV modules must comply with the WEEE Directive since 2012. A recycling strategy for the manufacturing process for PV modules is important, since it can ensure some secondary material flows for PV manufacturers and can also maximise profits. Therefore, development is required to recover/reuse resources. As this issue is important, but already being addressed, we assign this indicator a score of 2.
Supply chain complexity (score: 2)
The supply chain of silicon-based PV panels involves a series of steps that start with raw materials and end with the installation of solar panels. Raw materials like silicon, silver and glass must be extracted and processed before being assembled into modules. Ancillary components such as mounting structures, inverters and wiring are also part of the supply chain. Once

installed, some maintenance and monitoring are needed to ensure optimal performance. Because the supply chain is quite complex, but not unusually so, and is already established, we assign this indicator a score of 2.

Supply chain location (score: 3)

China dominates nearly all aspects of solar PV manufacturing and use. The most vulnerable step along the PV supply chain is at the component level, as China dominates supply with around 89% of the market.[9] China covers about 70% of global production capacity of polysilicon (Research and Markets, 2019, retrieved from EC, 2020). China supplies 53% of the raw materials for solar PV.[9] Africa is the second biggest supplier of raw materials, at 13%.

The EU supplies 6% of raw materials used in PV systems. According to Bloomberg, the EU manufacturing capacity for crystalline silicon cells accounted for only 0.3% in 2019, concentrated in Italy, Germany and France.[9]

There is no sufficient manufacturing capacity of solar cells in the EU, which appears to be the weakest link of the solar PV value chain in the EU. Entering the market with EU cells and modules is difficult due to lower production costs in Asia.

As current mining and manufacturing are largely based outside the EU, and mainly in one country (China), we assign this indicator a score of 3.

Digital vulnerability (score: 2)

Solar cells themselves are not vulnerable to digital attacks. However, PV systems include an inverter that uses software vulnerable to cyberattacks. If inverters are hacked on large scale, this can cause significant (physical) damage or electricity shortages – therefore a score of 2 is assigned.

Physical vulnerability (score: 1)

- Solar panels are vulnerable to mechanical damage. Extreme weather conditions, such as hailstorms or hurricanes, can damage or crack of PV, causing malfunctions, leakage of chemicals into the environment, or scattering of loose fragments of glass from the protective glass plate.
- Accumulation of dust, dirt, bird faeces and leaves on solar panels, as well as severe air pollution, can reduce electricity output.
- High temperatures reduce the efficiency and performance of solar cells.

Although sabotage and extreme weather events can never be excluded, there is no particular physical risk for this technology compared to other value chains, and the damage resulting from physical events will probably be local. Therefore, a score of 1 is assigned.

Broader sustainability (score: 2)

This energy security indicator concerns broader sustainability aspects such as legal restrictions and public opposition:

- Raw material extraction such as silicon dioxide must be mined, which can face local opposition or cause disruption to ecosystems around mining areas.
- Lead usage: lead is used in small quantities in the solder material joining the copper strings of the solar cells. There are three potential risk situations in which this substance could be released: fire, leaching after panel breakage, or leaching after dumping in poorly managed landfill. Studies show that emissions of lead into the

environment remain within the applicable safety standards even under worst-case conditions.[4]

- Land use and biodiversity around solar farms: large-scale solar farms require significant land area – or, in the case of floating PV, water area. This can lead to local opposition. Concerns over competition with agriculture, disruption to the local environment and biodiversity, or aesthetical concerns, can arise. However, by planting shrubs and plants that encourage biodiversity, this can be partly prevented. The EU biodiversity strategy specifically mentions solar farms providing biodiversity-friendly soil cover as a win-win solution for energy and biodiversity.[9]
- End-of-life waste management: proper disposal and recycling of PV modules are essential to prevent environmental contamination, as in case of physical damage.

Even though these individual risks are not very high, since for this value chain various risks exist related to different sustainability aspects, an overall score of 2 is assigned for broader sustainability.

Affordability (score: 1)

Silicon-based PV solar cells are economically competitive and solar PV system costs have fallen by over 80% since 2010, due to improvements made possible by R&D efforts over the past decades, combined with industrialisation of the manufacturing process and massive expansion of the market. The global weighted-average LCOE for utility-scale projects fell by 88% between 2010 and 2021, from 0.417 USD/kWh to 0.045 USD/kWh. Projections for the EU indicate that it will further decrease from the 2020 values of 0.050 EUR/kWh (northern Europe) and 0.020 EUR/kWh (southern Europe) to 0.020 EUR/kWh (northern Europe) and 0.010 EUR/kWh (southern Europe) in 2050, rendering PV technology a competitive renewable energy technology.[3] Therefore, we assign this indicator a score of 1.

Skills (score: 2)

R&D for silicon-based PV is needed to further improve efficiency, as well as production and recycling processes. The necessary skills require relatively long, university-level education. The manufacturing, installation, maintenance and recycling of solar panels also requires skilled labour. Necessary skills can be acquired in under a year – however, installation and maintenance in particular require a relatively large workforce. Therefore, we assign this indicator a score of 2.

9.8.1.5. *Bibliography*

[1] SolarPower Europe (2022), EU Market Outlook for Solar Power 2022-2026.

[2] EnergySage (2022). Floating Solar Panels (Floatovoltaics): What To Know. https://www.energysage.com/community-solar/floating-solar-what-you-need-to-know/#what-is-floating-solar-and-how-does-its-work

[3] JRC (2022), CETO Photovoltaics. https://setis.ec.europa.eu/photovoltaics-european-union_en.

[4] NREL (2023), Best Research-Cell Efficiencies. https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.pdf

[5] JRC (2020), Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system. https://core.ac.uk/download/pdf/322747915.pdf.

[6] TNO (2021), Zonnestroom: van hernieuwbaar naar duurzaam. https://publications.tno.nl/publication/34638904/Mnc8mC/TNO-2021-tijd.pdf

[7] Fulvio Ardente, Cynthia E.L. Latunussa, Gian Andrea Blengini (2019), 'Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling'. *Waste management*, volume 91. https://doi.org/10.1016/j.wasman.2019.04.059.

[8] C.E.L. Latunussa, F. Ardente, G.A. Blengini, L. Mancini (2016*),* 'Life cycle assessment of an innovative recycling process for crystalline silicon photovoltaic panels'. *Solar Energy Materials and Solar Cells*, volume 156. https://doi.org/10.1016/j.solmat.2016.03.020.

[9] European Commission (2020), Critical Raw Materials for Strategic Technologies and Sectors in the EU. https://rmis.jrc.ec.europa.eu/uploads/CRMs_for_Strategic_Technologies_and_Sectors_in_the_EU_2020.pdf

9.8.2. Copper indium gallium selenide PV technology

Copper indium gallium selenide (CIGS) is a thin-film PV technology based on copper, indium, gallium and selenide. CIGS layers are thin enough to be flexible and can be deposited on flexible substrates such as plastic. Thin-film PV can be used for lightweight solar cells on roofs or integrated into buildings and products. The thin-film share of global production is only 5%, corresponding to 7.8 GWp of total PV module global production. Of this 7.8 GWp, 78% is CdTe and 19% CI(G)S.[1] The efficiency of commercial CIGS modules lags behind silicon-based PV solar panels. Mature upscaling of CIGS is needed to become compatible with silicon PV.

9.8.2.1. Characteristics

Role in EU energy system: CIGS modules are used for sustainable energy generation by converting solar energy into electricity, with efficiencies ranging from 12% to 14% in commercial CIGS modules. Laboratory-scale cell efficiencies range from 15% to 23% (the latter a laboratory record).[2]

Primary energy source: the primary energy source is solar radiation.

TRL: 8–9 since the technology is commercially available. However, CIGS is not yet compatible with silicon PV, and its market share is therefore relatively small.

9.8.2.2. Life cycle: construction phase

The raw materials for silicon-based solar cell modules are (EU-listed CRM in **bold**): **copper**, indium, **gallium**, selenium, molybdenum, sulphur, transparent conductive oxides (e.g. with zinc, plastic). Several chemicals and solvents are also used throughout the manufacturing processes of different PV technologies.[3]

For the total infrastructure of solar PV installation, the following are needed:

- Inverter (nickel)
- Cables (copper)
- Connection to the grid

9.8.2.3. Life cycle: use phase

During the use phase, only maintenance and cleaning of PV technology are needed.

9.8.2.4. Life cycle: end-of-life

In general, CIGS has a life expectancy of around 25 years. However, since CIGS has only been commercially available since the early 2000s, and only in small quantities, there is no strategy for convenient recycling as yet. PV suppliers are obliged by a European directive to collect and recycle solar panels at the end of their useful life. Recycling and reuse of solar panels are only beginning, since the volume of end-of-life products is still low. For CIGS in particular, the CRM copper, gallium and indium are of interest for recycling. R&D is needed to develop recycling and recovery methods for CIGS.[4]

Table C.14 Energy security indicators for copper indium gallium selenide PV technology

Geopolitical availability (score: 2)
The critical materials used in a CIGS PV and their relative geopolitical availability are as follows: • Copper: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Aluminium: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Nickel: 4 EU suppliers. Top suppliers have low political risk. Supply not concentrated in one country. Relatively low supply risk (score: 1). • Gallium: available in one EU country, worldwide supply is concentrated in one country with high political risk, therefore relatively high supply risk (score: 3). Since the average score for all materials is 2, this is the overall score assigned to this indicator.
Abundance (score: 2)
The critical materials in the technology and their abundance risk are: • Copper, which has a medium abundance risk (1 to 100 ppm, score 2). • Aluminium, which has a low abundance risk (>10 000 ppm, score 1). • Nickel, which has a medium abundance risk (1 to 100 ppm, score 2). • Gallium, which has a medium abundance risk (1 to 100 ppm, score 2). Since the average score for all materials is 2, this is the overall score assigned to this indicator.
Circularity (score: 2)
Recycling of CIGS PV is still being developed. Recovery of indium and gallium is particularly important, as the scarcity of these materials can be mitigated by recycling efforts and improvement in production processes.[4] An example of the latter can be an overall reduction of these materials in CIGS PV. Despite R&D efforts, how CIGS PV recycling processes will develop remains uncertain, and therefore a score of 2 is assigned.
Supply chain complexity (score: 2)
The supply chain for CIGS thin-film solar cells involves a series of steps that start with raw materials and end with the installation of thin-film in, for example, buildings or products. Raw materials like indium, gallium, copper, selenium and molybdenum must be sourced and processed. The CIGS absorber layer is deposited onto a substrate using techniques like co-evaporation, sputtering or other thin-film deposition methods. Multiple layers are stacked and processed to create the solar cell structure. Subsequently, the thin-film module must be assembled.[5] Ancillary components, such as inverters and wiring, are also part of the supply

chain. Once installed, regular maintenance and monitoring are needed to ensure optimal performance. Because the supply chain is quite, but not unusually, complex, we assign this indicator a score of 2.

Supply chain location (score: 3)

Indium is often sourced as a by-product of zinc or tin mining. Producers of indium include China, South Korea and Canada. Gallium is typically extracted as a by-product of aluminium and zinc production. Most of it is produced by China (over 95%).[6] Selenium is often recovered as a by-product during the refining of metals like copper, lead and zinc. Selenium is produced in different parts of the world: approximately one third in China, one third in Japan and one quarter in the EU.[7] Molybdenum is extracted from molybdenite, a mineral that contains molybdenum disulphide (MoS_2). The metal is commonly obtained as a by-product of copper mining, as molybdenite is frequently found in copper ores. Molybdenite is found in large quantities in several countries; major producers include China, the United States, Chile and Canada. Manufacturing facilities for CIGS solar cells are located in various regions around the world, such as Europe, United States and Asia. The total supply chain of CIGS is mostly operated outside the EU. Therefore, high risks are present and a score of 3 is assigned.

Digital vulnerability (score: 2)

Solar cells themselves are not vulnerable to digital attacks. However, PV systems include inverters that use software that is vulnerable to cyberattacks. If inverters are hacked on large scale, this can cause significant (physical) damage or electricity shortages, therefore a score of 2 is assigned.

Physical vulnerability (score: 1)

- Thin-film solar cells are vulnerable to mechanical damage, however flexible thin-film photovoltaics are less vulnerable than silicon-based solar panels, since they are flexible and not as rigid as silicon-based solar panels.
- Accumulation of dust, dirt, bird faeces and leaves on solar cells can reduce electricity output.

Although sabotage and extreme weather events can never be excluded, there is no particular physical risk for this technology compared to other value chains, and the damage resulting from physical events will probably be limited. Therefore, a score of 1 is assigned.

Broader sustainability (score: 2)

This energy security indicator concerns broader sustainability aspects such as legal restrictions and public opposition:[8]

- Raw material extraction: materials must be mined, which can cause local opposition or disruption to ecosystems around mining areas.
- Selenium exposure can be toxic – however, only small quantities of selenium are used. Studies show that emissions of selenium to the environment remain within the applicable safety standards even under worst-case conditions.
- Extreme weather conditions (such as hail) and fires can break PV systems and cause leakage of chemicals into the environment or scattering of loose pieces of glass from the protective glass plate.

Although these individual risks are not very high, since there are various risks for this value chain related to different sustainability aspects, an overall score of 2 is assigned for broader sustainability.

Affordability (score: 1)

CIGS is expected to become economically competitive in future, once challenges to broad application are overcome. The idea behind thin-film PV in general is the design of lightweight (lower material usage) and affordable PV, which makes it suitable for large-scale, low-cost manufacturing (e.g. roll-to-roll printing). Therefore, we assign this indicator a score of 1.

Skills (score: 3)

R&D for CIGS PV is needed to improve manufacturing processes and efficiencies do the technology can be broadly implemented. This requires a highly skilled labour force. Acquiring the necessary skills requires relatively long, university-level education. In addition, implementation and installation require skilled labour. The necessary skills can be acquired relatively quickly. Therefore, we assign this indicator a score of 3.

9.8.2.5. Bibliography

[1] JRC (2022), CETO Photovoltaics. https://setis.ec.europa.eu/photovoltaics-european-union_en.

[2] NREL (2023), Best Research-Cell Efficiencies. https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.pdf

[3] JRC (2020), Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system. https://core.ac.uk/download/pdf/322747915.pdf.

[4] A. Amato and F. Beolchini (2018). 'End-of-life CIGS photovoltaic panel: A source of secondary indium and gallium'. *Progress in Photovoltaics*. Volume 27(1). https://doi.org/10.1002/pip.3082.

[5] European Commission (2020), Critical Raw Materials for Strategic Technologies and Sectors in the EU. https://rmis.jrc.ec.europa.eu/uploads/CRMs_for_Strategic_Technologies_and_Sectors_in_the_EU_2020.pdf

[6] USGS, 2022. Gallium. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-gallium.pdf

[7] USGS, 2020. Selenium. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-selenium.pdf

[8] TNO (2021), Zonnestroom: van hernieuwbaar naar duurzaam. https://publications.tno.nl/publication/34638904/Mnc8mC/TNO-2021-tijd.pdf

9.8.3. Cadmium telluride (CdTe) PV technology

CdTe is a thin-film PV technology. CdTe photovoltaics appear to be a promising competitor with conventional solar cells, as they are likely to have a shorter energy payback time and a smaller carbon footprint. Thin-film PV can be used for lightweight solar cells on roofs or integrated into buildings or products. The thin film share of global production is only 5%, corresponding to 7.8 GWp of total global PV module production. Of this 7.8 GWp, 78% is CdTe, 19% CI(G)S.[1] The efficiencies of commercial CdTe modules are comparable to silicon-based PV solar panels, however outstanding challenges to production must be resolved before CdTe can be compatible with silicon PV.

9.8.3.1. Characteristics

Role in EU energy system: CdTe modules are used for sustainable energy generation by converting solar energy into electricity, with efficiencies ranging from 15% to 22% (the latter a laboratory record).[2]

Primary energy source: solar radiation.

TRL: 8–9 since the technology is commercially available. However, CdTe is not yet compatible with silicon PV and its market share is therefore relatively small.

9.8.3.2. Life cycle: construction phase

Silicon-based solar cell modules use the following materials (EU-listed CRM in **bold**):[3] zinc, cadmium, chloride, tellurium, **copper**, sulphur, transparent conductive oxides(e.g. with zinc, plastic). Several chemicals and solvents, such as cadmium chloride, are also used throughout the manufacturing processes of different PV technologies.

For the total infrastructure of solar PV installation, the following are needed:

- Inverter
- Cables (copper)
- Connection to the grid. In the long-term, grid reinforcement is needed.

9.8.3.3. Life cycle: use phase

Silicon-based solar cell modules use the following materials (EU-listed CRM in **bold**):[3] zinc, cadmium, chloride, tellurium, **copper**, sulphur, transparent conductive oxides(e.g. with zinc, plastic). Several chemicals and solvents, such as cadmium chloride, are also used throughout the manufacturing processes of different PV technologies.

9.8.3.4. Life cycle: end-of-life

In general, CdTe has a life expectancy around 25 years. However, since CdTe has only been commercially available since the early 2000s in small quantities, there is no strategy for the convenient recycling of CdTe modules as yet. Suppliers of PV are obliged by a European directive to collect and recycle solar panels at the end of their useful life. Recycling and reuse of solar panels are only beginning, since the volume of end-of-life products is still low. For CdTe, the CRM copper, cadmium and tellurium are of particular interest for recycling. R&D is needed to develop general recycling and recovery methods for CdTe. Due to the urgency of recycling tellurium, various high-value recycling methods are now industrially available.

Table C.15 Energy security indicators for CdTe technology

Geopolitical availability (score: 1)
The critical material used in CdTe PV and their relative geopolitical availability are as follows: • Copper: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). Since only one critical material is used with a score of 1, this is the overall score assigned to this indicator.
Abundance (score: 2)

The critical material used in this technology and abundance risk is:

- Copper, which has a medium abundance risk (1 to 100 ppm, score 2).

Since the average score for all materials is 2, this is the overall score assigned to this indicator.

Circularity (score: 2)

Recycling of CdTe PV is still being developed. Recovery of tellurium is particularly important, as the scarcity of this material can be mitigated by recycling efforts and improvement in production processes. Recycling of CdTe PV waste is essential, not only to avoid toxic cadmium and tellurium leaking in the environment, but also to conserve tellurium. Studies show that lack of accessible tellurium reserves and annual tellurium production can, to a certain extent, limit the market growth of CdTe.[4] Efforts are being made to extract tellurium from PV production scrap and end-of-life modules, and have potential to cover a significant share of feedstock and reduce the primary tellurium demand.[4] Due to the urgency of recycling tellurium, intense efforts are being made by R&D and various high-value recycling methods are already industrially available. Because of this urgency, and the fact that it is being addressed, we assign this indicator a score of 2.

Supply chain complexity (score: 2)

The supply chain for CdTe thin-film solar cells involves a series of steps that start with raw materials and end with the installation of the thin-film, in buildings or products, for example. Raw materials like cadmium, telluride and copper must be sourced and processed. Multiple layers are stacked and processed to create the solar cell structure. Subsequently, the thin-film module must be assembled. Ancillary components, such as inverters and wiring, are also part of the supply chain. Once installed, regular maintenance and monitoring are needed to ensure optimal performance. Because the supply chain is quite, but not unusually, complex, we assign this indicator a score of 2.

Supply chain location (score: 3)

Cadmium is a by-product of mining, smelting and refining sulphide ores of zinc during zinc refining. Cadmium is also found in lead and copper ores. Major cadmium-producing countries include China, Australia, Canada and Kazakhstan. Tellurium is almost exclusively obtained as a by-product of copper refining, with smaller amounts from lead and gold production. Major tellurium-producing countries include China, the United States, Canada and Japan. Copper is found in ores and typically extracted from sulphide ores. Major producing countries include Chile, Peru, China, the United States and Australia.[5] Therefore, the supply chain is mostly located outside the EU, and we assign this indicator a score of 3.

Digital vulnerability (score: 2)

Solar cells themselves are not vulnerable to digital attacks. However, PV systems include inverters that use software which is vulnerable to cyberattacks. If inverters are hacked on large scale, this can cause significant (physical) damage or electricity shortages – therefore a score of 2 is assigned.

Physical vulnerability (score: 1)

- Thin-film solar cells are vulnerable to mechanical damage – however flexible thin-film PV is less vulnerable than silicon-based solar panels, since they are flexible and not as rigid as silicon-based solar panels.

- Accumulation of dust, dirt, bird faeces and leaves on solar cells can reduce electricity output.

Although sabotage and extreme weather events can never be excluded, there is no particular physical risk for this technology compared to other value chains, and the damage resulting from physical events will probably be limited. Therefore, a score of 1 is assigned.

Broader sustainability (score: 2)

This energy security indicator concerns broader sustainability aspects such as legal restrictions and public opposition:[6]

- Raw material extraction: materials must be mined, which can face local opposition or disrupt of ecosystems around mining areas.
- Cadmium is highly toxic. However, when cadmium is incorporated in CdTe it is much less toxic and insoluble. Since cadmium is a by-product of refining zinc, CdTe PV modules can also provide a safe and stable use for cadmium, which would otherwise need to be stored for future use or disposed of in landfill as hazardous waste. When used for CdTe PV, it is very important to prevent cadmium getting into the environment. Partly due to uncertainties around careful end-of-life processing and recycling, it is not known whether CdTe solar cells are a major source of cadmium pollution.[7]
- Tellurium is mildly toxic, but within the stable CdTe crystalline lattice it is highly stable.
- Extreme weather (e.g. hail) and fires can break PV systems, causing leakage of chemicals into the environment or scattering of loose pieces of glass/plastic from the protective layer.

Although these individual risks are not very high, since there are various risks for this value chain related to different sustainability aspects, an overall score of 2 is assigned for broader sustainability.

Affordability (score: 1)

CdTe is expected to be economically competitive once challenges to broad application are overcome. The idea behind thin-film PV in general is the design of lightweight (lower material usage) and affordable PV, which makes it suitable for large-scale and low-cost manufacturing (for example roll-to-roll printing). Therefore, we assign a score of 1 to this indicator.

Skills (score: 3)

For CdTe PV to be broadly implemented, R&D for is needed to improve manufacturing process and efficiencies. This requires a highly skilled labour force. Acquiring the necessary skills requires relatively long, university-level education. Skilled labour is also required for implementation and installation. The necessary skills can be acquired relatively quickly. Therefore, we assign a score of 3 to this indicator.

9.8.3.5. Bibliography

[1] JRC (2022), CETO Photovoltaics. https://setis.ec.europa.eu/photovoltaics-european-union_en.
[2] NREL (2023), Best Research-Cell Efficiencies. https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.pdf.
[3] JRC (2020), Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system. https://core.ac.uk/download/pdf/322747915.pdf.

[4] Marwede, Max; Reller, Armin (2012). 'Future recycling flows of tellurium from cadmium telluride photovoltaic waste'. *Resources, Conservation and Recycling*. Volume 69. 35-49. https://doi.org/10.1016/j.resconrec.2012.09.003.

[5] European Commission (2020), Critical Raw Materials for Strategic Technologies and Sectors in the EU. https://rmis.jrc.ec.europa.eu/uploads/CRMs_for_Strategic_Technologies_and_Sectors_in_the_EU_2020.pdf

[6] TNO (2021), Zonnestroom: van hernieuwbaar naar duurzaam. https://publications.tno.nl/publication/34638904/Mnc8mC/TNO-2021-tijd.pdf

[7] Smets et al. (2016). Solar Energy: The physics and engineering of photovoltaic conversion, technologies and systems.

9.8.4. Perovskite PV technology

Perovskite PV is not yet commercially available due to stability issues of the solar cells but has promising research efficiency outcomes. It is a relatively new and rapidly evolving PV technology based on a crystal lattice structure. Perovskite PV has potential to become both more affordable than silicon-based PV and accessible due to ease of fabrication and it potential for flexible, lightweight applications.[1] However, to unleash this potential, stability issues and concerns over lead as an important material in perovskite must be addressed.

9.8.4.1. Characteristics

Role in EU energy system: perovskite PV technology is used for intermittent energy generation by converting solar energy into electricity, with efficiencies of around 25% to 26% (laboratory record).[2]

Primary energy source: solar radiation.

TRL: 4

9.8.4.2. Life cycle: construction phase

There are different types of crystal structures possible for perovskite solar cells, and therefore material composition can differ. The most studied perovskite is methylammonium lead trihalide: $CH_3NH_3PbX_3$, where X is a halogen ion such as iodide, bromide or chloride. Formamidinium lead trihalide ($H_2NCHNH_2PbX_3$) has also shown promising lab results. Another commonly studied perovskite is caesium lead halide ($CsPbX_3$). A common concern is the inclusion of lead as a component of perovskite materials. Tin-based perovskite absorbers such as $CH_3NH_3SnI_3$ are being researched as an alternative to lead, but so far, they have achieved lower power-conversion efficiencies.

Commonly used materials for perovskites solar cells include:

- Lead halide precursors, such as lead iodide (PbI_2) and lead bromide ($PbBr_2$).
- Organic cations such as methylammonium (MA) and formamidium (FA).
- Inorganic cations such as caesium iodide.
- Solvents, such as dimethylformamide, dimethyl sulfoxide and gamma-butyrolactone.
- Hole transport materials (HTMs), such as spiro-OMeTAD(2,2',7,7'-Tetrakis(N,N-di-p-methoxyphenylamine)-9,9'-spirobifluorene) and PEDOT:PSS(poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate)).

- Electron transport materials (ETM), such as titanium dioxide (TiO_2) and tin oxide (SnO_2).
- Perovskite precursor mixing additives, such as guanidinium iodide (GuaI) or other stabilising agents.
- Cleaning solvents, isopropanol or ethanol.
- Etchants, such as methylammonium iodide and isopropanol; acids such as hydrochloric acid or acetic acid can sometimes be used.
- Encapsulation materials, such as epoxy resins or glass.
- Conductive contacts such as gold or silver.

Perovskites can be printed roll-to-roll as flexible solar cell modules and can be embedded in products.

9.8.4.3. Life cycle: use phase

During the use phase, only maintenance and cleaning of the PV technology is needed.

9.8.4.4. Life cycle: end-of-life

Since perovskite solar cells are not commercially available, there is no common practice for the end-of-life stage and this needs to be developed before introduction to the market. In particular, leakage of lead must be taken care off.

Table C.16 Energy security indicators for perovskite PV technology

Geopolitical availability (score: 1)
The critical material used in perovskite PV and its relative geopolitical availability is: • Titanium is sometimes used as an ETM and is a critical raw material. Titanium is available in one EU country. Global suppliers (China and Russia) have high political risk, but the supply risk is relatively low and not concentrated (<50%) in one country (score: 2). However, since titanium is not an essential component, a score of 1 is given.
Abundance (score: 1)
The critical material used in the technology and the abundance risk is: • Titanium, which has a low abundance risk (>10 000 ppm, score 1). Since the average score for all materials is 1, this is the overall score assigned to this indicator.
Circularity (score: 2)
Perovskite solar cells are not commercially available yet. Therefore, a recycling method for perovskite solar cells is not yet operational and the infrastructure for recycling on a large scale is not established. This can eventually lead to modules being disposed of rather than recycled –

which should be prevented, and development therefore is needed.[3,4] Therefore, we assign a score of 2 to this indicator.

Supply chain complexity (score: 2)

The supply chain for perovskite solar cells involves a series of steps that start with raw materials and end with the installation of the thin film in for example buildings or products. Raw materials must be sourced and processed. Various layers are stacked and processed to create the solar cell structure. Subsequently, the thin-film module must be assembled. Ancillary components, such as inverters and wiring, are also part of the supply chain. Once installed, regular maintenance and monitoring are needed to ensure optimal performance. Because the supply chain is quite – but not unusually – complex, we assign this indicator a score of 2.

Supply chain location (score: 3)

- Lead: sourced from mining activities in several countries, mostly outside the EU. However, there are lead mining operations in some EU countries such as Ireland, Sweden, Spain and Greece.
- Organic cations (FA or MA): chemically synthesised from fossil sources.
- Inorganic cations: caesium is extracted from by-products of lithium and tantalum mining. Countries with significant lithium production, such as Australia, Chile and China are potential sources of caesium.

Since the supply chain is almost entirely operated outside EU Member States, the score is 3.

Digital vulnerability (score: 2)

Solar cells themselves are not vulnerable to digital attacks. However, PV systems include an inverter using software that is vulnerable to cyberattacks. If inverters are hacked on large scale, this can cause significant (physical) damage or electricity shortages – therefore a score of 2 is assigned.

Physical vulnerability (score: 1)

- Thin-film solar cells are vulnerable to mechanical damage. However, flexible thin-film photovoltaics are less vulnerable than silicon-based solar panels, since they are flexible and less rigid.
- Accumulation of dust, dirt, bird faeces and leaves on solar cells can reduce electricity output.

Although sabotage and extreme weather events can never be excluded, there is no particular physical risk for this technology compared to other value chains and the damage resulting from physical events will probably be limited. Therefore, a score of 1 is assigned.

Broader sustainability (score: 2)

- Raw material extraction: must be mined, which can face local opposition or disrupt ecosystems around mining areas.
- Lead is used in the perovskite variant that so far provides the best-performing solar cells. The amounts involved are very small (typically 0.3 grams per m^2), however regulation and market acceptance can still be difficult. Research focuses on lead-free perovskites – however, there is still uncertainty over whether they will come close enough to lead-based perovskites in terms of performance to be used on a large scale.

An alternative is to accept (including in regulation) that perovskite panels contain lead, because their (climate) benefits outweigh the disadvantages of using lead – in which case end-of-life management will be needed for disposal of perovskites containing lead.

- Extreme weather conditions or fires can break PV systems, causing leakage of chemicals into the environment or scattering of loose pieces of glass from the protective glass plate.

Although these individual risks are not very high, since there are various risks to this value chain related to different sustainability aspects, an overall score of 2 is assigned for broader sustainability.

Affordability (score: 1)

Perovskite PV is expected to easily be economically competitive, once challenges to broad application are overcome. Perovskite solar cells can be fabricated using abundant and relatively low-cost materials. Perovskite solar cells can be manufactured at large scale and low-cost using roll-to-roll printing processes. Due to the high production rate and relatively low investment costs, perovskite solar cells are expected to have low costs. Therefore, we assign a score of 1 to this indicator.

Skills (score: 3)

For perovskite PV to be broadly implemented, R&D is needed to improve the stability of the solar cells.[5] This requires highly skilled labour force. Acquiring the necessary skills requires relatively long, university-level education. Skilled labour would be needed in future for implementation and installation. The necessary skills can be acquired relatively quickly. Therefore, we assign a score of 3 to this indicator.

9.8.4.5. Bibliography

[1] JRC (2022), CETO Photovoltaics. https://setis.ec.europa.eu/photovoltaics-european-union_en.

[2] NREL (2023), Best Research-Cell Efficiencies. https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.pdf

[3] R. G. Charles, A. Doolin, R. García-Rodríguez, K. Valadez Villalobos and M. L. Davies (2023). 'Circular economy for perovskite solar cells – drivers, progress and challenges' *Energy & Environmental Science*. Volume 9. https://doi.org/10.1039/D3EE00841J.

[4] S. Maranghi, M.L. Parisi, R. Basosi, A. Sinicropi (2019). *Environmental Profile of the Manufacturing Process of Perovskite Photovoltaics: Harmonization of Life Cycle Assessment Studies* https://doi.org/10.3390/en12193746.

[5] European Commission (2020), *Critical Raw Materials for Strategic Technologies and Sectors in the EU.* https://rmis.jrc.ec.europa.eu/uploads/CRMs_for_Strategic_Technologies_and_Sectors_in_the_EU_2020.pdf.

9.9. Wind energy

9.9.1. Wind turbines – onshore

Onshore wind turbines use wind energy to generate electricity and are located on land. Most commercial wind turbines are horizontal axis, upwind, three-bladed turbines,[1] but other designs are possible, such as two-bladed turbines, vertical-axis turbines and downwind turbines.

9.9.1.1. Characteristics

Role in EU energy system: Onshore wind energy is an intermittent energy source where wind energy is converted into electricity. In 2021, 10 GW of onshore wind capacity was installed in the EU, adding to the bloc's existing 173.7 GW.[1] From 2010 to 2021, between 7 and 10 GW were added annually in the EU.[1]

Primary energy source: wind energy.

TRL: Overall**,** wind turbines a mature technology with a TRL of 9.[2] However, several innovations are currently being researched:

- Blades: multiple innovations on the composition of blades are being researched [1, including alternative materials that are biobased and/or recyclable (TRL 1–9).[1]

- Generator: multiple innovations are being researched to replace conventional generators with superconducting (TRL 5–8), or permanent magnet-free, generators (TRL 5).[1]

9.9.1.2. Life cycle: Construction phase

Components of a wind turbine

An onshore wind turbine consists of the following components:[1,3]

- Tower: the tower supports the nacelle module and is mainly constructed from steel.

- Blades: the blades are mainly composed of carbon fibre and woven glass fibres infused with epoxy resin. Polyurethane (PUR) glue is used to assemble blade shells. Balsa wood may also be used in the core of the blades.[1]

- Hub: the blades are attached to the hub made from consists of cast iron and glass fibre-reinforced polyester.

- Nacelle module:

  - Gearbox: cast iron and steel

  - Generator: mainly steel, cast iron and copper. May contain permanent magnets consisting of materials including dysprosium and neodymium.[1]

  - Nacelle foundation: cast iron

  - Nacelle cover: fibreglass, which consists of woven glass fibres, PET and styrene

- Turbine transformer: consists mainly of steel, copper, aluminium and resin.

- Cables: consist mainly of aluminium, copper, steel and polymers.

- Controller units and other electronics: consist mainly of signal and power electronics, which contain materials such as palladium, cobalt, gallium, germanium, silicon and rare earth elements (REE). Switchgears may contain sulphur hexafluoride.

- Foundation: mainly consists of concrete and steel.
- Site cables: Mainly consist of aluminium, copper, steel and polymers.

Summary of the materials

We summarise the materials according to three categories: crucial raw materials, non-critical raw materials, and other:[1]

- Critical raw material: silicon, copper, dysprosium, neodymium, praseodymium, terbium, borate, nickel, manganese
- Non-critical raw materials**:** chromium, molybdenum, aluminium, iron, silica, zinc, lead
- Other: balsa wood, polyurethane, polyethylene, PET, steel, carbon fibre, cement/concrete, glass fibre, polystyrene, epoxide resins

9.9.1.3. Life cycle: use phase

Onshore wind turbines require maintenance that generally includes the replacement of damaged components.

9.9.1.4. Life cycle: end-of-life

Wind turbines have an average lifetime of 20 years.[3] 80–95% of the total mass of a wind turbine can be recycled.[1] The circularity score for the V162-6.2 MW turbine is 0.64, which means 64% of its materials are managed in a closed-loop way, while 36% of materials are managed in a linear manner.[3] 89% of this turbine's total weight is recycled at end-of-life.[3].

- Tower: all large metal components are primarily steel (e.g. tower sections, cast iron frame in nacelle, etc.) and are assumed to be 98% recycled.[3]
- Blades: the recycling of blades poses a challenge,[1] but several initiatives are researching the possibility of manufacturing recyclable blades or blades made from biobased materials.[1]
- Switchgears: at end-of-life, switchgears are collected and the sulphur hexafluoride gas reclaimed for reuse in new equipment.[3]

Table C.17 Energy security indicators for onshore wind turbines

Geopolitical availability (score: 2)
The critical materials used in a wind turbine and their relative geopolitical availability are as follows: • Copper: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Aluminium: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1).

- Boron/borate: no EU suppliers. Supply not concentrated in one country. Relatively high supply risk (score: 3).
- Manganese: a single EU supplier. Top suppliers have low political risk. Supply not concentrated in one country. Relatively low supply risk (score: 1).
- Nickel: four EU suppliers. Top suppliers have low political risk. Supply not concentrated in one country. Relatively low supply risk (score: 1).
- Light REE: no EU supplier. Top suppliers have high political risk. Concentrated in one country (>50%). Relatively high supply risk (score: 3).
- Heavy REE: no EU supplier. Top suppliers with high political risk. Concentrated in one country (>50%). Relatively high supply risk (score: 3).

The average of all materials is a score of 2.

Abundance (score: 2)

Since almost all technologies contain permanent magnets (as part of generators) and copper (as part of the connection to the grid) these materials are considered a background risk (score 1). Besides, wind turbine designs without permanent magnets are already being developed.[1] Therefore, a score of 2 is given.

The critical materials in the technology’s core and their abundance risk are:

- Copper, which has a medium abundance risk (1 to 100 ppm, score 2)
- Aluminium, which has a low abundance risk (>10 000 ppm, score 1)
- Nickel, which has a medium abundance risk (1 to 100 ppm, score 2)
- Manganese, which has a low abundance risk (>10 000 ppm, score 1)
- Boron/borate, which has a medium abundance risk (1 to 100 ppm, score 2)

Since the average score for all materials is 2, this is the overall score assigned to this indicator.

Circularity (score: 1)

80–95% of the total mass of a wind turbine can be recycled.[1]

Only 2% of REE (which are found in the permanent magnets) are currently recycled, which is extremely low compared to steel, of which 90% is recycled.[4] Patil et al. states that low market prices of REE make recycling economically unfeasible. Recycling of REE is also complicated by their low concentrations in the end-of-life feedstocks, making them complex to retrieve.[4]

For most of the materials, a relatively high recycling rate is possible (>80%). As demand for REE continues to rise and more wind turbines reach the end-of-life, we foresee an increase in the recycling rate of REE in the coming years.

Since most components have high recycling rates, and there are prospects of increased recycling rates for REE, a score of 1 is given.

Supply chain complexity (score: 1)

The supply chain of a wind turbine roughly consists of the following steps:

- Obtaining key materials such as steel, concrete, glass fibre, carbon fibre, aluminium, etc.

- Manufacturing the tower, blades, hub, nacelle module, gearbox, generator, turbine transformer, cables, controller units, etc.
- Assembling the turbine from individual components
- Transport to the deployment site
- Deployment/installation: foundation needs to be constructed, turbines must be (further) assembled and site cables connected to the local power grid
- Maintenance of turbine such as lubricating and replacing damaged parts
- Decommissioning of a wind turbine requires disassembly, transport and recycling

We consider the technological complexity for most steps in this supply chain to be relatively low. Therefore, a score of 1 is given.

Supply chain location (score: 1)

The European manufacturing supply chain for wind turbines mainly involves companies located in the EU.[1] In 2020 and 2021, EU companies held between 80% and 90% of the EU onshore wind rotor market, respectively.[1] European manufacturers mainly source their onshore wind rotor components from companies based in EU Member States. European manufacturers obtain components from multiple suppliers and cooperate with those manufacturing globally.[1]

Since most of the supply chain is location in the EU a score of 1 is given.

Digital vulnerability (score: 2)

Most wind turbines are controlled and monitored using remote communication systems.[5] A zero-dynamics attack is a cyberattack that cannot be detected by the monitoring output and exploits the internal dynamics of a system to cause damage.[5] In case of a wind turbine, this may involve an attack that causes uncontrolled/unstable rotational speed.

Since a potential cyberattack can cause substantial damage to this technology, a score of 2 is given.

Physical vulnerability (score: 2)

Weather and climate change

Projections indicate increased frequency of lightning activity across many regions globally.[6,7] Combined with the use of taller wind turbines and higher angular blade speed, upward lightning strikes (from wind turbine to atmosphere) are likely to increase.[6]

Climate change is predicted to change wind speed patterns across the globe.[8,9] A study by Gernaat et al. predicts that the technical potential (kWh/y) of onshore wind will be reduced by 4.1% globally when comparing historical data with projections for 2070–2100.[9] The decrease in technical potential for wind energy in northern European countries is predicted to be significant.[9]

Lastly, storms can lead to a complete shutdown of (onshore) wind turbines and a halt in electricity production. Due to several weather-related vulnerabilities, a score of 2 is assigned.

Broader sustainability (score: 2)

Pollution

Raw material and component production are the main source of environmental impacts.[3] Most sulphur dioxide and nitrogen oxides emissions, for example, are associated with the production of iron, steel, glass fibres, aluminium and concrete.[3] There is no direct soil pollution caused by wind turbines during the operation and maintenance phase.[1]

Balsawood

Increased demand for balsa wood due to the increased deployment for wind turbines has resulted in over-logging in the Amazon.[1] However, alternatives to balsa wood are currently used and being further researched.

Impacts on birds

Wind turbines pose a risk to (flying) birds. To reduce the impact on migrating birds, measures such as temporarily shutting down turbines during significant migratory events are already used.[10] However, the success of such measures is still being evaluated.

Public acceptance

Enevoldsen et al. conclude that deployment of onshore wind turbines faces a lack of social acceptance.[11] Factors that impact acceptance include: the visual impact of the wind turbines, the sentimental value of deployment sites, (local) ownership of the turbines and impacts on the local economy.[11] Increased public acceptance can be achieved by addressing all these factors.[11]

Although the individual risks are not very high, since there are several concerns/issues related to different sustainability aspects of this value chain, an overall score of 2 is assigned for broader sustainability.

Affordability (score: 1)

Onshore wind energy has a global weighted average LCOE of 0.033 USD/kWh.[12] Globally, onshore wind energy the cheapest technology compared to several other technologies: offshore wind (0.075 USD/kWh), concentrated solar energy (0.114 USD/kWh), hydropower (0.048 USD/kWh), solar photovoltaic (0.048 USD/kWh), geothermal energy (0.068 USD/kWh) and bioenergy (0.067 USD/kWh). Since this technology has a relatively low LCOE, a score of 1 is given.

Skills (score: 2)

The EU wind sector offers between 240 000 and 300 000 direct and indirect jobs.[1] EU total wind energy workforce account for about a quarter of the estimated global employment in the wind energy sector.[1] Future scenarios estimate global wind energy employment growing almost fivefold by 2050 to about 5.5 million jobs.[1] Risks mostly relate to the availability of a sufficient/skilled workforce. Considering the rapidly growing demand for skilled workers, a score of 2 is given.

9.9.1.5. Bibliography

[1] JRC (2022), Wind energy in the European Union. https://setis.ec.europa.eu/wind-energy-european-union_en

[2] Beurskens (2021), Wind onshore, TNO. https://energy.nl/media/data/Technology-Factsheet-Wind-Onshore.pdf

[3] Mali et al. (2023), Life Cycle assessment V162-6.2MW wind plant. https://www.vestas.com/content/dam/vestas-com/global/en/sustainability/reports-and-ratings/lcas/LCA%20of%20Electricity%20Production%20from%20an%20onshore%20EnVentus%20V162-6.2.pdf.coredownload.inline.pdf

[4] Patil et al. (2022), ‘Separation and Recycling Potential of Rare Earth Elements from Energy Systems: Feed and Economic Viability Review’. *Separations*. Volume 9(3) https://www.mdpi.com/2297-8739/9/3/56

[5] Kim et al. (2021), Zero-Dynamics Attack on Wind Turbines and Countermeasures Using Generalized Hold and Generalized Sampler. https://www.mdpi.com/2076-3417/11/3/1257

[6] Zhang et al. (2019), 'Economic and sustainability promises of wind energy considering the impacts of climate change and vulnerabilities to extreme conditions'. *The Electricity Journal*. Volume 32(6). https://www.sciencedirect.com/science/article/abs/pii/S1040619019301344

[7] Pérez-Invernón et al. (2023), 'Variation of lightning-ignited wildfire patterns under climate change'. *Nature Communications*. Volume 14(739). https://www.nature.com/articles/s41467-023-36500-5

[8] Pryor et al. (2020), 'Climate change impacts on wind power generation'. *Nature Reviews Earth & Environment*. Volume 1. 627-643. https://www.nature.com/articles/s43017-020-0101-7

[9] Gernaat et al. (2021), 'Climate change impacts on renewable energy supply'. *Nature Climate Change*. Volume 11, 119-125. https://www.nature.com/articles/s41558-020-00949-9

[10] Rijksoverheid (2023), Windparken op zee voor het eerst stilgezet om trekvogels te beschermen. https://www.rijksoverheid.nl/actueel/nieuws/2023/05/15/windparken-op-zee-voor-het-eerst-stilgezet-om-trekvogels-te-beschermen

[11] Enevoldsen et al. (2016), 'Examining the social acceptance of wind energy: Practical guidelines for onshore wind project development in France'. *Sustainable Energy Reviews*. Volume 53, 178-184. https://www.sciencedirect.com/science/article/abs/pii/S1364032115009028

[12] IRENA (2021), Renewable Power Generation Costs in 2021. https://www.irena.org/Publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021

9.9.2. Wind turbine – offshore

Offshore wind turbines use wind energy to generate electricity and are located offshore. The majority of commercial wind turbines are horizontal axis, upwind, three-bladed turbines,[1] but other designs are possible such as two-bladed wind turbines, vertical-axis turbines and downwind turbines. Several types of bottom-fixed foundations are known:[1,2] monopiles, jackets, tripods, triples, gravity base and suction buckets.

There is growing interest in floating offshore wind turbines, where the turbines are placed on a floating structure, making offshore wind energy more feasible in deeper waters. Several floating structures are known: spar-buoy, semi-submersible, tension-leg platform, barge or multi-platforms substructures.[1,2] Several floating offshore projects have been already realised, such as the Hywind Scotland and the WindFloat Atlantic projects.

9.9.2.1. Characteristics

Role in EU energy system: Offshore wind energy is an intermittent energy source where wind energy is converted into electricity. In 2021, 1 GW of offshore wind energy capacity was installed in the EU, adding to the bloc's existing 15.6 GW.[1] From 2010 to 2021, between 0.5 and 2.4 GW were added annually in the EU.[1] The deployment of offshore wind energy is expected to increase to about 8–9 GW/year by 2030, and up to an estimated 12–13 GW by 2050.[1]

Primary energy source: wind energy.

TRL:[1]

- Commercial offshore wind turbines: offshore wind turbines that have reached commercial readiness use bottom-fixed foundations and are generally horizontal axis, three-bladed, upwind rotor turbines.
- Floating offshore: offshore floating wind has reached TRLs between 4–9. Spar-buoy and semi-submersible concepts have reached TRL 8-9.

9.9.2.2. Life cycle: construction phase

The fundamental components of an offshore wind turbine closely resemble those used in onshore turbines, with the notable distinction that offshore turbine components are typically larger in scale. The onshore wind turbine analysis above therefore largely overlaps with the analysis for offshore wind turbines.

The construction of an offshore differs from the construction of an onshore wind turbine in the following aspects:

- Transport and construction: specialised ships are required to place the turbines at sea.[3] Several types of vessel can be used depending on market availability, budget, wind turbine technology, size and number of components,[3] including tugboat, crane barge, heavy lift cargo vessel, jack-up barge, purpose-built jack-up vessel, semi-submersible crane vessel.[3]

- Bottom-fixed foundations (TRL 8–9):[3] The steps required to construct the foundation largely depend on the type of foundation used. Examples include: monopiles, jackets and gravity-based foundations.

- Floating:[4] new vessels are currently being developed for the deployment/installation of floating offshore wind turbines.

- Electricity infrastructure: offshore wind energy requires undersea cables to transfer the electricity to shore, as well as transformers, converter stations, etc.

9.9.2.3. Life cycle: use phase

Offshore wind turbines require maintenance that generally includes the replacement of damaged components. Yildiz et al. assume that during the lifetime of a wind turbine, the gearbox needs replacing once, and specialised personnel must examine all components – and lubricate some components – twice a year.[5]

9.9.2.4. Life cycle: end-of-life

Yildiz et al. assume that concrete, glass fibre and glass-reinforced plastic are landfilled. The recycle rate for steel and cast iron is assumed to be 85%. The recycle rate for copper and aluminium 90%, for nylon fibre 100%, and for polyurethane foam 80%.[5]

Table C.18 Energy security indicators for offshore wind turbines

Geopolitical availability (score: 2)
The critical materials used in a wind turbine and their relative geopolitical availability are as follows: • Copper: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Aluminium: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1).

- Permanent magnets: materials not available in EU and mostly concentrated in China, supply risk relatively high (score: 3).
- Boron/borate: no EU suppliers. Top suppliers have low political risk. Supply not concentrated in one country. Relatively high supply risk (score: 3)
- Manganese: single EU supplier. Top suppliers have low political risk. Supply not concentrated in one country. Relatively low supply risk (score: 1).
- Nickel: four EU suppliers. Top suppliers have low political risk. Supply not concentrated in one country. Relatively low supply risk (score: 1).
- Light REE: no EU supplier. Top suppliers have high political risk. Concentrated in one country (>50%). Relatively high supply risk (score: 3).
- Heavy REE: no EU supplier. Top suppliers have high political risk. Concentrated in one country (>50%). Relatively high supply risk (score: 3).

Since the average score for all materials is 2, this is the overall score assigned to this indicator.

Abundance (score: 2)

Since almost all technologies contain permanent magnets (as part of generators) and copper (as part of the connection to the grid) these materials are considered a background risk (score 1). Besides, wind turbine designs without permanent magnets are already being developed.[1] Therefore, a score of 2 is given.

The critical materials in the technology's core and their abundance risk are:

- Copper, which has a medium abundance risk (1 to 100 ppm, score 2)
- Aluminium, which has a low abundance risk (>10 000 ppm, score 1)
- Nickel, which has a medium abundance risk (1 to 100 ppm, score 2)
- Manganese, which has a low abundance risk (>10 000 ppm, score 1)
- Boron/borate, which has a medium abundance risk (1 to 100 ppm, score 2)

Since the average score for all materials is 2, this is the overall score assigned to this indicator.

Circularity (score: 1)

80–95% of the total mass of a wind turbine can be recycled.[1] WindEurope (2020) estimates that by 2023, about 14 000 blades (circa 60 000 tonnes) will be at end-of-life and that composite waste from blades will amount to around 400 000 (tonnes) by 2040.[1] However, several companies are investigating ways to improve re-use and recycling of waste materials.[1]

Only 2% of REE (which are found in the permanent magnets) are currently recycled, which is extremely low compared to steel, 90% of which is recycled. Patil et al. states that low market prices for REE make recycling economically unfeasible. Recycling REE is also complicated by their low concentrations in end-of-life feedstocks making them complex to retrieve.[6]

For most materials a relatively high recycle percentage is possible (>80%).

As demand for REE continues to rise and more wind turbines reach end-of-life, we foresee a rise in the recycling rate of REE in the coming years.

Since most materials are already recycled, and recycling of the more critical materials is possible, we assign a score of 1 to this indicator.

Supply chain complexity (score: 2)

The supply chain of a wind turbine roughly consists of the following steps:

- Obtaining key materials such as steel, concrete, glass fibre, carbon fibre, aluminium, etc.
- Manufacturing of tower, blades, hub, nacelle module, gearbox, generator, turbine transformer, cables, controller units and other electronics.
- Assembling turbine from the individual components.
- Transport to the deployment site, which involves specialised vessels.
- Deployment/installation: foundation needs to be constructed, turbines must be (further) assembled, and (sea)cables must connect the turbine to the power grid located on the mainland.
- Maintenance of turbines, such as lubricating and replacing damaged parts. This task is more challenging for offshore wind turbines with respect to onshore wind turbines.
- Decommissioning of the wind turbine requires disassembly, transportation and recycling.

We consider the technological complexity for most steps in this supply chain to be relatively low. However, the transportation, deployment, maintenance and decommissioning of offshore turbines is complicated by their location at sea and requires specialised vessels and equipment. Therefore, we assign this indicator a score of 2.

Supply chain location (score: 1)

Commercial offshore wind turbines[1]

The majority of Tier 1 and Tier 2 offshore components originate from European manufacturers.

About 84% of manufacturers located in the EU also have their headquarters in the EU.

Floating offshore

Several European companies, such as Damen, SBM Offshore and Equinor are taking interest in the (local) production of floating offshore wind turbines,[4,7,8] which includes the assembly of the steel floating devices, logistics, assembly, marine services and construction.[7]

Since most of the supply chain is in the EU, we assign a score of 1 to this indicator.

Digital vulnerability (score: 2)

Zero-dynamics attacks are also a potential threat for offshore wind turbines (see wind turbines – onshore, above).

In the context of floating wind turbines, digital vulnerability is expected to have an increased risk since tower movements and forces on moorings can be reduced by regulating turbine blades in relation to the wind gusts,[8] thereby increasing the dependence of digitalisation on its robustness.

Since a potential cyberattack can cause substantial damage to this technology, a score of 2 is given.

Physical vulnerability (score: 3)

Sabotage

Undersea cables (including cables from offshore wind parcs) are vulnerable to sabotage. In May 2023, NATO's intelligence chief stated that were increased concerns that Russia may target undersea cables and infrastructure.[9]

Weather and climate change

Climate change is predicted to change wind speed patterns across the globe.[10] A study by Gernaat et al. predicts that the technical potential (kWh/y) for offshore wind will be reduced by 2.1% globally when comparing historical data with projections in 2070–2100.[10] The reduction of wind energy's technical potential for in northern European countries is predicted to be significant.[10]

Projections have indicated increased frequency of lightning activity across many regions globally.[11,12] Combined with the use of taller wind turbines and higher angular speed of the blades, upward lightning strikes (from wind turbine to atmosphere) are likely to increase.[11]

Additionally, increasing sea levels may pose an increased risk to offshore wind tower structures and foundations.[11]

Robustness of floating wind turbines

Floating wind turbines (e.g. spar buoy designs) are stabilised using anchors and mooring lines.[8] The ability of these structures to withstand waves and storms remains to be demonstrated.

Because offshore wind energy faces many different physical vulnerabilities, we assign a score of 3 to this indicator.

Broader sustainability (score: 2)

Environmental impact

Offshore wind turbines can have both positive and negative environmental impacts.[13,14] Van Hoey et al. shows that the installation and operation of offshore wind structures may lead to changes in the seafloor ecosystem.[13]

A study by Galparsoro et al. shows that more negative effects were observed (72%) than positive effects (13%).[14] A significant portion (32%) of moderate to high negative impacts were associated with changes in bird abundance due to collision mortality, displacement, changes in distribution patterns and alteration of behaviour.[14] To reduce the impact on migrating birds, measures such as temporarily shutting down turbines during significant migratory events are already used.[15] However, the success of such measures is still being evaluated.

Furthermore, the authors reported that marine mammals are affected in terms of abundance and distribution, especially during the development phase.[14] Fish are affected in various ways, depending on species: for example, fish species from rocky environments were more abundant close to offshore wind turbines than those originating from sedimentary environments.[14]

Impacts on fishing industry

Offshore wind farms can affect the fishing industry by reducing space available for fishing activities.[1] Fishing activities near offshore wind farms pose safety risks such as collision risks and risk of damage to (undersea) cables.[1]

Impacts on tourism

Offshore wind farms can affect the tourism sector due to the visual impact of wind turbines and loss of attractiveness of a coastal site and can restrict recreational activities.[1]

Impacts on defence

Offshore wind farms and their associated activities (e.g. construction, operation and maintenance activities) can conflict with military infrastructure (radar, underwater cables), of naval training zones or storage sites.[1] Offshore wind turbines can interfere with air defence detection capabilities and electronic navigation systems.[1]

Since several issues are found to be related to broader sustainability, we assign a score of 2 to this indicator.

Affordability (score: 2)

Offshore wind energy has a global weighted average LCOE of 0.075 USD/kWh.[17] Maienza et al. calculated an average LCOE of 0.0974 EUR/kWh for floating offshore wind farm with a semi-submersible platform, the spar buoy and the tension leg platform.[16]

Compared to several other technologies, offshore wind energy is relatively expensive – only concentrated solar energy has a higher LCOE of 0.114 USD/kWh.[17] The LCOE of other technologies: onshore wind (0.033 USD/kWh), hydropower (0.048 USD/kWh), solar photovoltaic (0.048 USD/kWh), geothermal energy (0.068 USD/kWh), bioenergy (0.067 USD/kWh).[17] Therefore, we assign a score of 2 to this indicator

Skills (score: 2)

The EU wind sector offers between 240 000 and 300 000 direct and indirect jobs.[1] The total EU wind energy workforce accounts for about a quarter of the estimated global employment in the wind energy sector.[1] Future scenarios estimate global wind energy employment expanding almost fivefold by 2050, to about 5.5 million jobs.[1] Around 70% of jobs (in FTE) in the oil and gas sector show good or partial overlap with the offshore renewable segment.[1]

Considering the rapidly growing demand for skilled workers and complexity of stalling offshore wind turbines, a score of 2 is given.

9.9.2.5. Bibliography

[1] JRC (2022), Wind energy in the European Union. https://setis.ec.europa.eu/wind-energy-european-union_en

[2] Watson et al. (2019), Future emerging technologies in the wind power sector: A European perspective. https://www.sciencedirect.com/science/article/pii/S1364032119304782

[3] Liang (2012), Installation of offshore wind turbines: A technical review. https://www.sciencedirect.com/science/article/pii/S1364032120308601

[4] Damen (2022), Damen Shipyards to develop new class to support the oncoming roll-out of floating offshore wind turbines. https://www.damen.com/insights-center/news/damen-to-develop-new-class-to-support-the-oncoming-roll-out-of-fowt

[5] Yildiz et al. (2021), Life Cycle Assessment of a Barge-Type Floating Wind Turbine and Comparison with Other Types of Wind Turbines. https://www.mdpi.com/1996-1073/14/18/5656

[6] Patil et al. (2022), Separation and Recycling Potential of Rare Earth Elements from Energy Systems: Feed and Economic Viability Review. https://www.mdpi.com/2297-8739/9/3/56

[7] SBM Offshore (2022), SBM Offshore declares interest in Northern Ireland Floating Offshore Wind Project. https://www.sbmoffshore.com/newsroom/news-events/sbm-offshore-declares-interest-northern-ireland-floating-offshore-wind-project

[8] Equinor (2023), Industrialising floating offshore wind https://www.equinor.com/energy/floating-wind

[9] Siebold (2023), NATO says Moscow may sabotage undersea cables as part of war on Ukraine. https://www.reuters.com/world/moscow-may-sabotage-undersea-cables-part-its-war-ukraine-nato-2023-05-03/

[10] Gernaat et al. (2021), 'Climate change impacts on renewable energy supply'. Nature Climate Change. Volume 11, 119-125. https://www.nature.com/articles/s41558-020-00949-9

[11] Zhang et al. (2019), Economic and sustainability promises of wind energy considering the impacts of climate change and vulnerabilities to extreme conditions. https://www.sciencedirect.com/science/article/abs/pii/S1040619019301344

[12] Pérez-Invernón et al. (2023), Variation of lightning-ignited wildfire patterns under climate change. https://www.nature.com/articles/s41467-023-36500-5

[13] European Climate (2021), Infrastructure and Environment Executive Agency (ECIEEA), Overview of the effects of offshore wind farms on fisheries and aquaculture.

https://cinea.ec.europa.eu/publications/overview-effects-offshore-wind-farms-fisheries-and-aquaculture_en

14 Galparsoro et al. (2022), Reviewing the ecological impacts of offshore wind farms. https://www.nature.com/articles/s44183-022-00003-5

15 Rijksoverheid (2023), Windparken op zee voor het eerst stilgezet om trekvogels te beschermen. https://www.rijksoverheid.nl/actueel/nieuws/2023/05/15/windparken-op-zee-voor-het-eerst-stilgezet-om-trekvogels-te-beschermen

16 Maienza et al. (2020), A life cycle cost model for floating offshore wind farms. https://www.sciencedirect.com/science/article/abs/pii/S0306261920302282

17 IRENA (2021), Renewable Power Generation Costs in 2021. https://www.irena.org/Publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021

9.9.3. Airborne wind energy systems

Airborne Wind Energy Systems (AWES) convert wind energy into electricity using kites or unmanned aircraft, which remain connected to the ground.

Compared to wind turbines, AWE systems require fewer materials[1-4] – making them cheaper[1,3] – and allow access to wind energy available at higher altitudes (600m), inaccessible to wind turbines that require towers.[3]

9.9.3.1. Characteristics

Role in EU energy system: several types of AWE systems are currently being developed and pilot studies have started.[4] Currently, AWE systems do not fulfil any role in Europe's energy system.

Primary energy source: wind energy.

TRL: Due to reliability problems with current prototypes, Watson et al. (2019) estimate the current TRL of AWE systems at between 3 and 5, with AWE systems estimated to reach commercialisation in roughly 10 years.[4]

9.9.3.2. Life cycle: construction phase

Materials used in kites:[5] for this analysis, we assume AWES kites to consists of similar materials to those used in kites used for kitesurfing. Most of these kites are made from polyester. Polyester is made from terephthalic acid (PTA) or its dimethyl ester dimethyl terephthalate (DMT) and monoethylene glycol (MEG). Newer models may be reinforced with materials such as: cuben fibre (CTF_3), mylar, dacron DP175, high tenacity dacron, polyurethane (TPU), ballistic kevlar or neoprene.

Materials used in aircraft:

- AWES aircraft are mainly composed of carbon reinforced fibre polymers (CFRP).[1]
- Core materials: plastic foams, balsa wood and geometric honeycomb structures
- Fibres: carbon fibre production is a highly energy-intensive process. Polyacrylonitrile based carbon fibre is commonly used but can also be made from lignin.
- Polymers: thermoset plastic and epoxy resin mix.

Other materials/components: AWE systems require electronics (containing REE) to control the kites/aircraft. Copper is required for cables connecting the AWE systems to the (local) grid. Tethers are usually made from ultra-high-molecular weight polyethylene (UHMWPE).[5] Aluminium, batteries, motors (containing permanent magnets), titanium, stainless steel, high-strength steel and low-alloy steel are also found in AWE systems.

9.9.3.3. Life cycle: use phase

Data availability on the use phase is limited. We anticipate that maintenance is required, but maintenance frequency depends on the overall robustness of the AWE system.

9.9.3.4. Life cycle: end-of-life

Since AWE systems have not been deployed on a large scale, little information is available on their end-of-life phase. We anticipate that materials such as aluminium, steel, copper and titanium will have recycling rates above 80%. However, the recycling of carbon-fibre-reinforced polymer and glass-fibre-reinforced polymers remains a challenge.[2]

Table C.19 Energy security indicators for airborne wind systems

Geopolitical availability (score: 2)
The critical materials used in a wind turbine and their relative geopolitical availability are as follows: • Copper: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Aluminium: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Titanium: 1 EU supplier. Supply risk relatively low. Supply not concentrated in one country. (score: 1). • Lithium: no EU suppliers but EU supply risk relatively low (score: 1). • Heavy REE: no EU supplier. Top supplier is high political risk. Concentrated in one country (>50%). Relatively high supply risk (score: 3). The average of all materials is a score of 2.
Abundance (score: 2)
Since almost all technologies contain permanent magnets (as part of generators) and copper (as part of the connection to the grid) these materials are considered background risk (score 1). The critical materials in the technology's core and their abundance risk are: • Copper, which has a medium abundance risk (1 to 100 ppm, score 2). • Aluminium, which has a low abundance risk (>10 000 ppm, score 1). • Titanium, which has a low abundance risk (>10 000 ppm, score 1). • Lithium, which has a medium abundance risk (1 to 100 ppm, score 2). Since the average score for all materials is 2, this is the overall score assigned to this indicator.

Circularity (score: 2)

Carbon-fibre-reinforced polymers, used in fixed-wing kites, are estimated to be 21 times more polluting than glass-fibre-reinforced polymers.[2] Although AWE systems use fewer materials overall, the AWE industry should find ways to recycle these materials to further lower its environmental impact.[2] For this reason, a score of 2 is given.

Supply chain complexity (score: 1)

The supply chain involves the production of kites/aircraft, tethers, power generators, control systems, batteries and a ground base. The production of batteries and generators is mainly dependent on suppliers from outside the EU. AWE systems require fewer materials, and the complexity of the overall technology (excl. the production of required electronics) is estimated to be relatively low. For this reason, a score 1 is given.

Supply chain location (score: 1)

Several European companies are developing AWE systems: WindFisher (France), KiteX (Denmark), Kitekraft (Germany), Airborne Wind Europe (Belgium), X-wind (Germany), Enerkite (Germany), SkySails (Germany), KitePower (The Netherlands), Ampyx Power (The Netherlands), e-Kite (The Netherlands). This suggests that Europe has an independent position with respect to the development and deployment of AWE systems. For this reason, a score of 1 is given.

Digital vulnerability (score: 2)

Since AWE systems are controlled by software, we anticipate zero-dynamics attacks to pose a risk to AWE systems (see Wind turbine – onshore). We anticipate that such attacks could lead to substantial damage to this technology, and therefore a score of 2 is given.

Physical vulnerability (score: 3)

Weather and climate change

AWE systems are an upcoming technology, and physical vulnerabilities are still largely unknown. Most of AWES systems make use of tethers to connect kites or aircrafts to a ground station. No data on the robustness of the systems is available. However, we anticipate that storms, for example, may pose a risk to the integrity of the system(s). Hailstorms may also pose a risk to the kites and aircraft.

Projections indicate an increased frequency of lightning activity across many regions globally.[6,7] Lightning discharges to AWE systems may cause catastrophic damage.[8] Cherubini et al. anticipate that AWE systems will not operate during thunderstorms.[5] This implies that an increased occurrence of lightning events will reduce the overall operational time of AWE systems.

Climate change is predicted to change wind speed patterns across the globe.[9,10] A study by Gernaat et al. predicts that the technical potential (kWh/y) for onshore/offshore wind will fall by 4.1% (2.1%) globally, comparing historical data to projections for 2070–2100.[10] The decrease in technical potential for wind energy in northern European countries is predicted to be significant.[10]

We anticipate that AWE systems will be more vulnerable to extreme weather events such as lighting, hail and storms than other wind technologies. For this reason, a score of 3 is given.

Broader sustainability (score: 1)

Safety

A reliable operation of AWE systems has not been demonstrated yet. Therefore, it is recommended that AWES test sites are located far from populated areas.[2] AWES cannot be stopped in mid-air and require controlled landing,[2] which could be perceived as more hazardous, and thus less acceptable, than ground-based wind turbines.

Visual aspects

Due to the high operating altitude of AWE systems, they are less noticeable than wind turbines, which can positively affect public acceptance.[2] However, future studies should investigate other aspects, such as the colour of the kites, flight patterns, etc.[2]

Acoustic aspects

Sound emissions from AWE systems are considered less than conventional wind turbines.[2]

Environmental impacts

Collisions with birds and bats and the disturbance of mammals and avian wildlife are expected to be the main ecological effects of AWE systems.[2] Based on a single study, the annual bird fatalities for a single AWE system are estimated at between 13 and 24, implying fewer bird fatalities compared to wind turbines.[2]

Despite the use of carbon fibre-reinforced polymers, which are 21 times more polluting than glass-fibre-reinforced polymers used in wind turbine blades, initial research suggests that AWE systems have a lower environmental impact than wind turbines, since fewer materials are needed.[2]

Siting of AWE Systems

Involving the (local) community before and during the development of an AWE plant will positively affect public acceptance.[2] Offshore AWES may have negative and positive impacts on tourism, marine wildlife, the fishing industry and the recreational activity sector.[2]

We do not anticipate high individual risks of issues above, and therefore a score of 1 is assigned for broader sustainability.

Affordability (score: 1)

Zolfaghari et al. estimated a LCOE of 0.0766 USD/kWh for a kite pump system.[11] Joshi et al. calculated a LCOE of circa 0.055 EUR/kWh for a 2-MW onshore AWES system.[12] In 2025, Airborne Wind Europe estimates the LCOE to be circa 0.1 EUR/kWh.[13] However, Airborne Wind Europe predicts that the LCOE for AWE systems will drop below the LCOE of onshore wind energy around the year 2037.[13] The authors estimate an LCOE of 0.045, 0.024 and 0.015 EUR/kWh for the years 2030, 2040 and 2050 respectively.[13]

With prospects of declining LCOE in the future, and current LCOE similar to existing renewable energy technologies, we assign a score 1.

Skills (score: 2)

Since the AWE industry is planning to develop floating offshore plants,[2] we expect a large overlap in skills between the deployment of an offshore AWE system and an offshore floating wind turbine. Companies and manufactures that develop/install offshore floating wind turbines therefore may also play a role in the deployment of offshore AWE systems. Considering the increasing demand for skilled workers in the offshore wind energy sector, a score of 2 is assigned.

9.9.3.5. *Bibliography*

[1] Van Hagen, Life Cycle Assessment of Multi-Megawatt Airborne Wind Energy, 2021. https://repository.tudelft.nl/islandora/object/uuid:472a961d-1815-41f2-81b0-0c6245361efb?collection=education
[2] Schmidt et al., The Social Acceptance of Airborne Wind Energy: A Literature Review, 2022. https://www.mdpi.com/1996-1073/15/4/1384
[3] Mendonça et al. (2020), Airborne Wind Energy Systems: Current state and challenges to reach the market. http://portalabepro.educacao.ws/ijcieom/restrito/arquivos/icieom2020/FULL_0010_37171.pdf
[4] Watson et al. (2019), Future emerging technologies in the wind power sector: A European perspective. https://www.sciencedirect.com/science/article/pii/S1364032119304782
[5] Cherubini et al. (2015), Airborne Wind Energy Systems: A review of the technologies. https://www.sciencedirect.com/science/article/pii/S1364032115007005
[6] Zhang et al. (2019), Economic and sustainability promises of wind energy considering the impacts of climate change and vulnerabilities to extreme conditions. https://www.sciencedirect.com/science/article/abs/pii/S1040619019301344
[7] Pérez-Invernón et al. (2023), Variation of lightning-ignited wildfire patterns under climate change. https://www.nature.com/articles/s41467-023-36500-5
[8] Malinga et al. (2016), Lightning field behavior around grounded airborne systems. https://www.sciencedirect.com/science/article/abs/pii/S0960148115304006
[9] Pryor et al. (2020), Climate change impacts on wind power generation. https://www.nature.com/articles/s43017-020-0101-7
[10] Gernaat et al. (2021), Climate change impacts on renewable energy supply. https://www.nature.com/articles/s41558-020-00949-9
[11] Zolfaghari et al. (2020), Feasibility Analysis of Airborne Wind Energy System (AWES) Pumping Kite (PK). https://www.akademiabaru.com/index.php/archives/article/view/586
[12] Joshi et al. (2023), Value-Driven System Design of Utility-Scale Airborne Wind Energy. https://www.mdpi.com/1996-1073/16/4/2075
[13] Blanch et al. (2022), Getting airborne – the need to realise the benefits of airborne wind energy for net zero. https://airbornewindeurope.org/wp-content/uploads/2023/03/BVGA-Getting-Airborne-White-Paper-220929.pdf

9.9.4. Downwind wind turbines

Downwind wind turbines are horizontal axis turbines where the rotor is positioned on the downwind side of the tower. Where upwind rotor blades require stiff blades to prevent collision with the tower, downwind rotors can be lighter and more flexible since the blades bend in the opposite direction to the tower.

Increasing rotor diameters reduce the LCOE for (up)wind turbines but the minimum clearance between rotor tip and tower in order to prevent strikes complicates this increase in diameter.[1] Therefore, downwind rotor designs may pose a solution to this challenge.[1]

The main disadvantage of downwind rotor turbines is the passing of the rotor blades through the wind shade of the tower, thereby increasing mechanical stresses and reducing energy production.

9.9.4.1. *Characteristics*

Role in EU energy system: Downwind wind turbines play no role (yet) in Europe's energy system.

Primary energy source: wind energy.

TRL: Since 2015, an onshore 2B6 downwind 6 MW wind turbine has been tested. Based on this project, Watson et al. estimate the TRL for downwind turbines to be between 7 and 8.[2] In 2015, Hitachi also developed a prototype 5 MW downwind turbine.[3] More recently, the National Renewable Energy Laboratory (United States), in collaboration with several universities, developed a downwind turbine for research purposes.[4]

9.9.4.2. Life cycle: construction phase

Most of the components in a downwind turbine are also found in an upwind turbine. They differ mainly on volumes of material required to manufacture blades, with downwind designs using less.

9.9.4.3. Life cycle: use phase

Data availability on the use phase is limited. Potentially, more maintenance is required compared to upwind turbines due to additional mechanical stresses caused by the wind-shadowing effect of the tower.

9.9.4.4. Life cycle: end-of-life

Data availability about the end-of-life phase for downwind turbines is limited. However, we anticipate a large overlap between upwind turbines (see Wind turbines – onshore and Wind turbines - offshore).

Table C.20 Energy security indicators for downwind wind turbines

Geopolitical availability (score: 2)
We anticipate that the same critical raw materials are used in downwind turbines as upwind turbines. For this reason, we apply the same analysis performed for onshore and offshore wind turbines to this technology (see Wind turbines – onshore and Wind turbines – offshore), and therefore a score of 2 is assigned for this energy security indicator.
Abundance (score: 2)
We anticipate that the same critical raw materials are used in downwind turbines as upwind turbines. For this reason, we apply the same analysis as performed for onshore and offshore wind turbines to this technology (see Wind turbines – onshore and Wind turbines – offshore), and therefore a score of 2 is assigned for this energy security indicator.
Circularity (score: 1)
We anticipate that the same materials are used in downwind turbines as upwind turbines. For this reason, we apply the same analysis as performed for onshore and offshore wind turbines to this technology (see Wind turbines – onshore and Wind turbines – offshore), and therefore a score of 2 is assigned for this energy security indicator.
Supply chain complexity (score: 1)
The supply chains for downwind turbines are similar to the supply chains of onshore and offshore turbines, depending on deployment location (see Wind turbines – onshore and Wind turbines – offshore).

Supply chain location (score: 1)

The supply chains for downwind turbines are similar to the supply chains of onshore and offshore turbines, depending on deployment location (see Wind turbines – onshore and Wind turbines – offshore).

Digital vulnerability (score: 2)

Risks related to digital vulnerability overlap with the risks related to any other type of wind turbine (see Wind turbines – onshore and Wind turbines – offshore). Since a potential cyberattack could cause substantial damage to this technology, a score of 2 is given.

Physical vulnerability (score: 3)

Weather and climate change

Downwind rotor turbines are considered more resilient to storms/high wind speeds due to increased flexibility of the rotor blades compared to upwind turbines. Morphing downwind-aligned rotor (MoDaR) in particular, are expected to withstand extreme weather conditions by folding the blades, thereby reducing the risk of damage.[2] However, other weather and climate change related risks overlap with the analysis for onshore and offshore wind turbines (see Wind turbines – onshore and Wind turbines – offshore).

The overall risk score for this energy security indicator also depends on deployment location – i.e. onshore or offshore. Given the potential benefits of downwind turbines accommodating larger rotor blades, we anticipate that these turbines will be mainly deployed in offshore regions. For this reason, we assign a score of 3 to this technology – the same score assigned to offshore wind turbines.

Broader sustainability (score: 2)

Depending on deployment location, this analysis overlaps with the analysis for onshore and offshore wind turbines (see Wind turbines – onshore and Wind turbines – offshore).

Given the potential benefits of downwind turbines in accommodating larger rotor blades, we anticipate that these turbines will be mainly deployed in offshore regions. For this reason, we assign a score of 2 for this technology (the same score that was assigned for offshore wind turbines).

Affordability (score: 2)

Cost reduction could be obtained in downwind configurations due to lighter and more flexible blades.[1] Pao et al. and Yao et al. describe downwind rotor designs with an estimated reduction of 25% in LCOE.[5,6] However, in another study by Wanke et al. the estimated reduction was 1.3%.[7]

Bortolotti et al. show that downwind rotors have a smaller swept area under loading.[1] Consequently, the downwind design produces less annual energy production (−1.2%). On the other hand, lighter blades for the downwind configuration mean lower capital costs (−1.7%). Since the difference between the two factors is small, Bortolotti et al. concludes that the reduction in LCOE is limited.[4]

Considering the large uncertainty in LCOE for downwind turbines, we assume that energy costs for downwind turbines will be similar to upwind turbines. Furthermore, as mentioned above, we expect downwind turbines to be mainly deployed in offshore regions, and therefore the costs will match the costs for offshore wind energy. For these reasons, a score of 2 is assigned.

Skills (score: 2)

Similar skills and personnel are required for the construction, installation and maintenance of a downwind rotor wind turbine as for an upwind turbine. For this reason, we assign the same score of 2, using the same argumentation used for scoring this energy security risk for onshore and offshore wind turbines.

9.9.4.5. Bibliography

[1] Bortolotti et al. (2019), Comparison between upwind and downwind designs of a 10MW wind turbine rotor. https://wes.copernicus.org/articles/4/115/2019/

[2] Watson et al. (2019), Future emerging technologies in the wind power sector: A European perspective. https://www.sciencedirect.com/science/article/pii/S1364032119304782

[3] Kiyoki et al. (2016), Development of 5-MW Downwind Turbine and Floating Substation Facility for Offshore Wind Power. https://www.hitachi.com/rev/pdf/2016/r2016_04_106.pdf

[4] Bortolotti et al. (2021), Challenges, opportunities, and a research roadmap for downwind wind turbines. https://onlinelibrary.wiley.com/doi/10.1002/we.2676

[5] Pao et al. (2021), Control co-design of 13 MW downwind two-bladed rotors to achieve 25% reduction in levelized cost of wind energy. https://www.sciencedirect.com/science/article/abs/pii/S1367578821000079

[6] Yao et al. (2021), Structural design and optimization of a series of 13.2MW downwind rotors. https://journals.sagepub.com/doi/full/10.1177/0309524X20984164

[7] Wanke et al. (2021), Redesign of an upwind rotor for a downwind configuration: design changes and cost evaluation. https://wes.copernicus.org/articles/6/203/2021/

9.10. Direct solar fuels

9.10.1. Direct solar fuels from photochemical/photobiological routes

Direct solar fuels convert solar energy directly into chemical energy in the form of liquid or gaseous fuel. The photochemical route makes use of solar photon energy for photobiological processes. The main difference between the photochemical route and the thermochemical route is that thermochemical processes use concentrated solar heat to drive chemical reactions, while photochemical processes utilise light-absorbing materials to directly convert solar energy into chemical fuels. The development of direct solar fuels is still in early phases and therefore there is limited information available to complete this factsheet (compared to other value chains).

9.10.1.1. Characteristics

Role in EU energy system: liquid solar fuels have potential to directly substitute fossil fuels.

Primary energy source: solar radiation.

TRL: The technology is not yet commercialised and is in the R&D phase giving it a TLR of 1–3.[1]

9.10.1.2. Life cycle: construction phase

Large scale production would require a set-up similar to current refineries.[2] Specifically, the following components are needed:

- Light absorbers (photocatalysts): convert solar energy into chemical energy

- metal complexes, titanium dioxide (TiO_2) or bismuth vanadate ($BiVO_4$).[3]

- Sensitisers: molecules that absorb light energy and transfer it to the photocatalyst
  - dye-sensitised solar cells.[4]
- Reductants: provide electrons to the photocatalyst after light absorption
  - methanol or water.
- Oxidants: accept electrons in the oxidation half-reaction.
- Oxygen
- Electrodes
- Electrolyte

Supporting materials: membranes and coatings.

9.10.1.3. Life cycle: use phase

Inflow of CO_2 and H_2O. Moreover, if the fuels are used for transport, infrastructure will be required for utilisation.

9.10.1.4. Life cycle: end-of-life

The expectation is that the critical materials in the photocatalysts can be recovered at end-of-life. However, as the technology is still in its early phase there is no infrastructure or facilities available for the collection and recycling of these materials.

Furthermore, as this technology is not yet commercialised, not much is known about the lifetime or possibility of recycling components.

Table C.21 Energy security indicators for direct solar fuels from photochemical/ photobiological routes

Geopolitical availability (score: 1)
Direct solar fuels use the following materials from the EU CRM list:[3] • Bismuth: available in one EU and multiple global countries. Even though the supply is relatively concentrated in one country, the EU supply risk relatively low (score: 1). • Titanium: available in one EU and multiple global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). Since the average score for all materials is 1, this is the overall score assigned to this indicator.
Abundance (score: 2)
The critical materials in the technology and their abundance risk are:

- Bismuth, which has a high abundance risk (0.01 to 1 ppm, score 3).
- Titanium, which has a low abundance risk (100–10 000 ppm, score 1).

Since the average score for all materials is 2, this is the overall score assigned to this indicator.

Circularity (score: 1)

As CO_2 is required as input there is a possibility of utilising emissions from nearby factories that would otherwise be emitted to the air. However, from 2041 on the use of fossil CO_2 to produce recycled carbon fuels is prohibited, meaning other sources of CO_2 must be deployed.

The technology itself may have components that are recyclable, but this information is not available yet. Given these two factors, a score of 1 is given.

Supply chain complexity (score: 3)

The components required for direct solar fuels are highly specialised. Once the technology is in its commercial phase, it will have flexible deployment options (degraded lands, built environment, infrastructure) and is scalable.[1] To summarise, although the technology has potential to be scalable, the components and required R&D are highly specialised, giving this a score of 3.

Supply chain location (score: 2)

Operations: in regions with high sun irradiation but not all over EU.

R&D: EU organisations have a strong, but not leading, role in solar fuel research.[1]

Since the EU has a role but is not leading direct solar fuel R&D, a score of 2 is given.

Digital vulnerability (score: 1)

Although cyberattacks can never be excluded, there is no particular digital risk for this technology compared to other value chains, and the damage resulting from a cyberattack could probably be limited. Therefore, a score of 1 is assigned.

Physical vulnerability (score: 1)

Although sabotage and extreme weather events can never be excluded, there is no particular physical risk for this technology compared to other value chains, and the damage resulting from physical events will probably be limited. Therefore, a score of 1 is assigned.

Broader sustainability (score: 2)

Public opinion on renewable fuels (especially for the aviation industry) is generally positive. As the technology requires PV cells, the associated sustainability risks (see 9.7) are also relevant here, hence a score of 2 is assigned.

Affordability (score: 3)

A 2021 European Commission funded study assessed different solar fuel pathways for producing hydrogen, methanol, ethanol and methane compared to fossil-based methods. The direct solar pathway struggled to be competitive, even in the long term (2050–2100), mainly due to high costs of energy and other inputs. Therefore, a score of 3 is given to this energy security indicator.[5]

Skills (score: 3)
R&D for direct solar fuels is needed to bring the technology to maturity so it can be broadly implemented. This requires highly skilled labour force. Acquiring the necessary skills requires relatively long, university-level education. The relative level of R&D – and specialised skills – gives this criterium a high score of 3.

9.10.1.5. Bibliography

[1] JRC (2022). Direct solar fuels in the European Union. Luxembourg: Publication Office of the European Union. https://setis.ec.europa.eu/direct-solar-fuels-european-union_en

[2] Mi and Sick. (2020). Taking a Shortcut: Direct Power-to-X Conversion. *Front. Energy. Res.* Volume 8. Frontiers. https://www.frontiersin.org/articles/10.3389/fenrg.2020.00153/full

[3] Ganesh (2015). Solar fuels vis-à-vis electricity generation from sunlight: The current state-of-the-art (a review). *Renewable and Sustainable Energy Reviews.* Volume 44 (904-932). https://www.sciencedirect.com/science/article/abs/pii/S1364032115000295

[4] Brennaman (2016). Finding the Way to Solar Fuels with Dye-Sensitized Photoelectrosynthesis Cells. *Journal of the American Chemical Society.* Volume 138 (13085-13102). https://pubs.acs.org/doi/10.1021/jacs.6b06466

[5] Buffi et al. (2022). Energy and environmental assessment of hydrogen from biomass sources: Challenges and perspectives. *Biomass and Bioenergy.* Volume 165. https://www.sciencedirect.com/science/article/pii/S0961953422002185?via%3Dihub

9.10.2. Direct solar fuels from thermochemical routes

Direct solar fuels convert solar energy directly into chemical energy in the form of liquid or gaseous fuel. The thermochemical route uses solar heat at moderate and/or high temperatures, followed by an endothermic thermochemical process.[1] The main difference between the photochemical route and the thermochemical route is that thermochemical processes use concentrated solar heat to drive chemical reactions, while photochemical processes utilise light-absorbing materials to directly convert solar energy into chemical fuels. The development of direct solar fuels is still in early phases and therefore there is limited information available for to complete this factsheet (compared to other value chains).

9.10.2.1. Characteristics

Role in EU energy system: Liquid solar fuels have the potential to directly substitute fossil fuels.

Primary energy source: solar radiation.

TRL: first commercial demonstration (Synhelion), giving it a TLR of 4–5.[1]

9.10.2.2. Life cycle: construction phase

Based on Synhelion,[2] a big plant will contain the following components:

- CSP system (see 1.9)

- Chemical reactor where the high-temperature reaction takes place (water, carbon dioxide and catalyst (CeO_2) to produce fuels such as syngas)
- Heat exchanger
- Control systems

9.10.2.3. Life cycle: use phase

Input of CH_4, CO_2 and H_2O. Moreover, if the fuels are used for transport, infrastructure will be required for the utilisation.

9.10.2.4. Life cycle: end-of-life

As there is only one commercial plant currently in operation, not much is known about the lifetime or possibility of recycling of components.

Table C.22 Energy security indicators for direct solar fuels from thermochemical routes

Geopolitical availability (score: 1)
CSP systems contain permanent magnets (as part of generators) and copper (as part of the connection to the grid). These materials are considered a background risk (score 1). Besides this, no CRM are used so the average score assigned to this indicator is 1.
Abundance (score: 1)
CSP systems contain permanent magnets (as part of generators) and copper (as part of the connection to the grid). These materials are considered a background risk (score 1). Besides this, no CRM are used so the average score assigned to this indicator is 1.
Circularity (score: 1)
CO_2 and CH_4 are required as inputs, meaning there is a possibility of utilising emissions of nearby factories that would otherwise be emitted to the air. However, from 2041 on the use of fossil CO_2 to produce recycled carbon fuels is prohibited, meaning other sources of CO_2 must be deployed. The technology itself may have components that are recyclable, but this information is not available yet. Given these two factors, a score of 1 is given.
Supply chain complexity (score: 2)
The components required for direct solar fuels are highly specialised. Once the technology is in its commercial phase, it will have flexible deployment options (degraded lands, built environment, infrastructure) and is scalable.[1] To summarise, although the technology has potential to be scalable, the components and required R&D are highly specialised. Compared to direct solar fuels from photochemical routes, this technology is further developed, giving a score of 2.
Supply chain location (score: 2)

Operations: in regions with high sun irradiation, but not all over the EU.

R&D: EU organisations have a strong, but not leading, role in solar fuel research.[1]

Since the EU has a role but is not leading direct solar fuel R&D, a score of 2 is given.

Digital vulnerability (score: 1)

Although cyberattacks can never be excluded, there is no particular digital risk for this technology compared to other value chains, and the damage resulting from a cyberattack could probably be limited. Therefore, a score of 1 is assigned.

Physical vulnerability (score: 1)

Although sabotage and extreme weather events can never be excluded, there is no particular physical risk for this technology compared to other value chains, and the damage resulting from physical events will probably be limited. Therefore, a score of 1 is assigned.

Broader sustainability (score: 2)

Public opinion on renewable fuels (especially for the aviation industry) is generally positive. However, CSP plants (see 9.3) do come with some sustainability risks, such as a high land and water requirement. Therefore, a score of 2 is given.

Affordability (score: 3)

A 2021 European Commission funded study assessed different solar fuel pathways for producing hydrogen, methanol, ethanol and methane compared to fossil-based methods. The direct solar pathway struggled to be competitive, even in the long term (2050–2100), mainly due to high costs of energy and other inputs. Therefore, a score of 3 is given to this energy security indicator.[3]

Skills (score: 3)

R&D for direct solar fuels is needed to bring the technology to maturity so it can be broadly implemented. This requires highly skilled labour force. Acquiring the necessary skills requires relatively long, university-level education. The relative level of R&D – and specialised skills – gives this criterium a high score of 3.

9.10.2.5. Bibliography

[1] JRC (2022). Direct solar fuels in the European Union. Luxembourg: Publication Office of the European Union. https://setis.ec.europa.eu/direct-solar-fuels-european-union_en

[2] Schäppi et al. (2022). Drop-in Fuels from Sunlight and Air. *Nature*. Volume 601 (63-68). https://www.nature.com/articles/s41586-021-04174-y

[3] Buffi et al. (2022). Energy and environmental assessment of hydrogen from biomass sources: Challenges and perspectives. *Biomass and Bioenergy.* Volume 165. https://www.sciencedirect.com/science/article/pii/S0961953422002185?via%3Dihub

9.11. Carbon capture and storage

9.11.1. Carbon capture and storage

Carbon Capture and Storage (CCS) is a critical technology designed to mitigate GHG emissions and combat climate change. It involves capturing carbon dioxide (CO_2) emissions from industrial processes and power generation, transporting the captured CO_2 to storage sites, and securely storing it underground to prevent its release into the atmosphere. CCS plays a pivotal role in reducing CO_2 emissions from sectors that are difficult to decarbonise entirely, such as heavy industry and fossil fuel-based power generation. This technology is a key component of efforts to achieve global climate goals.

9.11.1.1. Characteristics

Role in EU energy system: CCS is a critical component of the EU's strategy to reduce emissions, decarbonise energy-intensive industries and achieve its climate and environmental goals. It is one of the tools in the transition to a sustainable and low-carbon energy system, providing an intermediate solution for sectors where emissions reduction is challenging.

In 2022, 73 CCS facilities were being developed in Europe and the UK.[1]

Primary energy source: electricity is used to compress CO_2 gas, either for liquid or gaseous transport. However, this criterium for CCS is not relevant in the context of this assessment.

TRL: Carbon capture and storage includes three steps: capture, transport and storage. The first step is to capture CO_2 from a source, which could be flue gas from power generation, fuel production or other industrial processes. The capturing processes involve either capturing media in solid (adsorbents) or liquid (solvents) form or membranes. The TRLs of mature capturing technologies are as follows:[2]

- Traditional amine solvents (liquid): 9
- Physical solvents (liquid): 9
- Benfield process and variants (liquid): 9
- Pressure swing (adsorbents): 9
- Gas separation membranes for natural gas processing (membranes): 9

There are other, less mature, technologies capture technologies in trial or research.

Transport of CO_2 is highly developed and could proceed via pipeline, ship or tanker.[3]

The most mature CO_2 storage technologies are in enhanced oil recovery. Other options are saline formations (early adoption stage) and storage in depleted oil and gas reservoirs (demonstration projects).[2]

9.11.1.2. Life cycle: construction phase

The construction phase for CCS projects starts with obtaining required permits and subsidies. Generally speaking, a subsidy is required to make such projects commercially viable. The construction phase is complex and capital-intensive, requiring careful planning, strict adherence to regulations and strong commitment to safety and environmental responsibility. Once construction is complete, the project moves into the operational phase, where CO_2 capture, transportation and storage become fully operational, contributing to carbon emissions reduction.

9.11.1.3. Life cycle: use phase

During the use phase, CO_2 is captured, transported and injected into the storage site, where it is permanently stored until.

9.11.1.4. Life cycle: end-of-life

Once a storage site has reached maximum capacity, closing down the site involves removing infrastructure and ensuring the CO_2 is contained to avoid leaks. Operational and research experience over several decades demonstrates that injected CO_2 can be monitored to confirm its containment. In the unlikely event of a CO_2 leak, decades of experience in detecting and remediating CO_2 leaks can be drawn on. Techniques and technologies adopted from the oil and gas industry include emergency shutdown procedures and well recompletion and recementing. To date, there has been no significant leak of CO_2 from a CCS operation.[4]

Table C.23 Energy security indicators for carbon capture and storage

Geopolitical availability (score: 1)
CO_2 storage sites are present throughout Europe, with a concentration of sites in the form of storage reservoirs and hydrocarbon fields in northern Europe and saline aquifers, which represent about 98% of all potential CO_2 storage capacity,[5] found all over Europe. The widespread availability of CO_2 storage sites across Europe[6] means there is little risk with regards to geopolitical availability.
Abundance (score: 1)
The materials required for CCS are mainly in piping, which is made from steel. This is considered abundantly available, hence not critical. Solvents are used from a variety of chemical feedstock, such as H_2, N_2, O_2 and ethylene. Some of these feedstocks are produced from petrochemical feedstocks, but there are alternative renewable pathways for producing these feedstocks. Other CCS technologies use membranes to separate CO_2, which are polymers and often produced from petrochemical feedstock but could also be produced from bio-based feedstock. The material abundance risk associated with CCS is scored low. Regarding CCS locational abundance – in other words possible storage sites – there is also a wide abundance in Europe. Storage capacity for CCS globally is approximately 13 000 Gt.[5] For the EU, total CO_2 storage capacity is approximated at 117 Gt.[6] In comparison, EU carbon dioxide emissions from fossil fuel combustion for energy use was about 2.4 Gt in 2022, according to Eurostat estimates. The risk of running out of storage capacity for the foreseeable future is therefore low, hence is scored 1.
Circularity (score: 1)

Pipelines made from steel can generally be recycled after their service life. With respect to the use of old gas/oil fields, CCS is a technology that repurposes these sites and permanently closes these them once CCS storage capacity has reached its maximum. Currently, there is no other use for completed CCS storage sites.

Regarding circularity risk, this is evaluated at 1.

Supply chain complexity (score: 1)

There is relatively little supply chain complexity related to CCS. The materials required for capture, transport and storage are readily available and do not depend on CRM.

With regards to the transport, pipelines transport CO_2 to the permanent storage facility. These pipelines are often made from steel. Transport can also be done by shipping, which requires shipping tankers.

With regards to the location of storage facilities, there is a concentration in the North Sea and several hotspots in eastern Europe. Many smaller sites can be found across Europe. However, due to a lack of abundant CCS sites in southern Europe, cooperation between EU Member States and other European countries should be established to enable CCS across the whole of Europe.

Methods employed in construction and use phases are well established, therefore there is no extraordinary risk involved.

Supply chain location (score: 1)

The bulk material used for CCS technology is in the pipelines, which are made from steel. This material is not considered critical. The capture phase requires solvents, which could be based on petrochemical or bio-based feedstock. Either way, these feedstocks are not considered critical with respect to locational dependence.

Digital vulnerability (score: 2)

Most offshore gas platforms (on the North Sea) are remotely controlled using glass fibre cables. There is a risk of hackers taking over control, which in this context may also be a CSS platform.

Physical vulnerability (score: 2)

Sabotage

Some CCS projects involve undersea infrastructure, such as pipelines to transfer CO_2 from land to undersea gas fields. Similar to undersea cables and natural gas pipes, we anticipate that these pipelines are equally vulnerable to sabotage.

Unintentional damage

Undersea gas pipes may also be damaged unintentionally, for example by anchors passing CSS infrastructure.

Broader sustainability (score: 3)

One of the most frequently applied methods to inject CO_2 into storage sites is enhanced oil recovery.[2] Therefore, using CO_2 for enhanced oil recovery could lead to more oil extraction, offsetting the climate benefits of storing CO_2. Methods such as storing CO_2 in saline formations, or in old oil or gas fields, are not associated with enhanced fossil fuel extraction and are therefore preferred for CCS. However, due to the technological maturity of enhanced oil recovery, it could be a transitional technology until alternative become more technologically developed.

Offshore CCS projects may affect marine ecosystems

Marine carbon storage poses risks to local biodiversity and marine ecosystems. Construction of offshore CCS projects may also cause damage to marine ecosystems.[7]

Risk of leakage

There are concerns over potential CO_2 leakages during the operational and closure phases of CCS. Leakage of stored CO_2 can destroy groundwater, plant life and soil quality and contribute to global warming. However, as decades of CO_2 storage experience has indicated, there is little risk of CO2 leaking, hence storage of CO_2 in geological formations is considered safe. A special report by the Intergovernmental Panel on Climate Change concluded that 'appropriately selected and managed geological reservoirs are very likely" to retain over 99% of the sequestered CO_2 for longer than 100 years and "likely" to retain 99% of it for longer than 1 000 years".[1,7]

Seismic activity

Trapping CO2 underground may lead to seismic activity. Particularly in populated areas, underground CCS may face public opposition.[7]

Risks of fossil fuel lock-in

There are concerns that CCS may lead to reinforced fossil fuel lock-in since CCS may reduce the need to transition from a fossil fuel-based economy to a renewable energy economy.

Affordability (score: 3)

CCS is a technology with limited financials revenues. Carbon markets could play a role in generating revenues for CCS, especially where negative emissions are involved. The avoided emissions from power or industrial plants equipped with carbon capture facilities reduce emissions costs relating the EU-ETS. As the cost of emissions via the EU-ETS rises, CCS becomes financially more attractive. However, in general CCS projects are not lucrative cash generating endeavours, hence subsidy is required.

CAPEX

CCS projects are very costly. For example, the capital required to construct the infrastructure for a project in the Netherlands called Porthos, which will store 37 Mton of CO_2, is about EUR 500 million. In the Netherlands, the subsidy intensity per ton of CO_2 is in the range of EUR 146–265/ton CO2.[8]

Skills (score: 2)

Increased deployment of CCS projects will increase demand for skilled personnel to construct, operate and maintain these projects. The IEA estimates that at least 1 200 direct construction jobs could be created at each new large-scale capture facility, and potentially more than 4 000 depending on location, application and size.[9]

9.11.1.5. Bibliography

1 Global CCS Institute. (2022). Global Status of CCS 2022. https://status22.globalccsinstitute.com/wp-content/uploads/2023/03/GCCSI_Global-Report-2022_PDF_FINAL-01-03-23.pdf

2 European Commission. (2022). Carbon Capture Utilisation and Storage in the European Union. https://setis.ec.europa.eu/carbon-capture-utilisation-and-storage-european-union_en

[3] Shen, M., Kong, F., Tong, L., Luo, Y., Yin, S., Liu, C., Zhang, P., Wang, L., Chu, P. K., & Ding, Y. (2022). Carbon capture and storage (CCS): development path based on carbon neutrality and economic policy. Carbon Neutrality, 1(1), 37. https://doi.org/10.1007/s43979-022-00039-z

[4] Global CCS Institute. (2023). Where is CO2 Stored and How Do We Know it Works? https://co2storageresourcecatalogue.com/wp-content/uploads/2021/05/10365GLOB_CSRC_CYCLE-2_2020_v3.0.pdf

[5] Pale Blue Dot. (2021). CO2 Storage Resource Catalogue – Cycle 2. https://co2storageresourcecatalogue.com/wp-content/uploads/2021/05/10365GLOB_CSRC_CYCLE-2_2020_v3.0.pdf

[6] K. L. Anthonsen, N. P. C. (2021). EU Geological CO_2 storage summary. https://cdn.catf.us/wp-content/uploads/2021/10/20183953/EU-CO2-storage-summary_GEUS-report-2021-34_Oct2021.pdf

[7] Wilberforce, T., Baroutaji, A., Soudan, B., Al-Alami, A. H., & Olabi, A. G. (2019). Outlook of carbon capture technology and challenges. Science of the Total Environment, 657, 56-72. https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.11.424

[8] PBL. (2023). Eindadvies basisbedragen SDE++ 2023. https://www.pbl.nl/publicaties/eindadvies-basisbedragen-sde-2023

[9] IEA (2021), Global Energy Review 2021, IEA. License: CC BY 4.0. Paris https://www.iea.org/reports/global-energy-review-2021

9.12. Electricity and heat storage: batteries

Batteries are an important part of many (portable) devices and are essential for a future sustainable energy system. In energy systems, batteries have two important functions: energy balancing and reducing network congestion. Batteries are used in response to energy prices, charging at low prices and discharging when prices are high. In this way, batteries can help balance supply and demand at any moment, ensuring a reliable energy system. Batteries can also resolve grid congestion by charging and discharging at required moments, thereby reducing the peak load on the electricity network.

A wide range of chemistries and materials are employed in battery manufacturing. The evaluation of the battery value chains focuses on four primary groups, each with key battery technologies that are crucial to shaping the future energy landscape in Europe, as outlined below:

- Batteries that contain several CRM:
    - Lithium-ion (Li-ion), used in EVs, electronic devices and grid storage
    - Li-based solid-state batteries
    - Mg-ion (substitute for Li-ion, better recycling capabilities)
- Batteries without CRM:
    - Ni-Cd
    - Sodium-ion (Na-ion)
    - Sodium-ion (Na-ion) saltwater
    - Sodium-sulphur room temperature
    - Zinc-air (Zn-air)

  - Zinc-ion (Zn-ion)
  - Aluminium-ion (Al-ion)
- Redox flow batteries:
  - Vanadium
  - Iron-chromium
  - Zinc-bromine
  - Organic
- Molten salt batteries:
  - Sodium-sulphur high temperature
  - $Na\text{-}NiCl_2$

9.12.1. Batteries that contain several CRM

Batteries that contain CRM are energy storage devices that rely on materials considered essential for their functionality and production. The technologies assessed in this category are: Li-ion, Li-based solid state batteries, Mg-ion. These CRM include elements like lithium, cobalt, natural graphite, Mg and rare earth metals. Lithium batteries are commercially used for EVs and grid energy storage, whereas Li-based solid state and Mg-ion batteries are promising alternatives to EV batteries with lower TRLs. The use of these materials has raised concerns over their availability, ethical sourcing and environmental impact. Efforts are being made to reduce dependence on these critical materials through recycling, alternative chemistries and sustainable mining practices, to ensure a more secure and environmentally responsible energy storage future.[1,2]

Cobalt (Co), natural graphite and lithium (Li) are key components of Li-ion batteries. Magnesium is the charge carrier in Mg-ion batteries and is very promising, due to potentially higher energy densities with a magnesium chemistry instead of lithium. Many CRM present in these batteries, such as like Li, Co and Mg, are mined and produced outside the EU, which poses a supply risk.[3] Production of these batteries is also located largely outside the EU, with China and other Asian countries such as South-Korea and Japan playing a major role on a global scale.[4]

The basic working principle of the above-mentioned battery technologies is the charge and discharge of charge carriers (Li- or Mg-ions) between the anode and cathode of a battery cell. During charging, the charge carriers migrate from the anode through the electrolyte and separator to the cathode; and vice-versa during discharge. Electrons flow through an external circuit.

9.12.1.1. Characteristics

Role in EU energy system: Li-ion and lead-acid batteries are widely used in the EU in consumer electronics, EVs, and as storage devices for renewable energy. In applications where light weight and high energy density are required, Li-ion will likely remain dominant for the foreseeable future. In large-scale energy storage applications, Li-ion can be applied for storage on a timescale of hours. For energy storage of days or more, other technologies are more applicable and cost effective.

The EU industry has invested significantly in the batteries value chain. Since the inception of the European Battery Alliance in 2017, the EU has generated investments exceeding EUR 100 billion (mostly in the application segment and battery cell segment).[1]

Primary energy source: renewable energy, for example solar or wind energy.

TRL: Li-ion and lead-acid batteries are mature technologies with a TRL of 9.[1] Other lithium-based battery technologies, like Li-air and Li-metal, have a lower TRL rage of 4–8.[1] Mg-ion batteries have a TRL of 3–4.[1] Li-based solid-state batteries have a TRL range of 4–7.[5]

9.12.1.2. Life cycle: construction phase

To produce Li-ion batteries, raw materials are needed for production of electro(chemically) active materials (e.g. Li, Co, Mn, Al, Ni, graphite). Production steps require advanced machinery, skilled labour and generally have very high energy consumption. Alternatively, recycled materials can be used.[6]

Mg-ion batteries are considered a drop-in technology, meaning contemporary cell design and assembly of Li-ion batteries can be replaced with minimal alterations. Mg-ion cell manufacturing is considered less energy-intensive and less toxic than equivalent processes with Li-ion batteries.[6]

9.12.1.3. Life cycle: use phase

During the use of Li-ion batteries, there is no additional material requirement. Thermal management systems are common with Li-ion batteries requiring electrical energy. Furthermore, batteries lose energy due to the conversion of AC to DC-current, for example. For Li-ion batteries, round-trip efficiency is 85% and energy loss thus 15%.[1]

9.12.1.4. Life cycle: end-of-life

Li-ion batteries are largely recycled. In the last few years, many novel recycling initiatives have been initiated in Europe to reduce material dependence on Li and other critical materials like cobalt.[6]

Table C.24 Energy security indicators for CRM-containing batteries

Geopolitical availability (score: 3)
Batteries containing CRM have inherent supply chain risk. Globally, China is the largest lithium supplier (56%). Further down the supply chain, China controls 80% of the world's Li-ion battery raw material refining capacity and 75% of all battery cell manufacturing capacity.[3] Most of Europe’s imports came from China, followed by South Korea and the United States. While

Europe is responsible for 19% of global EV production, it controls very little of the upstream supply chain (except cobalt processing), since Europe lacks the natural resources required for batteries.[3] For example, cobalt is primarily mined in the D.R. Congo (63%), which is associated with unstable political conditions and various business difficulties. Lithium, a crucial element in Li-based batteries, is considered a CRM by the EU, since production is dominated by China (56%).[3]

The CRM used in batteries that contain several CRM and their relative geopolitical availability are as follows:

- Li (3)
- Co (3)
- Graphite (2)

Since the average score for these materials is 3, this is the overall score assigned to this indicator.

Abundance (score: 2)

Global lithium reserves are estimated at 21 000 000 Mton,[3] with global annual production in 2022 at around 130 000 Mton, excluding recycling.[7] The EU estimates that Europe will need 18 times more lithium in 2030 than in 2020 and 60 times more in 2050. Assuming other parts of the world will also drastically increase their lithium requirement, the pressure on lithium supply will clearly increase in the coming years.

Demand for cobalt has increased in the last few years, pushing the market to reduce the cobalt content of batteries. However, with many battery technologies (largely in e-mobility sector) still dependent on cobalt, demand in the period 2006–2021 increased continually.[4] One prognosis showed that cobalt will have a significant supply deficit by the year 2028.[8] Dependency on D.R. Congo for the raw supply of cobalt, combined with ever-increasing demand, means that cobalt introduces significant risk in the value chain of batteries with CRM.

In the case of global production of natural graphite, supply is concentrated predominantly in China. However, synthetic graphite is a viable substitute for natural graphite so the supply risk for graphite can be considered moderate.

The abundance of several above-mentioned CRM is questionable, hence they provide a medium risk.

Circularity (score: 2)

There is a growing need for capacity to recycle Li-ion batteries. Since there is no CRM supply of Li, Co or graphite in Europe, recycling will play a critical role in the production of batteries with CRM. The upstream raw materials segment remains the least resilient of the battery value chain, and spent batteries are still mostly sent to Asia for recycling. The EU has taken steps to increase its capacity to recycle batteries containing CRM. EU recycling capabilities will strengthen especially in 2030 perspective, covering 40% of needs in 2025 and 70% in 2030.[1]

Given the current dependence on CRM sourced from outside the EU, but significant developments towards recycling of batteries, the overall score on circularity is average.

Supply chain complexity (score: 2)

Globally, China is the main producer of Li-ion batteries.[9] Increased efforts on recycling Li-ion and other types of battery would make Europe less dependent on countries like China and D.R. Congo, who are major producers of most of the CRM needed for production of Li-ion batteries. For now, the most important supply chain complexities are the lower price of Li-ion batteries from

China and lack of raw resources in Europe. As long as China's prices are more competitive, European-made batteries (mainly from recycling) will continue to struggle to reach the market. Since the European continent lacks the raw resources for battery production, it will remain critically depended on the global market. Since the mining, refining and production of CRM are geographically diverse, supply chain complexity is scored medium.

Supply chain location (score: 3)

To produce Li-ion batteries, several raw materials are required: Li, Co, Mg, Al, Ni and graphite. The first three and graphite are considered critical because of their geographically concentrated origin and scarce availability/absence in Europe. Practically all the world's lithium mining is located in just four countries: Australia (55%), Chile (23%), China (9.7%) and Argentina (8.3%).[7] Chile has the biggest known reserves, followed by Australia, Argentina and then China. China refines most Australian lithium and is therefore the biggest producer of refined lithium. Most of the manufacturing of Li-ion batteries (among other batteries) occurs in China.

Cobalt is mainly sourced from D.R. Congo (63%) with no European sources, and so also is considered critical. Graphite is largely produced in China (67%) but there are some European locations where graphite is produced: Ukraine (1.2%), Norway (1%), Germany (<0.1%) and Austria (<0.1%).

Because most raw materials used for batteries are sourced from one or few countries whose relations with the EU are politically questionable, location risk to the supply chain for batteries with CRM is scored 3.

Digital vulnerability (score: 2)

Stationary batteries are controlled by software and respond to price signals from the market. If all batteries were suddenly turned on or off, this would pose a significant challenge to the energy system. Because this risk is present, however unlikely, a score of 2 is assigned.

Physical vulnerability (score: 1)

Although sabotage and extreme weather events can never be excluded, there is no particular physical risk for this technology compared to other value chains, and the damage resulting from physical events will probably be limited. Therefore, a score of 1 is assigned.

The fire risk associated with Li-ion batteries is a critical concern. EVs are known to be very hard to extinguish when they start burning. Solid-state batteries are claimed to be safer in this regard. Since Li-ion EVs are widely adopted in the EU, there is a certain inherent risk of the possibility and consequences of fires. A ship carrying hundreds of EVs recently burned for several days off the coast of Netherlands, with significant risk to the environment and people living near the coast should it have capsized.

Broader sustainability (score: 3)

Working conditions in mining operations are one of the key SDG-related risks associated with batteries with CRM. D.R. Congo is an infamous example of the very poor mining conditions often associated with CRM.

Lithium mining is also associated with harmful environmental effects, including exacerbated droughts, pollution and contamination of water and soils.

The sustainability risks associated with working conditions in CRM mines and their environmental impacts are dire and locally significant – therefore the broader sustainability risk is given the highest score of 3.

The global warming potential/GWP (equivalent CO_2 emission/kWh of battery produced) of Li-ion batteries produced for EVs ranges from 30 to 200 $kgCO_2e/kWh$.[10,11]

Affordability (score: 1)

The cost of batteries with CRM has fallen drastically over the last decade. Wide adoption, especially in the e-mobility sector, has contributed to this decrease.[1,9]

Li-ion batteries have a LCOE of 90–175 EUR/kWh and are considered the most affordable of various battery technologies, [1,6] hence is scored a 1.

Skills (score: 2)

The increasing labour demand in the electrical energy sector is expected to be a limiting factor for the adoption of this technology. The EU faces a shortage of skilled workers in this industry. Other developments, such as the installation of solar PV, heat pumps, and broader electrification of homes and businesses, increase demand and put pressure on the available workforce in this sector. Since this introduces a certain risk regarding the implementation of this technology, this risk category is scored 2.

9.12.1.5. Bibliography

[1] European Commission. (2022). Batteries for energy storage in the European Union. https://setis.ec.europa.eu/batteries-energy-storage-european-union_en

[2] Lebrouhi, B. E., Baghi, S., Lamrani, B., Schall, E., & Kousksou, T. (2022). Critical materials for electrical energy storage: Li-ion batteries. Journal of Energy Storage, 55, 105471. https://doi.org/https://doi.org/10.1016/j.est.2022.105471

[3] BloombergNEF. (2022). China's Battery Supply Chain Tops BNEF Ranking for Third Consecutive Time, with Canada a Close Second. https://about.bnef.com/blog/chinas-battery-supply-chain-tops-bnef-ranking-for-third-consecutive-time-with-canada-a-close-second

[4] J. Huisman, T. C., F. Mathieux. (2020). RMIS – Raw materials in the battery value chain. https://publications.jrc.ec.europa.eu/repository/handle/JRC118410

[5] Mandade, P., Weil, M., Baumann, M., & Wei, Z. (2023). 'Environmental life cycle assessment of emerging solid-state batteries: A review'. *Chemical Engineering Journal Advances*, 13, 100439. https://doi.org/https://doi.org/10.1016/j.ceja.2022.100439

[6] Fraunhofer. (2023). Europe expands recycling of lithium-ion batteries: Focus on capacity development, demand analysis and market players.

[7] Statista. (2023). Mine production of lithium worldwide from 2010 to 2022. https://www.statista.com/statistics/606684/world-production-of-lithium/

[8] Alves Dias, P., Blagoeva, D., Pavel, C. and Arvanitidis, N. (2018). Cobalt: demand-supply balances in the transition to electric mobility. https://publications.jrc.ec.europa.eu/repository/handle/JRC112285

[9] Marjolin, A. (2023). Lithium-ion battery capacity to grow steadily to 2030. https://www.spglobal.com/marketintelligence/en/news-insights/research/lithium-ion-battery-capacity-to-grow-steadily-to-2030

[10] MIT. (2022). How much CO2 is emitted by manufacturing batteries? https://climate.mit.edu/ask-mit/how-much-co2-emitted-manufacturing-batteries

[11] Transport & Environment. (2023). How to guarantee green batteries in Europe. https://www.transportenvironment.org/wp-content/uploads/2023/04/2023_04_Battery_carbon_footprint_position_paper.pdf

9.12.2. Batteries without CRM

Batteries without CRM are energy storage devices designed to reduce or eliminate reliance on materials considered scarce, ethically challenging to source, or environmentally detrimental. These batteries often employ chemistries and materials that are more abundant and sustainable. The batteries assessed under this category are metal-ion batteries (Na-ion, Zn-ion, Al-ion), Na-ion saltwater, zinc-air (Zn-air) and sodium-sulphur (Na-S) room temperature. By avoiding CRM like cobalt, lithium and rare earth metals, these batteries aim to provide a more environmentally friendly and ethically sound solution for energy storage. They also work towards enhancing the security and sustainability of battery production and use, especially in the context of EVs and renewable energy systems.

The working principle and structure of metal-ion batteries are similar to those of Li-ion, but use an alternative charge carrier instead of Li. The basic working principle of metal-ion batteries is the charge and discharge of metal-ions between anode and cathode. During charging, the metal-ions migrate from the anode through the electrolyte and separator to the cathode, and vice versa during discharge. Electrons flow in the same direction as with Li-ions, but through an external circuit since they cannot pass through the separator between the electrodes.

Other alternative battery categories, with different working principles, are beyond the scope of this assessment.[1]

9.12.2.1. Characteristics

Role in EU energy system: The application of batteries without CRM depends on energetic characteristics and use-cases of the various battery types under this category. Due to low-cost, high energy storage potential and abundance of resources, technologies like Na-ion saltwater, Zn-ion, Na-S room temperature and Zn-air make sense for use in stationary applications over longer timescales – for example for seasonal storage. Al-ion batteries are particularly interesting wherever rapidly changing energy and power are required, for example for grid stabilisation in smart grids. Widespread application in the EU of alternative battery technologies with high TRLs (Na-ion saltwater, Na-ion, Na-S high temperature) is generally limited by higher costs or poorer performance, compared to Li-ion. Na-ion is very promising for similar applications as Li-ion and close to commercialisation – however, it doesn’t perform as well as Li-ion on energy capacity and cell voltage.

With respect to mobile applications, a battery technologies like Na-ion could be an interesting alternative due to their high energy density and high cycle stability characteristics.

Saltwater Na-ion batteries are already available on the market. Other technologies like Na-ion and Zn-ion are likely to be adopted in the near future for stationary applications, due to their high resource availability, safety and deep discharge capability. Al-ion, Zn-ion and Zn-air batteries are less well developed and not expected to be commercialised in the next few years.[1]

Primary energy source: renewable energy, for example solar or wind energy.

TRL:

- Na-ion: 8–9
- Na-ion saltwater: 9
- Na-S room temperature: 4
- Zn-ion, Al-ion: 2–4
- Zn-air: 2–4

9.12.2.2. Life cycle: construction phase

Na-ion (saltwater) batteries use raw materials that are much more abundant that those used in Li-ion batteries, and so have a lower material cost. Na, for example, is incomparably more abundant than Li, and aluminium, the anode current collector in Na-ion batteries, is more abundant that the cobalt used in Li-ion batteries. Overall, the material cost for Na-ion batteries is approximately 40–60% of that for Li-ion.[1]

For some technologies – like Na-S, Zn-ion, Al-ion and Zn-air batteries – there is currently no manufacturing and assembly on a considerable scale because of low TRLs.

9.12.2.3. Life cycle: use phase

There is no additional material requirement for the use phase for Na-ion batteries. Thermal management systems are common with Na-ion batteries requiring electrical energy. Furthermore, batteries lose energy, for example due to the conversion of AC to DC-current. The round-trip efficiencies of various battery technologies are as follows:

- Na-ion: 90%
- Na-ion saltwater: 75–98%
- Na-S room temperature: 70%
- Na-S high temperature: 70–80%
- Zn-ion: 80%
- Al-ion: 68–85%
- Zn-air: 55–65%

9.12.2.4. Life cycle: end-of-life

Generally speaking, batteries with high TRLs that contain no CRM, are more recyclable than Li-ion batteries. However, the recycling potential of lower TRL technologies is less evident.

Table C.25 Energy security indicators for batteries without CRM

Geopolitical availability (score: 1)
The CRM used in batteries without CRM and their relative geopolitical availability are considered good compared to batteries with CRM. Since the average score for these materials is 1, this is the overall score assigned to this indicator.
Abundance (score: 1)
There are very few or no CRM in the technology of batteries without CRM. Therefore, a score of 1 is assigned.
Circularity (score: 2)

Batteries without CRM imply little supply chain risk. This could mean either excellent availability of natural resources, or strong supply of recycled materials. A risk is identified for low-cost non-critical materials like Na, as their availability as a natural resource could hamper circularity practices for these types of batteries. From a circularity perspective, recycling should always be prioritised over extraction of raw natural resources.

Elements like the aluminium used in the current collector and cell casing should be recycled as production from recycled aluminium is around 90% less energy-intensive than from raw ores.

Zn-air are known to have excellent recyclability. The recycling of Zn-ion batteries is expected to only require minor modifications with respect to widely adopted primary Zn-batteries.

For Na-S batteries, circularity is expected to be unproblematic, but it should be noted that this technology is still being researched (TRL 4).[1]

Supply chain complexity (score: 2)

The lack of CRM in the value chain of batteries without CRM implies wider availability of resources, generally in the EU. However, current production and manufacturing of these batteries are not yet scaled. Metal-ion batteries like Zn-ion, Al-ion and Na-ion have similar production processes as Li-ion, for which manufacturing is largely concentrated in China, South-Korea and Japan. If metal-ion battery manufacturing is used as drop-in technology to replace Li based chemistries, dependence on these countries will persist. To establish secure supply chains for metal-ion batteries, supply chains and manufacturing should be set up in Europe to avoid the dependency associated with Li-ion battery technology. A crucial aspect of reducing the complexity of the supply chain is to increase recycling of these batteries.

Because of dependency relating battery manufacturing element of the supply chain, a score of 2 is assigned for this indicator.

Supply chain location (score: 1)

Sodium and sulphur are readily available in Europe, with significant production capacity and plenty of reserves. Zinc is mined and produced in Europe on a small to medium scale, with most supply from China. Aluminium is produced in Norway, which has relatively small natural reserves but significant recycling facilities. China is the biggest producer of aluminium.

Because materials in batteries without CRM are more readily available, a score of a is assigned for this indicator.

Digital vulnerability (score: 2)

Stationary batteries are controlled by software and respond to price signals from the market. If all batteries were suddenly turned on or off, this would pose a significant challenge to the energy system. Because this risk is present, however unlikely, a score of 2 is assigned.

Physical vulnerability (score: 1)

Although sabotage and extreme weather events can never be excluded, there is no particular physical risk for this technology compared to other value chains, and the damage resulting from physical events will probably be limited. The fire risk for most battery technologies under this category, is less than for lithium. Therefore, a score of 1 is assigned.

Broader sustainability (score: 1)

Batteries without CRM imply good availability of resources required for production. While this is an advantage in the context of supply security, it could pose a risk associated with broader sustainability. Low-cost resources like Zn, Na and saltwater can make recycling economically uninteresting. However, from a circularity and sustainability perspective, recycling/reuse should always be prioritised overuse of primary resources from mining or other extraction methods.

The global warming potential (GWP) per stored kWh is an important indicator to quantify emissions from a technology's production.[1] The GWP of batteries without CRM are:

- Na-ion: 50 to 90 kg CO_2eq/kWh
- Na-ion saltwater: 30–50 kg CO_2eq/kWh
- Na-S room temperature: no reliable data could be obtained
- Zn-ion: 20–100 kg CO_2eq/kWh
- Al-ion: no reliable data
- Zn-air: 22.1–95.2 kgCO_2eq/kWh

Affordability (score: 2)

Of the assessed battery technologies without CRM, only Na-ion has reached commercial application. Other technologies – Na-S at room temperature (Na-S RT), Al-ion, Zn-ion and Zn-air – have a lower TRL, meaning LCOEs are less certain or not reliable. LCOEs for these technologies in 2023, and as expected by experts in 2035 are:[1]

Na-ion

- 2023: 80–120 EUR/kWh
- Estimation 2035: <40 EUR/kWh (assuming large scale production)

Na-ion saltwater

- 2023: 880 – 1 000 EUR/kWh
- Estimation 2035: ~200 EUR/kWh (assuming large scale production)

Na-S room temperature:

No reliable data could be obtained.

Zn-ion

- Estimation 2025: 80 EUR/kWh
- Estimation 2030: 40–50 EUR/kWh

Al-ion

No reliable data could be obtained.

Zn-air

- 2023: 100–150 EUR/kWh
- Estimation long-term: 10 EUR/kWh

The affordability of batteries without CRM varies. Na-ion and Zn-air batteries are more affordable than Li-ion in terms of LCOE but have lower performance, and lower a TRL, respectively. Li-ion batteries are and will remain superior in terms of energy density, which is a crucial KPI for sectors like mobility and consumer devices. For large-scale energy storage in the EU, batteries without CRM like Na-ion and Zn-air could play a significant role in the future because of their affordability and more secure supply chain. Due to the lower energetic properties of batteries without CRM compared to Li-ion, but substantial research efforts being made, the score for the affordability of this battery category is scored 2.

Skills (score: 2)

The technologies covered in this assessment are widely researched around the world. Academia and research centres will play a crucial role in developing these technologies. Later, when production and industry take over, the skilled labour force will shift towards more logistical- and production-oriented workers. Robotics and automation will likely play a crucial role in the manufacturing and assembly processes of these batteries, helping to reduce production costs.

The increasing labour demand in the electrical energy sector is expected to be a limiting factor for the adoption of this technology. The EU faces a shortage of skilled workers in this industry. Other developments, such as the installation of solar PV, heat pumps, and broader electrification of homes and businesses, increase demand and put pressure on the available workforce in this sector. Since this introduces a certain risk regarding the implementation of this technology, this risk category is scored 2.

9.12.2.5. Bibliography

1 Fraunhofer (2023). Alternative Battery Technologies Roadmap 2030+. https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2023/abt-roadmap.pdf

9.12.3. Redox Flow Batteries

Redox flow batteries (RFB) store electrical energy in the form of fluid chemical solutions (electrolytes) within separate tanks. During operation, electrolytes flow through electrochemical cells where chemical reactions occur, producing electrical energy. These batteries are known for their scalability and large energy storage capacity, making them suitable for grid energy storage and renewable energy integration. RFBs typically have a round trip efficiency of 70% to 80%. They are often used in applications where long-duration energy storage and flexibility are important, although they have slightly lower energy efficiency compared to some other battery technologies, such as Li-ion. In RFB, energy and power can be scaled separately by scaling the electrolyte tanks (energy) and the electrode area in the battery cell (power). The future market relevance of RFBs for energy storage system applications will depend mainly on the price per stored kWh.[1,2]

9.12.3.1. Characteristics

Role in EU energy system: Redox flow batteries can help integrate intermittent renewable energy sources like solar and wind energy, by storing large electrical energy surpluses during periods of high generation, and releasing as needed, enhancing grid stability. The role of redox flow batteries in the EU energy system is expected to grow as the EU continues to prioritise renewable energy integration, grid stability and energy security while working towards its ambitious energy and climate targets. Redox flow battery systems with supply periods between 5 and 10 hours are typically used to buffer renewable energies (wind and solar)[2] – i.e., they can be fully charged or discharged within this time. In future, however, redox flow batteries with larger energy capacity will be able to store energy for multiple days, hence they have a different function from Li-ion batteries, which act on shorter timescales.

Primary energy source: intermittent renewable energy sources like solar and wind energy.

The most well-developed redox flow battery is based on vanadium and is commercially available with a TRL of 9. Other redox flow battery systems, such as zinc/bromine, iron/iron, iron/air or organic electroactive molecules, have lower TRLs than vanadium redox flow.

9.12.3.2. Life cycle: construction phase

Redox flow batteries are currently produced by expensive manual labour. Automated production processes and scale-ups are necessary to reduce costs.

9.12.3.3. Life cycle: use phase

RFB are designed to operate autonomously without additional material inputs. Repair, maintenance or replacement of components, such as electrolyte and membranes, could be required during its use phase. Temperature control systems are required for optimal functionality and performance of the system.

9.12.3.4. Life cycle: end-of-life

It is possible to recycle the chemical compounds in RFB electrolytes, but exact processes must be developed when the first large RFBs reach their end-of life. Recycling the battery cell or stack is more complicated. However, as no rare or critical materials are used here, it is less relevant than for some electrolytes. Tanks and tubes can be recycled with standard polymer and metal recycling methods.[3]

Table C.26 Energy security indicators for redox flow batteries

Geopolitical availability (score: 2)
Vanadium pentoxide is the main material for vanadium redox flow batteries. While vanadium is not a rare element, it is not mined in Europe. Supply of vanadium therefore depends on countries like China, Russia and South Africa. For this reason, alternative redox flow chemistries are being researched, which depend on less critical elements like Zn, Br, Fe or organic molecules. The non-weighted average score for the most common materials in redox flow batteries is 2.
Abundance (score: 1)
There is no vanadium production in Europe. Global vanadium reserve amount to around 26 Mt, of which 100 kt is mined annually. The largest supplier of vanadium is China (62%), followed by Russia (20%) and South Africa (11%).[4]
Circularity (score: 1)
Recycling the chemical compounds in RFB electrolytes is possible, but exact processes will need to be developed when the first large RFBs reach end-of life. The battery cells or stacks are more complicated. However, as no rare or critical materials are used, recycling is less relevant than for some electrolytes. Tanks and tubes can be recycled using standard polymer and metal recycling methods.[5]
Supply chain complexity (score: 2)

Supply chain location poses inherent risks for redox flow batteries based on vanadium chemistry. Alternative RFBs use materials that are less critical than vanadium, which would ease supply chain complexity. In theory, Europe could independently control more of supply chain for RFB systems with chemistries like Br, Fe, organic molecules and Zn.

With regards to the current dependency on vanadium, with promising potential for other RFB chemistries, the supply chain complexity score is evaluated at 2.

Supply chain location (score: 3)

The largest supplier of vanadium is China (62%), followed by Russia (20%) and South Africa (11%).[4]

Since there is a large locational dependence on a few countries, this criterium is scored a 3.

Digital vulnerability (score: 2)

Stationary batteries are controlled by software and respond to price signals from the market. If all batteries were suddenly turned on or off, it would pose a significant challenge to the energy system. Because this risk is present, however unlikely, a score of 2 is assigned.

Physical vulnerability (score: 1)

Although sabotage and extreme weather events can never be excluded, there is no particular physical risk for this technology compared to other value chains, and the damage resulting from physical events will probably be limited. Therefore, a score of 1 is assigned.

Broader sustainability (score: 1)

Due to the energy-intensive production of V2O5, vanadium RFBs have the biggest ecological footprint, with a global warming potential of 180 kg CO_2eq/kWh.[2]

For the lower TRL redox flow batteries in development, global warming potentials are lower; Zn/Br RFB: 160 kg CO_2eq/kWh; iron RFB: 75 kg CO_2eq/kWh.[3,5]

Affordability (score: 2)

Vanadium RFB system-level costs are approximately 430 EUR/kWh, of which 80% is due to material costs. In the long-term, it is expected that these costs could halve. For other chemistries, costs could potentially be significantly lower. Long-term costs of <25 EUR/kWh are anticipated for Fe-air RFB. Redox flow batteries are currently much less affordable than Li-ion, hence is scored a 3.[2]

Skills (score: 2)

The skilled workforce required for RFB is relatively low compared to other battery storage technologies like Li-ion. With the expected increase in large-scale storage capacity in Europe, the application and corresponding workforce for RFB is expected to increase simultaneously.[6]

The increasing labour demand in the electrical energy sector is expected to be a limiting factor for the adoption of this technology. The EU faces a shortage of skilled workers in this industry. Other developments, such as the installation of solar PV, heat pumps, and broader electrification of homes and businesses, increase demand and put pressure on the available workforce in this sector. Since this introduces a certain risk regarding the implementation of this technology, this risk category is scored 2.

9.12.3.5. Bibliography

[1] Fraunhofer. (2023). Europe expands recycling of lithium-ion batteries: Focus on capacity development, demand analysis and market players. https://www.isi.fraunhofer.de/en/blog/themen/batterie-update/recycling-lithium-ionen-batterien-europa-kapazitaeten-bedarf-akteure-markt-analyse.html
[2] Fraunhofer. (2023). Alternative Battery Technologies Roadmap 2030+. https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2023/abt-roadmap.pdf
[3] He, H., Tian, S., Tarroja, B., Ogunseitan, O. A., Samuelsen, S., & Schoenung, J. M. (2020). Flow battery production: Materials selection and environmental impact. Journal of Cleaner Production, 269, 121740. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.121740
[4] USGS. (2023). Mineral Commodity Summaries 2023. https://pubs.usgs.gov/publication/mcs2023
[5] Weber, S., Peters, J. F., Baumann, M., & Weil, M. (2018). Life Cycle Assessment of a Vanadium Redox Flow Battery. Environmental Science & Technology, 52(18), 10864-10873. https://doi.org/10.1021/acs.est.8b02073
[6] European Commission. (2023). Energy Storage - Underpinning a decarbonised and secure EU energy system. https://energy.ec.europa.eu/system/files/2023-03/SWD_2023_57_1_EN_document_travail_service_part1_v6.pdf

9.12.4. Molten Salt Batteries

Batteries using molten salts as an electrolyte must operate at high temperature. Globally abundant sodium (Na) is a key active material in these batteries, which are designed for large-scale energy storage applications such as grid energy storage, due to their high energy density, long cycle life and round-trip efficiency of about 85%.[1] (Dis)charge is in the range of a few hours, hence useful for applications such as grid support and load shifting. The basic working principle of a molten salt battery involves the movement of ions between electrodes through a molten salt electrolyte. High-temperature sodium-based batteries, such as sodium-chloride ($Na\text{-}NiCl_2$) and Na-S high temperature, are a potentially interesting alternative to large-scale Li-ion based energy storage, since sodium-based batteries are based on abundant non-critical raw materials (non-CRM).[1-3]

9.12.4.1. Characteristics

Role in EU energy system: Energy storage for grid support and load shifting, in the range of a few hours. Hence, they compete with the most dominant battery technology, Li-ion. The combination of long cycle life, low cost, abundant materials and considerable energy density means molten salt batteries have significant potential for large-scale grid energy storage. It should be noted that integrating batteries into the future global energy storage will almost certainly involve a multitude of chemistries and technologies, as no single battery technology is the perfect fit for every application.[3]

Primary energy source: renewable energy, for example solar and wind energy.

TRL: 9 – innovations in materials and cell design are likely to make significant reductions in capital costs possible, facilitating continued expansion of these technologies.[3]

9.12.4.2. Life cycle: construction phase

Molten salt batteries can be categorised into three material groups: sodium-sulphur, sodium-nickel-chloride, and liquid calcium batteries, where the names imply the respective materials used. The main investment is the nickel for the core of the cathode. Containers/frames are typically made of steel since they must withstand very high temperatures (300–500 °C). Separators/membranes are typically made of polymers or ceramic materials. Insulation material is required to maintain high operating temperatures.[2]

9.12.4.3. Life cycle: use phase

Due to high operating temperatures, these batteries require a continuous supply of heat and could take several hours, or up to a few days, to reach required operating temperatures.

This type of battery has an energy efficiency of about 85%.[1]

9.12.4.4. Life cycle: end-of-life

Molten salt batteries are characterised by long lifetimes, and therefore have many charge/discharge cycles. For example, in 2010 General Electric announced a Na-NiCl2 battery with a lifetime of 20 years. Batteries with end-of-life status are decommissioned because of lower efficiency, capacity and/or safety. Degradation of materials in contact with liquid sodium remains an issue with this type of battery.

The recycling industry for batteries is mostly concentrated in China and South-Korea, where the vast majority of batteries is produced.

Table C.27 Energy security indicators for molten salt batteries

Geopolitical availability (score: 1)
Molten salt batteries only require relatively easily sourced elements (Ni, Fe, Al, Na, S). These metals are sourced from many different countries, with no concentration in any geographical region.
Abundance (score: 1)
Widely available, in both Europe and elsewhere. Global supply is diverse.
Circularity (score: 1)
Materials used in molten salt batteries are fully recyclable. In general, the battery recycling industry is concentrated in China and South-Korea. Battery recycling in Europe is upcoming, for example Northvolt in Sweden.
Supply chain complexity (score: 1)
Materials used are widely available and often used in various industries. Supply of these materials is geographically diverse, hence there is no extraordinary risk in supply chain complexity.
Supply chain location (score: 1)

Aluminium is widely available, with main suppliers being Australia (28%), China (20.8%) and Guinea (18%). European suppliers are Greece (0.5%), Montenegro (0.2%), France (<0.1%) and Croatia (<0.1%).

Nickel is widely available, with main suppliers being Indonesia (26%), Philippines (14%) and Russia (10%). European suppliers are Finland (1.5%), Greece (1%), and Norway and Poland (<0.1%).

The origins of these metals are diverse, hence there is no extraordinary supply chain location risk.

Digital vulnerability (score: 1)

Although cyberattacks can never be excluded, there is no particular digital risk for this technology compared to other value chains, and the damage resulting from a cyberattack could probably be limited. Therefore, a score of 1 is assigned.

Physical vulnerability (score: 1)

Although sabotage and extreme weather events can never be excluded, there is no particular physical risk for this technology compared to other value chains, and the damage resulting from physical events will probably be limited. Therefore, a score of 1 is assigned.

Broader sustainability (score: 1)

One of the most widespread concerns regarding molten salt batteries is the high temperature requirement. A high temperature is required to maintain the molten state of electrochemically active components, but it also facilitates rapid the ion transport and reaction kinetics needed for reasonable power output. However, this heat could lead to accelerated degradation of material components, with potentially detrimental (or dangerous) side reactions, requiring more advanced (and often expensive) thermal management systems – and so significantly increasing cost and application space of the system. The high temperature also demands to stringent safety requirements for operators.

Affordability (score: 2)

The affordability of molten salt batteries depends on the technology used. On average, molten salt batteries have an LCOE of about 100–400 EUR/kWh.[1]

Stringent safety requirements (due to the high operating temperature) entail high system cost and materials that are stable and resistant to corrosion. Thermal management is another crucial aspect of the safe operation of this type of battery. Although the electrochemical active materials and components are abundantly available, hence no critical rare earth metals are used, the above-mentioned additional systems result in a high total cost of the system. Innovations in materials and cell design are likely to make significant reductions in capital costs possible, facilitating continued expansion of these technologies. Since the LCOE of molten salt batteries is currently higher than for Li-ion, it is scored a 2 on affordability.

Skills (score: 2)

Molten salt batteries have been a well-developed technology for many years.[2] There are several commercial players selling these types of systems. One of the most developed types, the Na-$NiCl_2$ battery – or ZEBRA type – has been installed at three places in Europe:

- FIAMM Green Energy Island, Italy (230 kWh, 180 kW)

- EDF EN Gabardone Project, France (70 kWh, 20 kW)

- Terna Storage Lab, Italy (10 000 kWh, 3 400 kW)

The increasing labour demand in the electrical energy sector is expected to be a limiting factor for the adoption of this technology. The EU faces a shortage of skilled workers in this industry. Other developments, such as the installation of solar PV, heat pumps, and broader electrification of homes and businesses, increase demand and put pressure on the available workforce in this sector. Since this introduces a certain risk regarding the implementation of this technology, this risk category is scored 2.

9.12.4.5. Bibliography

[1] Brinsmead, T., Graham, P., Hayward, J., Ratnam, E., & Reedman, L. (2015). Future energy storage trends: An assessment of the economic viability, potential uptake and impacts of electrical energy storage on the NEM 2015–2035.

[2] Armand, M. (2023). Salt Batteries: Opportunities and applications of storage systems based on sodium nickel chloride batteries. https://www.europarl.europa.eu/RegData/etudes/IDAN/2023/740064/IPOL_IDA(2023)740064_EN.pdf

[3] European Commission. (2022). Batteries for energy storage in the European Union. https://setis.ec.europa.eu/batteries-energy-storage-european-union_en

[4] Spoerke, E. D. (2020). Molten Sodium Batteries. https://www.osti.gov/servlets/purl/1763564

9.13. Electricity and heat storage: hydrogen

Electrolysis is the process of splitting of water into hydrogen and oxygen using electricity. Electrolysis using renewable electricity produces green hydrogen. This process takes place in electrolytic cells that are combined in a stack. There are currently four available technologies: alkaline, PEM (proton exchange membrane), AEM (anion exchange membrane) and solid oxide. Many variations of each technology are possible. In addition to the stack, an electrolyser has a balance of plant, consisting of power supply, water supply and purification, compression and hydrogen processing. Electrolyser technologies are in various stages of development, and none has reached the final development phase. Only 1% of the hydrogen produced globally is currently made through electrolysis. The main obstacles to large-scale development and use of electrolysis capacity are high investment cost for electrolyser systems (including equipment), availability of renewable electricity, and high renewable electricity prices, resulting in a high green hydrogen production cost price.

9.13.1. Alkaline electrolysis

Electrolysis uses two electrodes separated by an electrolyte. In Alkaline electrolysis, an electrolyte, typically a highly concentrated potassium hydroxide solution, transports the generated chemical charges from one electrode to the other. Electrodes and produced gases are separated by an inorganic diaphragm.[1] It has an operating temperature of 70–90 °C. One disadvantage of alkaline electrolysis is that the system is not well adapted to flexible system operation.

9.13.1.1. Characteristics

Role in EU energy system: Storage/energy carrier

Primary energy source: renewable electricity.

TRL: 8–9 for alkaline, which is the main technology currently applied in electrolysis and commercially available. It is generally assumed that alkaline electrolysis will be used until 2030.[2]

9.13.1.2. Life cycle: construction phase

Alkaline electrolysers consist mainly of stainless steel with a nickel coating or mesh/raney nickel. The frames and sealing are made of polysulfone (PSU), polytetrafluoroethylene (PTFE) and EPDM. Alkaline electrolysers can be manufactured without the use of the critical materials platinum and cobalt, but these are applied in some designs. Stacks are made mainly of nickel.

The amount of critical materials in an alkaline electrolyser is much lower than in other electrolysers.[1]

9.13.1.3. Life cycle: use phase

Alkaline electrolysers have a lifetime of around 30 years. Stacks, in which nickel is the main critical material, will typically need to be taken out for repair or renewal every 7 to 12 years.[1] Water impurity is an operational risk.

9.13.1.4. Life cycle: end-of-life

There are no known significant waste streams.

Table C.28 Energy security indicators for alkaline hydrolysis

Geopolitical availability (score: 1)
Nickel is relatively uncritical in supply. The largest supplier (Indonesia) has a 34% global market share.[3,4]
Abundance (score: 2)
Stainless steel, nickel. Nickel is moderately critical with regards to abundance. Alkaline electrolysers can be designed without platinum and cobalt (which are critical).
Circularity (score: 1)
No information, but unlikely to influence energy security. The facilities needed to produce hydrogen might be subject to circularity objectives.
Supply chain complexity (score: 1)
The supply chain to produce alkaline electrolysers is not characterised by high complexity. However, the manufacturing of electrolysers is a highly specialised industry.
Supply chain location (score: 1)
Nickel is globally available, with Indonesia, Russia and the Philippines as the primary producers. A dozen of companies manufacture alkaline electrolysers, including McPhy (France)

Hydrogenics (Canada), Teledyne (United States), NEL (Norway) and Wasserelektrolyse Hydrotechnik (Germany).[5]

Digital vulnerability (score: 2)

The value chain is not particularly affected by digital threats, but like all digitally connected applications, the operation of electrolysers might be vulnerable. As this value chain relies on large quantities of electricity, and the electricity system is vulnerable to cyberattacks, this value chain is also vulnerable. Therefore, a score of 2 is assigned to this energy security indicator.

Physical vulnerability (score: 1)

N/A.

Broader sustainability (score: 2)

Sustainable operation of electrolysers depends renewable electricity and pure water. The large amount of water needed might increase water scarcity.

Affordability (score: 3)

Operational costs depend on the number of operating hours and the electricity price. At maximum operating hours (8760 hrs), hydrogen production costs might be just under 2 EUR/kg, depending mostly on the electricity price.[1]

Capital costs currently amount to 500–1 000 USD/kW, which might decline to less than 200 USD/kW in 2050.

Skills (score: 2)

The production and installation of electrolysers requires technically skilled labour, which might not always be abundantly available. But this is not exactly a value chain risk because it depends mostly on the available workforce.

9.13.1.5. Bibliography

[1] IRENA (2020), Green hydrogen cost reduction, Abu Dhabi: IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

[2] JRC (2022), Water electrolysis and hydrogen in the European Union, Luxembourg: Publications Office of the European Union. https://setis.ec.europa.eu/hydrogen-electrolysis-european-union_en

[3] S. Kiemel, et al. (2021), Critical materials for water electrolysers at the example of the energy transition in Germany, Hoboken: Wile. https://onlinelibrary.wiley.com/doi/full/10.1002/er.6487

[4] M. Biegel, et al. (2022), Critical raw materials for electrolyser production. https://www.wasserstoff-kompass.de/fileadmin/user_upload/img/news-und-media/dokumente/Materials_for_Electrolysers_.pdf

[5] B. Yudwong, et al. (2020), AC-DC Converters for Electrolyzer Applications: State of the Art and Future Challenges, Basel: MDPI. https://www.mdpi.com/2079-9292/9/6/912

9.13.2. Proton exchange membrane electrolysis

Electrolysis uses two electrodes separated by an electrolyte. In proton (or polymer) exchange membrane (PME) electrolyser, a thin perfluorosulfonic acid (PFSA) membrane is used for separation. This is done under higher pressure than in an alkaline electrolyser and, therefore, requires robust materials, such as titanium-based materials, noble metal catalysts, and protective coatings. Consequently, a PEM electrolyser is more expensive than an alkaline one.

A PEM system requires circulation pumps, heat exchangers, pressure control and monitoring. An advantage of PEM electrolysis is that it can function under a variable power supply, making it better suited for volatile electricity generation such as wind and solar. It has an operating temperature of 50-80 °C. The complexity of the membrane and use of noble materials are disadvantages.[1,5]

9.13.2.1. Characteristics

Role in EU energy system: Storage/energy carrier

Primary energy source: N/A

TRL: PEM technology is commercially available, with a TRL of 8–9.[2]

9.13.2.2. Life cycle: construction phase

PEM electrolysers are made from stainless steel with platinum, titanium, gold and iridium. The most common membrane is made from a fluoropolymer copolymer (Nafion) with titanium plates.

The frames and sealing are made of PSU, polytetrafluoroethylene (PTFE) and ETFE.[1]

9.13.2.3. Life cycle: use phase

PEM electrolysers have a reported lifetime of 50 000 hours. Water impurity is an operational risk.

9.13.2.4. Life cycle: end-of-life

No significant waste streams.

Table C.29 Energy security indicators for PEM electrolysis

Geopolitical availability (score: 2)
Titanium sponge (a porous form of titanium created during the first stage of processing) is produced in few countries, but the supply risk of titanium is generally relatively low.[3] China was responsible for around 50% of global production in 2020, and thus the primary supply country, followed by Japan and Russia.[4] Iridium is a by-product of platinum and palladium, and its production fluctuates yearly. The main producers are South Africa and Russia, but there are also deposits in Canada and Scandinavia. Over 75% of platinum is produced in South Africa. Platinum and iridium have a risk of high concentration in just a few countries.[3]
Abundance (score: 3)
Titanium has a low to moderate supply risk. Platinum and iridium have a high risk. Iridium is very rare in the earth's crust.[3]

Circularity (score: 1)
The facilities needed to produce hydrogen may be subject to circularity objectives.
Supply chain complexity (score: 2)
The supply chain to produce PEM electrolysers is moderately complex, related to geopolitical availability and company concentration. The manufacturing of electrolysers is a highly specialised industry.
Supply chain location (score: 2)
Platinum and Iridium: South-Africa, Russia. Titanium: China, Japan, Russia.
Digital vulnerability (score: 2)
The value chain is not particularly affected by digital threats, but, like all digitally connected applications, the operation of electrolysers might be vulnerable. As this value chain relies on large quantities of electricity, and the electricity system is vulnerable to cyberattacks, this value chain is also vulnerable. Therefore, a score of 2 is assigned to this energy security indicator.
Physical vulnerability (score: 1)
N/A.
Broader sustainability (score: 2)
The sustainable operation of electrolysers depends on the availability of renewable electricity and a sustainable supply of pure water. The large amount of water needed could increase water scarcity. Under the EU chemicals strategy for sustainability, PFAS (of which fluoropolymers are a subcategory) might be restricted. This would pose a serious problem for the production of fluoropolymer membranes in PEM electrolysers, as there is currently no alternative to PFAS.[6]
Affordability (score: 3)
Operational costs depend on the number of operating hours of the electrolyser and electricity price. At maximum operating hours (8760 hrs), hydrogen production costs might be just under 2 USD/kg.[1] Capital costs amount to 700–1 400 USD/kW (minimum 10 MW), which could fall to less than 200 USD/kW in 2050.
Skills (score: 2)
The production and installation of electrolysers requires technically skilled labour, which might not always be abundantly available. But this is not exactly a value chain risk because it depends mostly on the available workforce.

9.13.2.5. Bibliography

1 IRENA (2020), Green hydrogen cost reduction, Abu Dhabi: IEA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

2 JRC (2022), Water electrolysis and hydrogen in the European Union, Luxembourg: Publications Office of the European Union. https://setis.ec.europa.eu/hydrogen-electrolysis-european-union_en

3 S. Kiemel, et al. (2021), Critical materials for water electrolysers at the example of the energy transition in Germany, Hoboken: Wiley. https://onlinelibrary.wiley.com/doi/full/10.1002/er.6487

4 M. Biegel, et al. (2022), Critical raw materials for electrolyser production. https://www.wasserstoff-kompass.de/fileadmin/user_upload/img/news-und-media/dokumente/Materials_for_Electrolysers_.pdf

5 Hydrogen Europe (2023), Position paper on PFAS, the importance of fluoropolymers across the hydrogen value chain, and impacts of the proposed PFAS restriction for the hydrogen sector, Brussels: Hydrogen Europe. https://hydrogeneurope.eu/wp-content/uploads/2023/02/Hydrogen-Europe-position-paper-on-PFAS-ban_v12_FINAL.pdf

9.13.3. Solid oxide electrolysis

Solid oxide electrolysis, like other electrolysers, uses electrodes separated by an electron-insulating electrolyte – but it operates at very high temperatures (700–850 °C), allowing the use of relatively cheap nickel electrodes, low electricity demand and, potentially, waste heat. It can also be coupled with solar systems supplying both electricity and heat. This makes a solid oxide electrolyser (SOE) very energy efficient. On the other hand, a fluctuating operating regime leads to faster degradation of materials. SOEs only exist in lab environments and only a few original equipment manufacturers (OEMs) produce them.[1]

9.13.3.1. Characteristics

Role in EU energy system: Storage/energy carrier.

Primary energy source: N/A

TRL: 3–5 (our estimate).

9.13.3.2. Life cycle: construction phase

Electrodes and catalysts are made of perovskite (a calcium titanium oxide mineral, like LSCF or LSM), nickel and/or yttria-stabilised zirconia (YSZ), the doping material, which consists of scandium. Transport layer anodes are made of coarse nickel mesh or foam. Bipolar plate cathodes are made of cobalt-coated stainless steel, and frames and sealing are made of ceramic glass.[1]

9.13.3.3. Life cycle: use phase

SOE can reach lifetimes of 20 000 hours but requires stable supply and production conditions to operate. Flexible operation can decrease lifetime. The lifetime could increase to 80 000 hours by 2050.[1] Water impurity is an operational risk.

9.13.3.4. Life cycle: end-of-life

N/A

Table C.30 Energy security indicators for solid oxide electrolysis

Geopolitical availability (score: 3)
Currently, almost 95% of the critical materials necessary for SOE production are sourced from China. China also produces 75% of the world's scandium, while Russia and the Philippines have other known deposits.[1,2]
Abundance (score: 2)
SOEs require several critical materials, of which scandium poses the biggest problem in terms of abundance. Demand for scandium is expected to exceed production levels in 2040, although new deposits (e.g. in Australia) might be unlocked.[2]
Circularity (score: 1)
No research has been published on this subject, but the facilities needed to produce hydrogen might be subject to circularity objectives.
Supply chain complexity (score: 2)
The geopolitical availability of materials complicates the supply chain.
Supply chain location (score: 1)
EU manufacturers are in Denmark, Italy and Germany, but SOE is not yet produced for the market.[1]
Digital vulnerability (score: 2)
The value chain is not particularly affected by digital threats, but, as with all digitally connected applications, the operation of electrolysers might be vulnerable. As this value chain relies on large quantities of electricity, and the electricity system is vulnerable to cyberattacks, this value chain also vulnerable. Therefore, a score of 2 is assigned to this energy security indicator.
Physical vulnerability (score: 1)
N/A.
Broader sustainability (score: 2)
The sustainable operation of electrolysers depends on the availability of renewable electricity and pure water. The large amount of water needed might increase water scarcity.
Affordability (score: 2)
Information on affordability is not available, as the development of SOE is a long way from commercial operation.
Skills (score: 2)

The production and installation of electrolysers requires technically skilled labour, which might not always be abundantly available. But this is not exactly a value chain risk because it depends mostly on the available workforce.

9.13.3.5. Bibliography

[1] IRENA (2020), Green hydrogen cost reduction, Abu Dhabi: IEA https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

[2] S. Kiemel, et al. (2021), Critical materials for water electrolysers at the example of the energy transition in Germany, Hoboken: Wiley, https://onlinelibrary.wiley.com/doi/full/10.1002/er.6487

9.13.4. Anion exchange membrane electrolysis

In AEM electrolysis, as in other electrolysers, electrodes are separated by an electron-insulating electrolyte. The AEM electrolyser combines alkaline media with solid electrolytes. AEM technology is still in the research stage and suffers from chemical and mechanical stability problems. It operates at moderate temperatures (40–60 °C) and has a similar mode of operation to PEM. It is the least developed electrolysis technology and a long way from commercial deployment.[1,2]

9.13.4.1. Characteristics

Role in EU energy system: storage/energy carrier

Primary energy source: N/A

TRL: 3–5.[2]

9.13.4.2. Life cycle: construction phase

The AEM electrolyser consists of nickel-coated stainless steel with a solid electrolyte separator and DVB polymer electrolytes, with specific material as KOH or $NaHCO_3$ 1 mol L^{-1}. Oxygen and hydrogen side catalysts are both made of high surface area nickel. Frames and sealing are made of PTFE and silicon.

There still significant uncertainties over the exact components, since research continues to search for anion exchange membrane with suitable properties.[1]

9.13.4.3. Life cycle: use phase

Due to uncertainty over chemical and the mechanical instability of AEM, the lifetime of an AEM electrolyser is very short (<5 000 hrs). This could increase to 100 000 hours in 2050.[1] Water impurity is an operational risk.

9.13.4.4. Life cycle: end-of-life

N/A.

Table C.31 Energy security indicators for AEM electrolysis

Geopolitical availability (score: 1)
AEM electrolysis does not use extensive critical materials except nickel, which does not entail a high geopolitical availability risk.[1,3]
Abundance (score: 2)
The supply of nickel is moderately critical in terms of abundance. The largest supplier (Indonesia) has a 34% market share.[3,4]
Circularity (score: 1)
Unknown, but the facilities needed to produce hydrogen may be subject to circularity objectives.
Supply chain complexity (score: 2)
Unknown, due to uncertain design. Once the AEM electrolyser design has been established, the supply chain might not be very complex.
Supply chain location (score: 1)
EU manufacturers are located in Denmark, Italy and Germany, but production is only for R&D purposes.[1]
Digital vulnerability (score: 1)
The value chain is not particularly affected by digital threats, but, like all digitally connected applications, the operation of electrolysers might be vulnerable.
Physical vulnerability (score: 1)
N/A.
Broader sustainability (score: 2)
The sustainable operation of electrolysers depends on the availability of renewable electricity and pure water. The large amount of water needed might increase water scarcity.
Affordability (score: 2)
Information on affordability is unavailable as the development of AEM is far from commercial operation.
Skills (score: 2)
The production and installation of electrolysers requires technically skilled labour, which might not always be abundantly available. But this is not exactly a value chain risk because it depends mostly on the available workforce.

9.13.4.5. Bibliography

1 IRENA (2020), Green hydrogen cost reduction, Abu Dhabi: IEA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

2 JRC (2022), Water electrolysis and hydrogen in the European Union, Luxembourg: Publications Office of the European Union. https://setis.ec.europa.eu/hydrogen-electrolysis-european-union_en

3 S. Kiemel, et al. (2021), Critical materials for water electrolysers at the example of the energy transition in Germany, Hoboken: Wiley. https://onlinelibrary.wiley.com/doi/full/10.1002/er.6487

4 M. Biegel, et al. (2022), Critical raw materials for electrolyser production. https://www.wasserstoff-kompass.de/fileadmin/user_upload/img/news-und-media/dokumente/Materials_for_Electrolysers_.pdf

9.14. Renewable fuels of non-biological origin (RFNBOs)

9.14.1. Synthetic kerosene

Synthetic kerosene is made from green hydrogen and CO_2. Production involves electrolysis, direct air capture (DAC) or CO_2 capture from point sources, the reverse water gas-shift reaction (RWGS) and the Fischer-Tropsch process.

Synthetic kerosene can also be produced from methanol synthesis, but this technique has not been demonstrated at scale.

9.14.1.1. Characteristics

Role in EU energy system: energy carrier (production of hydrogen as a fuel is covered by Section 1.7)

In the maximum consumption scenario for the EU in 2050, aviation is projected to consume almost 20 Mtoe of e-liquids (including e-kerosene) – almost a third of the sector's total energy consumption.[1]

Primary energy source: renewable electricity.

TRL: 4–8 for the whole production chain.[2] The Fischer-Tropsch process has a TRL of 9 (in the fossil industry) but requires more development in other processes. RWGS has a TRL of 5–6.[3]

9.14.1.2. Life cycle: construction phase

Green hydrogen and CO_2 are needed to produce e-kerosene. Hydrogen is covered in Section 9.12. CO_2 can be extracted from a non-fossil point source or the air (DAC).[4-6] Use of fossil point sources of CO_2 will be prohibited from 2041 as per the Delegated Act on Recycled Carbon Fuels. At the same time, DAC is still low-TRL and very energy-intensive due to the relatively low concentration of CO_2 in the air and the high temperatures needed. The thermal energy required would be at least 250 kWh/tonne CO_2, but probably around 1000 kWh/tonne CO_2.

DAC can use both liquid and solid sorbent technology: air is put in contact with a potassium hydroxide solvent which forms potassium carbonate. Next, the potassium carbonate is heated to 900 °C to release CO_2. Alternatively, air is drawn into modular contractor units, after which the CO_2 is absorbed into a solid absorbent surface (typically amine-based), and then heated to 100 °C. DAC systems are mainly made of steel, brick, concrete, copper and aluminium. For 1 Gt of CO_2 removal, DAC would require a total mass of 17–36 Mt of steel, concrete, copper and aluminium for construction, and 3–7 Mt of chemical commodities in the form of liquid solvents and/or solid adsorbents.

The production of synthetic kerosene does not require any specific critical materials or depend on a specific location, although proximity to DAC and electrolysers would be an advantage, reducing costs and infrastructure needed for transport.

9.14.1.3. Life cycle: use phase

The main continuous input for both hydrogen production and DAC is renewable electricity.

9.14.1.4. Life cycle: end-of-life

Production facilities might be recycled at end-of-life. No specific literature is available, but recycling requirements are likely to be in force in 2050, including for e-kerosine facilities.

Table C.32 Energy security indicators for synthetic kerosene

Geopolitical availability (score: 1)
No particular geopolitical complexity, except for the complexities related to renewable hydrogen production. See factsheet on hydrogen.
Abundance (score: 1)
Dependent on the abundance of renewable electricity/hydrogen, covered below.
Circularity (score: 1)
There are no energy security issues are related to circularity.
Supply chain complexity (score: 2)
Supply complexity mainly relates to the costs and availability of DAC and renewable energy. For example, the EU would require a DAC capacity of 161–281 Mt of CO_2 annually to supply e-kerosene in 2050. DAC has not been demonstrated at the commercial level, so this remains a challenge.
Supply chain location (score: 1)
Synthetic kerosine can be produced anywhere, but it is more economically efficient to locate production facilities near either renewable electricity production/hydrogen supply/DAC, or consumers.
Digital vulnerability (score: 2)
As this value chain relies on large quantities of electricity, and the electricity system is vulnerable to cyberattacks, this value chain is as well. Therefore, a score of 2 is assigned to this energy security indicator.
Physical vulnerability (score: 2)

Moderate risk related to the high use of renewable electricity, hence vulnerability to electricity system disruptions.

Broader sustainability (score: 2)

There is a risk is associated with the availability of renewable electricity, as the additionality principle of the Delegated Act on RFNBOs under the RED III should be respected. A shortage of renewable electricity, and resulting use of electricity from the grid, would compromise the sustainability of the product. On the other hand, the massive development of electricity capacity required may cause sustainability risks at development locations (whether inside or outside the EU, obstruct other development or impact local energy availability. Wind parks also have a (mostly limited) negative impact on bird populations. However, even accounting for its renewable energy demand, synthetic kerosene production requires less land space than bio-kerosene.[3]

Affordability (score: 3)

Synthetic kerosene production costs largely depend on the price of electricity, which in turn depends on location and meteorological conditions. Costs in 2050 would be at least 75 EUR/MWh when produced in the EU, and 64 EUR/MWh when imported. In 2030, levelised costs are estimated at around 120 EUR/MWh.[3] The score is therefore a reflection of risks that is relatively high to fossil alternatives.

Skills (score: 2)

As parts of the value chain are still being developed and need specialised research skills, a score of 2 is assigned.

9.14.1.5. Bibliography

[1] European Commission (2018), A Clean Planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, Luxembourg: Publications Office of the European Union. https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

[2] JRC (2022), Renewable fuels of non-biological origin in the European Union, Luxembourg: Publications Office of the European Union. https://setis.ec.europa.eu/renewable-fuels-non-biological-origin-european-union_en

[3] Dena (2022), E-kerosene for commercial aviation, Berlin: Deutsche Energie-Agentur (Dena). https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2022/STUDY_E-Kerosene_for_Commercial_Aviation.pdf

[4] Ricardo (2022), European CO2 availability from point sources and direct air capture, Brussels: Transport & Environment, Ricardo report template. https://www.transportenvironment.org/wp-content/uploads/2022/07/DAC-final-report.pdf

[5] D.W. Keith et al. (2018), A Process for Capturing CO2 from the atmosphere, Cambridge: Cell Press. https://www.sciencedirect.com/science/article/pii/S2542435118302253

[6] IEA (2022), Direct air capture, Paris: IEA. https://iea.blob.core.windows.net/assets/78633715-15c0-44e1-81df-41123c556d57/DirectAirCapture_Akeytechnologyfornetzero.pdf

9.15. Heat pumps

9.15.1. Industrial heat pumps

A heat pump transfers heat from a low-temperature source (such as the surrounding air, energy stored in subsurface aquifers, or nearby sources like water or waste heat from a factory) to a higher-temperature demand by applying additional energy in the form of electricity. The ratio of heat output to power input is called the CoP (coefficient of performance). This technology is only ‘clean’ when the electricity input is renewable.

Compared to residential applications, large-scale heat pumps in commercial and industrial applications or district heating networks require higher input temperatures, which can be sourced from the waste heat of industrial processes, data centres or wastewater.

Industrial heat pumps are mainly used for low-temperature processes below 100 °C. Output temperatures of 150 °C can be achieved if waste heat at about 100 °C is available for input. Temperatures of >200 °C are still in the early prototype phase.[1]

9.15.1.1. Characteristics

Role in EU energy system: energy conversion.

Total cumulative installed capacity of 2 GW, consisting of 4 174 heat pumps capable of covering 641 PJ/a of process heat demand.[2]

Primary energy source: air, ground or water.

TRL: 5–7[1]

Heat pumps have most potential in energy-intensive process industries with heat demand at moderate temperatures (<200 °C).[1,3]

At temperatures above 200 °C, direct electrification is generally preferable.

9.15.1.2. Life cycle: manufacturing phase

A heat pump consists of:

- A compressor, which increases the pressure and the temperature of the refrigerant.
- A condenser – a heat exchanger that transfers the heat of a pressurised refrigerant to water, which then transfers the heat to the user.
- An expansion valve: reduces pressure of the cooled and condensed refrigerant so that it can evaporate at lower temperatures.
- Evaporator: extracts heat from the source and the refrigerant flows to the compressor for the next cycle.

The components accounting for most of the total value of a heat pump are: the compressor (~25%), the electronic controls (~25%), the heat exchanger (~15%), housing (~13%), valves (~10%), fan (~5%), pipework (~2%) and refrigerant (~2%).[4]

The design and technical specifications of industrial heat pumps differ substantially from residential ones in the following ways:

- Need for higher output temperature
- Use of warm industrial wastewater or heated airflows as input

- Refrigerants must be applied in higher quantities and must provide higher temperatures
- Require thicker piping to support higher pressures
- Compressors must withstand higher temperatures

Components are made from the following materials:

- Critical materials: copper, nickel, aluminium/bauxite[5,6]
- Only specialised heat pumps utilise permanent magnets (such as HVAC systems)
- Non-critical materials: iron, oil and gas, refrigerant, insulation[6]

9.15.1.3. Life cycle: use phase

Refrigerant supply and yearly maintenance.

9.15.1.4. Life cycle: end-of-life

Industrial heat pumps have an estimated lifetime of 15 years (according to Berenschot et al.) and need a major overhaul every 10 years (according to VNP).[3]

Research is needed to ensure safe end-of-life disposal of refrigerants and to develop new technologies for safe refrigerants that comply with F-gas regulation.

Table C.33 Energy security indicators for industrial heat pumps

Geopolitical availability (score: 1)
The critical materials for industrial heat pumps and their relative geopolitical availability are as follows: • Copper: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Aluminium: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Nickel: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). Since the average score of all materials is 1, this is the score given to this indicator.
Abundance (score: 2)
The critical materials in the technology and their abundance risk are: • Copper, which has a medium abundance risk (1 to 100 ppm, score 2). • Aluminium, which has a low abundance risk (>10 000 ppm, score 1). • Nickel, which has a medium abundance risk (1 to 100 ppm, score 2). Since the average score for all materials is 2, this is the overall score assigned to this indicator.

Circularity (score: 1)

Most metallic parts can be reused and recycled. Lifetime is 15 years.[3] Therefore, this indicator is assigned a score of 1.

Possible leakage of refrigerants should be treated very carefully during maintenance and end-of-life.

Supply chain complexity (score: 2)

Requirements for industrial heat pumps can vary by sector as they are designed for specific temperatures and processes, limiting opportunities for mass production. This requires specialised planning, design, manufacturing and installation.[1] Some industries have specific operational requirements: for example, refrigerants used in the food industry have stricter requirements than in other industries.[1] Because the supply chain is quite, but not unusually, complex, we assign this indicator a score of 2.

Supply chain location (score: 2)

Compressors are among the most critical components of heat pumps. Their design and manufacturing are dominated by several global suppliers within and outside Europe. Electronic controls also require specialised manufacturers. There are European suppliers, as well as the suppliers from the rest of the world. These specialised components pose a potential risk, especially to local manufacturers, who mostly buy and assemble ready-made components.[7]

Refrigerant supply is dominated by China and United States, posing a particular threat to the independence of local heat pump markets.

The manufacturing of heat exchangers, fans, pumps, housing, expansion tanks and conventional control systems is less specialised, and a vast number of companies distribute to a range of industries worldwide.[4]

For a typical non-domestic unit, around 50% of the components by sales value are European.[4]

As part, but not all of the supply chain is, or can be, located in the EU, we assign this indicator a score of 2.

Digital vulnerability (score: 2)

As this value chain relies on large quantities of electricity, and the electricity system is vulnerable to cyberattacks, this value chain is also vulnerable. Therefore, a score of 2 is assigned to this energy security indicator.

Physical vulnerability (score: 2)

Increased use of electricity for heating increases exposure to power outages and increased network connection capacity for companies. As with other value chains needing relatively large amounts of renewable electricity, we therefore assign a score of 2.

Broader sustainability (score: 2)

Heat pumps contain refrigerants with climate damaging potential if released into the atmosphere. According to new EU legislation, these refrigerants – called F-gases – must be phased out. There is a risk of this legislation slow down the adoption of heat pumps, which is why a score of 2 is assigned to this indicator.

Affordability (score: 2)

Various studies on the specific investment costs of heat pumps with heating capacities of more than 100 kW were analysed in units of cost per process heat output value (EUR/kWP). It was noted that costs vary greatly, but values were typically between 300 EUR/kWP and 1 000 EUR/kWP with a reported industry average of 400 EUR/kWP. Lower investment costs in the range of 200 EUR/kWP to 250 EUR/kWP have reportedly been achieved in China.[8]

At the EU level, the framework for technology development is set by the implementation plans of the SET Plan working group on energy efficiency in buildings, and the strategic research and innovation agenda of the European technology and innovation platform on renewable heating and cooling (RHC platform). The SET Plan working group aims to reduce the costs for small and large heat pumps by 50%, compared to the 2015 market price.[1] However, as this is still a target value, we assign this indicator a score of 2.

Skills (score: 3)

A shortage of skilled installers is already starting to create bottlenecks in the deployment of heat pumps in several countries.[1] Most literature focuses on residential heat pumps, but it reasonable to assume the same situation in the industrial market.

Manufacturing heat pumps for industry requires more specific design than residential heat pumps. Higher skills are therefore required because the process is not streamlined.

For the installation and maintenance of industrial heat pumps, we expect there to be more in-house engineering and electrical knowledge that can be used. However, because of the relatively large workforce needed, we assign this indicator a score of 3.

9.15.1.5. Bibliography

1 International Energy Agency (2022). The Future of Heat Pumps. https://iea.blob.core.windows.net/assets/4713780d-c0ae-4686-8c9b-29e782452695/TheFutureofHeatPumps.pdf

2 Marina et al. (2021). An estimation of the European industrial heat pump market potential. *Renewable and Sustainable Energy Reviews.* Volume 139. https://www.sciencedirect.com/science/article/pii/S1364032120308297

3 ECN and TNO (2018). Technology Factsheet: Industrial High Temperature Heat Pump. Industrial-high-temperature-heat-pump-2.pdf (energy.nl)

4 Eunomia Research & Consulting Ltd (2020). Heat Pump Manufacturing Supply Chain Research Project. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/943712/heat-pump-manufacturing-supply-chain-research-project-report.pdf

5 JRC (2022). Heat Pumps in the European Union. Luxembourg: Publications Office of the European Union. https://setis.ec.europa.eu/heat-pumps-european-union_en

6 International Energy Agency (2023). Energy Technology Perspectives 2023. https://iea.blob.core.windows.net/assets/a86b480e-2b03-4e25-bae1-da1395e0b620/EnergyTechnologyPerspectives2023.pdf

7 European Commission (2023). 'Study on the Critical Raw Materials for the EU 2023'. Final Report. Luxembourg: Publications Office of the European Union. https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

8 Meyers et al. (2018). The future of low carbon industrial process heat: A comparison between solar thermal and heat pumps. *Solar Energy*. Volume 173 (893-904). https://www.sciencedirect.com/science/article/abs/pii/S0038092X18307801?via%3Dihub.

9.15.2. Domestic heat pumps

A heat pump transfers heat from a low-temperature source (such as the surrounding air, energy stored in subsurface aquifers, or nearby sources like water or waste heat from a factory) to a higher-temperature demand by applying additional energy in the form of electricity. The ratio of heat output to power input is called the CoP (coefficient of performance). The technology is only 'clean' when the electricity input is renewable.

Air-air heat pumps are often used in residential buildings, as well as commercial buildings such as offices or hospitals. Ground-source heat pumps are often used in larger buildings due to economies of scale.

9.15.2.1. Characteristics

Role in EU energy system: energy conversion Capacity in the EU: 14.24 GW in 2020, producing 252.6 TWh of useful energy.[1]

Primary energy source: air, ground or water.

TRL: 9 (our assessment).

9.15.2.2. Life cycle: construction phase

A heat pump consists of:

- A compressor: increases the pressure and temperature of the refrigerant.
- A condenser: heat exchanger that transfers the heat of the pressurised refrigerant to water, which transfers the heat to the user.
- An expansion valve: reduces the pressure of the cooled and condensed refrigerant so that it can evaporate at lower temperatures.
- An evaporator: extracts heat from the source and the refrigerant flows to the compressor for the next cycle.

Components accounting for significant portions of the total value of a heat pump are the compressor (~25%), electronic controls (~25%), heat exchanger (~15%), housing (~13%), valves (~10%), fan (~5%), pipework (~2%) and refrigerant (~2%).[2]

Infrastructure: Ground-source heat pumps need equipment for drilling and making deep underground holes, and usually come with higher up-front costs.

Critical materials: copper, aluminium/bauxite, permanent magnets, nickel.[1,2]

Non-critical materials: iron, oil and gas, refrigerant, insulation.[2]

9.15.2.3. Life cycle: use phase

Refrigerant supply and yearly maintenance.

9.15.2.4. Life cycle: end-of-life

- Air-to-water heat pumps: 18 years.[3]
- Heat pump lifetimes vary between 14 and 20 years.[1]

Research is needed to ensure safe end-of-life disposal of refrigerants and development of new technologies for safe refrigerants that comply with F-gas regulation.

Table C.34 Energy security indicators for domestic heat pumps

Geopolitical availability (score: 1)
The critical materials for industrial heat pumps and their relative geopolitical availability are as follows: • Copper: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Aluminium: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Nickel: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). Since the average score of all materials is 1, this is the score given to this indicator.
Abundance (score: 2)
The critical materials in the technology and their abundance risk are: • Copper, which has a medium abundance risk (1 to 100 ppm, score 2). • Aluminium, which has a low abundance risk (>10 000 ppm, score 1). • Nickel, which has a medium abundance risk (1 to 100 ppm, score 2). Since the average score for all materials is 2, this is the overall score assigned to this indicator.
Circularity (score: 1)
Most metal parts can be reused or recycled. Lifetime is in between 14 and 20 years.[1] Therefore, this indicator is assigned a score of 1. However, during maintenance and end-of-life, possible leakage of refrigerant should be very carefully managed.
Supply chain complexity (score: 2)
In terms of supply chain maturity, the most expensive components in heat pumps (e.g. heat exchangers, compressors) have already been mass produced for some time, and several heat pump components are also common to other industries.[2] Installation and maintenance steps are relatively complex, as each house or housing complex requires separate installation and maintenance. Therefore, a score of 2 is given.
Supply chain location (score: 2)

Compressors are among the most critical components of heat pumps. Their design and manufacturing are dominated by several global suppliers within and outside Europe. Electronic controls also require specialised manufacturers. There are European suppliers, as well as the suppliers from the rest of the world. These specialised components pose a potential risk, especially to local manufacturers, who mostly buy and assemble ready-made components.[4]

Refrigerant supply is dominated by China and United States. This is a particular threat to the independence of the local heat pump markets. However, with the phasing out of F-gases, European countries could develop a market for natural refrigerants and become less dependent on non-EU countries.

Manufacturing of heat exchangers, fans, pumps, housing, expansion tanks and conventional control systems is less specialised, and a vast number of companies distribute to a range of industries worldwide.[2]

At least 70% of manufacturing capacity is in China.[2]

As part, but not all, of the supply chain is, or can be, located in the EU, we assign this indicator a score of 2.

Digital vulnerability (score: 2)

As this value chain relies on large quantities of electricity, and the electricity system is vulnerable to cyberattacks, this value chain is also vulnerable. Therefore, a score of 2 is assigned to this energy security indicator.

Physical vulnerability (score: 2)

Increased use of electricity for heating increases exposure to power outages and increased network connection capacity for companies. This means additional costs (contracted peak values) for the industry, as well as the investors in electricity infrastructure, including the state. As with other value chains needing relatively large amounts of renewable energy, we assign a score of 2.

Broader sustainability (score: 2)

Air quality

Electric heat pumps reduce NOx emissions relative to alternative technologies, improving outdoor and indoor air quality entailing health benefits.[1]

Public acceptance

Noise, visual impact and space requirement, but low risk compared to other technologies.

F-gases

Heat pumps contain refrigerants with climate damaging potential if released into the atmosphere. According to new EU legislation, these refrigerants – called F-gases – must be phased out. There is a risk of this legislation slow down the adoption of heat pumps, which is why a score of 2 is assigned to this indicator.

Affordability (score: 1)

The levelised cost of heat for domestic heat pumps in 2018 was 84–145 EUR/MWh.[5] Therefore, this indicator is assigned a score of 1.

Skills (score: 3)

A shortage of skilled installers is already starting to create bottlenecks in the deployment of heat pumps in several countries.[3]

There is a general shortage of planners, architects, engineers and qualified heating and cooling installers.[1] This barrier is common across heating and cooling technologies but more acute for heat pumps.[1]

However, shifting workers to install heat pumps does not require extensive training and can be done mostly on the job.[2]

To summarise, although the skills required to install a heat pump can be learned relatively quickly, a lot of installers are needed as each housing unit requires separate installation (see supply chain complexity). This is already creating a bottleneck in adoption in Europe. Therefore, the score is 3.

9.15.2.5. Bibliography

[1] JRC (2022). Heat Pumps in the European Union. Luxembourg: Publications Office of the European Union. https://setis.ec.europa.eu/heat-pumps-european-union_en

[2] International Energy Agency (2023). Energy Technology Perspectives 2023.; Meyers et al. (2018). 'The future of low carbon industrial process heat: A comparison between solar thermal and heat pumps'. *Solar Energy*. Volume 173 (893-904). https://www.sciencedirect.com/science/article/abs/pii/S0038092X18307801?via%3Dihub

[3] International Energy Agency (2022). The Future of Heat Pumps. https://iea.blob.core.windows.net/assets/4713780d-c0ae-4686-8c9b-29e782452695/TheFutureofHeatPumps.pdf.

[4] ECN and TNO (2018). Technology Factsheet: Industrial High Temperature Heat Pump. https://energy.nl/media/downloads/Industrial-high-temperature-heat-pump-2.pdf

[5] Enerdata, Trinomics and LBST (2020). Cost of Energy (LCOE): Energy costs, taxes and the impact of government interventions on investments, European Commission, Brussels. final_report_levelised_costs_0.pdf (europa.eu)

9.16. Smart energy grids

9.16.1. Electric vehicle smart charging

EV smart charging in the EU is a component of the region's strategy to transition towards sustainable and clean transportation. EVs have relatively high electricity demand.

Role in EU energy system: smart charging can be used for two goals:

Electricity network: There is a risk of increased adoption of EVs leading to significant overload on the grid during certain periods. EV smart charging can help minimise this risk, stabilise and make the grid more reliable. Advanced technologies and infrastructure can enhance the charging experience for EV owners and optimise the use of renewable energy. Smart charging systems focus on seamless grid integration, allowing EVs to communicate with the grid and enabling two-way energy flows. EVs can charge when renewable energy from sources like wind and solar are abundant, and discharge power back to the grid during periods of peak demand. Smart charging also encourages EV owners to participate in demand response programmes, adjusting their charging schedules in response to grid conditions. This helps balance grid loads and reduces the need for additional grid infrastructure.

Energy cost: Smart charging can be used to couple charging with electricity prices (hourly/day-ahead prices or balancing markets), resulting in lower electricity costs for EV owners and overall lower costs for the electricity system. In this way, EVs contribute to balancing of the electricity system and matching production and demand.

9.16.1.1. Characteristics

Role in EU energy system: Europe is elected to have 159 million electric cars on the road by 2050, consuming 347 TWh of electricity per year.[1] In 2022, nearly 2 million electric cars were sold in the EU – or around 21.6% of all new car registrations. Data show that the share of EVs in new registered cars in the EU has been growing steadily over the past few years. Charging infrastructure has been growing along with the rise of EVs. In 2022, there were 475 000 charging points in the EU – a rise of 48% on the 320 000 operating in 2021. Netherlands leads in public charging infrastructure, with about 577 publicly accessible charging points per 100 000 inhabitants in 2022.

Smart charging is applied in the EU with respect to adjusting and coupling charging to electricity prices. Vehicle to grid (V2G) capabilities are limited by the small fraction of EVs that are capable of this.

Primary energy source: electricity.

TRL: Smart charging based on price incentives is well developed, with a TRL of 9. Car owners can set time and/or price boundaries that determine whether an EV will charge.

EV smart charging is not currently applied on a wide scale. Several EU pilots (e.g. Smart Solar charging project, ChargePilot, Elaadnl) are underway or have completed. Although the technology is technically mature, there is a lack of supporting infrastructure and V2G capable EVs.

9.16.1.2. Life cycle: construction phase

The construction phase of smart charging infrastructure involves adding software to existing charging points and EVs to enable smart charging principles. EVs should also have V2G capabilities to enable smart charging. Currently, only a few EVs have V2G capabilities, so more V2G-capable EVs should enter market to enable V2G on a large scale.

9.16.1.3. Life cycle: use phase

During the use phase, smart charging principles balance electricity supply and demand. No material input is required. Regular software updates are required.

9.16.1.4. Life cycle: end-of-life

EV smart charging infrastructure includes charging stations and cables connected to the grid. End-of-life of these components includes e-waste and cable waste. For details of the smart metering devices used in smart charging infrastructure, please see the value chain for advanced metering infrastructure below. With regards to conventional EV charging infrastructure, there is no difference.

Table C.35 Energy security indicators for EV smart charging

Geopolitical availability (score: 1)
The geopolitical availability of EV smart charging depends on the adoption of EVs (with V2G) and smart charging infrastructure. Adoption of these technologies depends on the governmental regulations and supporting infrastructure. There are no geopolitical limitations to the adoption of EV smart charging, hence a score of 1.
Abundance (score: 1)
EV smart charging infrastructure is made of common non-critical metals and polymers.[2] Material abundance does not pose any limitations to adoption of EV smart charging, hence a score of 1.
Circularity (score: 2)
EV smart charging infrastructure – like non-smart charging infrastructure – is made of common non-critical metals and polymers. Metals like stainless steel, aluminium and copper can be readily recycled. Recycling of polymers such as PC resins, PC blends, elastomers and polyurethanes is technically possible but not widely adopted in the EU. About 32.5% of all plastic waste in the EU is recycled, 42.6% is incinerated for energy recovery and 24.9% landfilled. If more is plastic recycled, less can be landfilled and incinerated and the need for additional raw materials – largely petrochemical feedstock – is reduced. Circularity for metals is generally good, but there is room for significant improvement in the recycling rate of polymers, therefore the score of 2 is given for circularity.
Supply chain complexity (score: 1)
Since this technology uses only common non-critical metals and polymers, no extraordinary supply chain complexity could be identified, hence a score of 1.
Supply chain location (score: 1)
Since this technology uses only common non-critical metals and polymers, no extraordinary supply chain location risk could be identified, hence a score of 1.
Digital vulnerability (score: 3)
This technology is driven by software, hence there is an inherent risk of digital vulnerability. Digital infringement could lead to faulty functioning of smart charging principles. A grid where smart charging is embedded into the system could be vulnerable if smart charging principles are interrupted due to hacking of the underlying software. Cybersecurity is a solution to this problem. The inherent digital vulnerability risk of this technology, and the significant consequences relating to this, lead to a score of 3 for this risk indicator.
Physical vulnerability (score: 1)
EV smart charging infrastructure is influenced by temperature. In cold weather, low temperatures (~0 °C) affect the EV battery fast charging rate (>50 kW) due to the battery management system limiting current flow to avoid detrimental effect on battery cells.[3] This could lead to twice the fast-charging time, or half of the power, compared to charging rates at more moderate temperatures (~2 °C). At norming charging rates (5–25 kW), this temperature effect diminishes. While the

temperature influences fast charging rates, this is not expected to be a significant risk to the functionality of this technology.

Broader sustainability (score: 1)

EV smart charging could lead to enhanced grid balancing, less curtailment of renewable energy and fewer flexibility measures. Fully integrated smart charging infrastructure could act as a flexibility tool for the grid, similar to large scale battery systems. Practical considerations with regards to range requirements for EV owners could limit the application of smart charging principles. Infringement of smart charging systems on the state of charge of the battery, could be a crucial factor with respect to the adoption of smart charging in the EU. The potential benefit on grid balancing, while no extraordinary broader sustainability risks could be identified, leads the score of 1.

Affordability (score: 1)

It should be emphasised that this technology leads to a more balanced grid and less volatile electricity prices, which are inherently related to intermittent renewables like solar and wind energy.[1] Demand response tools for smart charging could also optimise the charging processes based on price incentives.

With respect to charging infrastructure, there is no considerable risk identified regarding costs. Therefore, the score is evaluated at 1, meaning low risk.

Skills (score: 2)

The successful integration of EV smart charging infrastructure into existing energy infrastructure requires a multidisciplinary approach, involving professionals with various skills and expertise – including electrical engineering, IT, cybersecurity, data management and analysis, and regulatory knowledge. Increasing labour demand in the electrical energy sector is expected to be a limiting factor for the adoption of this technology. The EU faces a shortage of skilled workers in this industry. Other developments, such as the installation of solar PV, heat pumps, and broader electrification of homes and businesses, increase demand and put pressure on the available workforce in this sector. Since this introduces a certain risk regarding the implementation of this technology, this risk category is scored 2.

9.16.1.5. Bibliography

[1] Blumberg, G., Broll, R., & Weber, C. (2022). 'The impact of electric vehicles on the future European electricity system – A scenario analysis'. *Energy Policy*, 161, 112751. https://doi.org/https://doi.org/10.1016/j.enpol.2021.112751

[2] Globe Newswire. (2022). Electric Vehicle (EV) Charging Station Raw Materials Market Worth $4.91 Billion by 2028 - Market Size, Share, Forecasts, & Trends Analysis Report with COVID-19 Impact by Meticulous Research. In.

[3] Bayram, S. (2021). Impacts of Electric Vehicle Charging under Cold Weather on Power Networks. https://strathprints.strath.ac.uk/79154/1/Bayram_UPEC_2021_Impacts_of_electric_vehicle_charging_under_cold_weather_on_power_networks.pdf

9.16.2. Advanced metering infrastructure

Advanced metering infrastructure (AMI) is the combination of digital meters, communication networks and data management to enable two-way communication and control between the energy demand side and the energy supply side for more efficient energy management. AMI is a network connecting smart meters, energy suppliers, consumers and energy storage infrastructure, and is thus not limited to a single technology.

9.16.2.1. Characteristics

Role in EU energy system: In the EU, nearly 225 million smart meters for electricity and 51 million for gas will be installed by 2024. By 2024, almost 77% of European consumers are expected to have a smart meter for electricity, and 44% for gas.[1]

AMI will be especially import with the adoption of smart grids, where real-time data collection, communication and management at the supply and demand side is crucial. The data can be used for billing, load forecasting and detecting irregularities or leaks in the system.

Primary energy source: electricity.

TRL: Smart meters, communication networks and data management are already well developed, hence AMI has a high TRL of 9.

9.16.2.2. Life cycle: construction phase

AMI technology consists of hardware and software. AMI technologies will replace older technologies – analogue or digital – which do not offer automatic two-way communication between energy supplier and consumer. Older (not advanced) meters require the end consumer to manually read the meter and communicate this to the energy supplier.

9.16.2.3. Life cycle: use phase

During the use phase, AMI hardware components are designed to function for about 10–20 years. Regular software updates are required for optimisation, to remove software bugs and for general functionality of the system.

9.16.2.4. Life cycle: end-of-life

In the context of AMI, the end-of-life phase involves the disposal of electronics. Since AMI components often contain valuable semiconductor materials, including CRM, recycling/reusing/repurposing is important to reduce dependence on raw materials. E-waste is one of the fastest growing waste streams in the EU. Members of the European Parliament want to increase product life through reusability and reparability. The European Commission is working on a rewards system to encourage the recycling of electronics.

Table C.36 Energy security indicators for AMI

Geopolitical availability (score: 2)
The CRM and their geopolitical availability score (in brackets) used in AMI are: light rare earth elements/LREE (3), magnesium (3), germanium (1), borates (3), cobalt (2), platinum group metals (2), natural graphite (1), vanadium (2), titanium (1), gallium (3), silicon metal (1), manganese (1) and copper (1). The average geopolitical availability score for these CRM is 2. These materials are critical since they originate from either one or a few countries, with disputable availability. Recycling AMI could partly meet demand for new AMI, but due to increasing pressure on these CRM from various other sectors in the economy, raw resources are likely to remain crucial to scaling this technology.

Abundance (score: 2)

There are some CRM in AMI, and the importance of these materials to the technology is high because they are required for the proper functionality of these devices. Therefore, a score of 2 is assigned. The average abundance score for the materials described in the geopolitical availability section above is 2.

Circularity (score: 2)

AMI consists of complex electronics, often containing CRM. Recycling AMI is therefore important to reduce dependence on CRM supply. No data could be found on the recycling rate of AMI, but approximately 40% of general e-waste is recycled in the EU. Regulations are being established to improve the recycle rate for e-waste. The European Commission has proposed the Critical Raw Materials Act to address risks of CRM supply disruption and the structural vulnerabilities of EU CRM supply chains. Here, circularity is a major pillar, but given the moderate e-waste recycling rate of 40%, this risk is given a score of 2.

Supply chain complexity (score: 2)

Since AMI encompasses a broad range of technology, consisting of meters, digital infrastructure, communication networks, servers and more, there are many different supply chains involved. This introduces a level of complexity.

Two aspects: i) dependence on CRM, and ii) multiple supply chains, lead to some supply chain complexity, hence is scored 2.

Supply chain location (score: 2)

AMI are produced globally, mainly by companies in the United States and Europe.[2] The supply chain of components – such as semiconductors and chips – is dominated by players such as Taiwan, South Korea, the United States and China.[3] Since manufacturing of advanced metering infrastructure is not centrally located in one part of the world and several companies in Europe are active in this sector, but raw materials are categorised as critical, the supply chain location risk is given a moderate score of 2.

Digital vulnerability (score: 3)

AMI technology is particularly vulnerable to digital risks.[4] The main risks are theft of smart meter data and cyberattacks.

Theft of smart meter data

Stealing encrypted digital information from smart meters is possible – if the encryption can be compromised, which demands significant computational resources. The EU has implemented several measures to improve data protection. Besides compromising encryption, hackers could also gain access by pretending to legitimately request access to data sources.

Cyberattacks

Cyberattacks on smart meters can be classified under four categories, based on the method and type of attack:

- Availability attacks:
  - Dos/DDos attack: disrupts a digital system by overwhelming it with excessive (digital) traffic

– Replay attack: maliciously inserts, fraudulently repeats, or delays, data

- Integrity attack: manipulation that compromises the integrity of data and causes the grid to lose power
- Confidentiality attack: breaches confidentiality of (personal) data
- Authenticity attack: attempts to obtain (log-in) authentication

Since digital vulnerability can entirely compromise the operation of AMI, the highest score is assigned for digital vulnerability.

Physical vulnerability (score: 1)

Digital components are generally vulnerable to overheating and may be disrupted by electromagnetic radiation. Furthermore, radiofrequency jamming attacks can distort the wireless communication of AMI.[4] There is no particular physical risk to this technology compared to other value chains, and the damage resulting from physical events would probably be limited. Therefore, a score of 1 is assigned.

Broader sustainability (score: 2)

The main function of AMI is to connect energy demand and supply, optimising energy use and generation, and providing valuable insights into load forecasting and system irregularities. With the adoption of more renewables and more energy storage to distribute the energy generated over the demand profile, AMI plays a critical role that could lead to lower energy use, and therefore a more sustainable system.

Since this technology contains CRM, it is important to consider their extraction processes in the context of broader sustainability. There are multiple concerns over mining operations, including human rights abuses,[5] environmental pollution[6] and high water-use.[7] The CRM used in semiconductors, electronics, batteries, etc, are vital to the energy transition, but the harmful effects of mining operations on communities and the environment remain an issue.

Affordability (score: 1)

In general, AMI aims to optimise energy generation and demand, and so lower energy use and reduce costs. To make this technology interesting to consumers, initial investment in AMI should be lower than the total savings it brings over a certain payback period.

Skills (score: 2)

Successfully integrating AMI into existing energy infrastructure requires a multidisciplinary approach, involving professionals with various skills and expertise – including electrical engineering, IT, cybersecurity, data management and analysis and regulatory knowledge. Growing demand for labour in the electrical energy sector is expected to be a limiting factor for the adoption of AMI. Other developments, such as the installation of solar PV, heat pumps, and broader electrification of homes and businesses, increase demand and put pressure on the available workforce in this sector. Since this introduces a certain risk regarding the implementation of this technology, this risk category is scored 2.

9.16.2.5. Bibliography

[1] European Commission. (2023). Smart grids and meters. https://energy.ec.europa.eu/topics/markets-and-consumers/smart-grids-and-meters_en

[2] Allied Market Research. (2021). Advanced Metering Infrastructure (AMI) Market by Product Type (Smart Metering Devices, Solutions, and Services) and End User (Residential, Commercials, and Industrial): Global Opportunity Analysis and Industry Forecast, 2021–2030.

[3] Teer, J. (2023). Reaching breaking point: The semiconductor and critical raw material ecosystem at a time of great power rivalry. https://hcss.nl/wp-content/uploads/2022/10/Reaching-Breaking-Point-Full-Version-HCSS-2022.pdf

[4] Balakrishnan, R., & Geetha, V. (2021). 'Review on home energy management system'. *Materials Today: Proceedings*, 47, 144-150. https://doi.org/https://doi.org/10.1016/j.matpr.2021.04.029

[5] Amnesty International. (2023). Democratic Republic of the Congo: Industrial mining of cobalt and copper for rechargeable batteries is leading to grievous human rights abuses. In: Amnesty International. https://www.amnesty.org/en/latest/news/2023/09/drc-cobalt-and-copper-mining-for-batteries-leading-to-human-rights-abuses

[6] Earth.Org. (2023). The Environmental Impacts of Cobalt Mining in Congo. In: Earth.Org, https://earth.org/cobalt-mining-in-congo

[7] Energy Transitions Commission. (2023). Material and Resource Requirements for the Energy Transition. In: Energy Transitions Commission. https://www.energy-transitions.org/wp-content/uploads/2023/08/ETC-Materials-Report_highres-1.pdf

9.16.3. Home energy management systems

Home energy management systems (HEMS) are technologies that monitor and control the energy usage within a household to improve efficiency and reduce costs. These systems can also help utilities by enabling demand response and lowering peak demand. HEMS focus on concentrate on four main areas: electricity usage, solar PV, solar thermal and battery storage. While some home management systems can address all these areas, others only address a couple.

The components of a HEMS are:

- Smart meters: Monitor renewable energy production and the energy consumption of appliances
- Sensors: Measure temperature, light or movement, for example
- Communication devices: connect sensors to meters
- Appliances: Home appliances consume energy – depending on the appliance, they can be controlled, semi-controlled or uncontrolled by the HEMS
- Controller/optimisation algorithms: Optimisation algorithms are the core of HEMS. They make decisions based on smart meters, sensing devices – and in some cases possibly electricity prices or consumer preferences
- Renewable energy sources and storage: All devices that generate renewable energy (e.g. PV) and store energy (e.g. batteries)

9.16.3.1. Characteristics

Role in EU energy system: The HEMS market is expected to grow at a compound annual grow rate (CAGR) of 12.5%.[1] Potential demand for HEMS in Europe is high due to significant production and use of smart meters. A study by Berg Insight estimated that there are currently 1.5 million HEMS installed in Europe, where a HEMS was defined as a system that contains at least a PV system, battery storage and a web-based management portal or smartphone app allowing remote monitoring and control of the system.[2] The same study forecast that this market will grow rapidly, to about 5 million HEMS in 2027.

Primary energy source: electricity.

TRL: 9 – HEMS are readily available commercially.

9.16.3.2. Life cycle: construction phase

The construction phase of HEMS involves installation and setup of the hardware and software components necessary to monitor and manage a household's energy usage. Key aspects of the construction phase include:

- Hardware installation: This involves deployment of physical components such as smart meters, sensors and other devices that can monitor energy consumption and generation within the home. These devices may be installed at various points, including the electrical panel, HVAC systems and individual appliances.

- Network setup: During construction, network infrastructure is established to connect the HEMS components. This network can be wired or wireless, depending on the design of the system. It should provide reliable communication between the various devices.

The construction phase is a crucial step in deploying a HEMS, as it lays the foundation for energy monitoring, control and optimisation.

9.16.3.3. Life cycle: use phase

Once a HEMS is constructed and operational, homeowners can actively manage and reduce their energy consumption, leading to potential cost savings and environmental benefits.

The use phase of HEMS involves ongoing operation and utilisation of the system to actively manage and optimise energy consumption within a household. Key aspects of the use phase include:

- Real-time monitoring: HEMS continuously monitors and collects data on energy consumption, often in real-time. This data includes information on electricity usage, temperature and other relevant parameters.

- User interface interaction: Homeowners interact with the HEMS through user friendly interfaces, typically accessible via mobile apps or web platforms. These interfaces allow users to view energy consumption patterns, receive recommendations and adjust settings as needed.

- Energy optimisation: Based on collected data and user preferences, HEMS can automatically optimise energy usage by implementing strategies like load shifting, demand response and integration with renewable energy sources. This leads to energy efficiency and potential cost savings.

- Smart automation: HEMS can automate various processes, such as adjusting thermostat settings, controlling lighting and appliances, and managing home energy storage systems to ensure efficient energy use.

The use phase of HEMS is characterised by active energy management, giving homeowners greater control over their energy usage, to reduce energy bills and contribute to environmental sustainability. This represents the practical application of the system’s capabilities and the realisation of its benefits.

9.16.3.4. *Life cycle: end-of-life*

The end-of-life phase of HEMS refers to the stage when the system or its components reach the end of their operational life. Key aspects of the end-of-life phase include:

- System decommissioning: At end-of-life, HEMS components including smart meters, sensors and communication devices are decommissioned. This may involve de-installing and removing the system from a home.

- Environmental impact: Proper disposal and recycling of HEMS components are important to minimise environmental impact. Recycling or disposing of electronic components should follow local regulations and environmental standards.

- Data management: Careful handling of any user data and system data is crucial. Data should be securely deleted or anonymised to protect user privacy.

The end-of-life phase is an important aspect of sustainable HEMS implementation, as it ensures that disposal and recycling of equipment and data is carried out in an environmentally responsible and secure manner. Since HEMS components often contain valuable semiconductor materials, often including CRM, recycling/reusing/repurposing is important to reduce dependence on raw materials. E-waste is one of the fastest growing waste streams in the EU. Members of the European Parliament want to increase product life through reusability and reparability. In March 2023, the European Commission adopted a new proposal on rules promoting the repair of goods.[3]

Table C.37 Energy security indicators for HEMS

Geopolitical availability (score: 2)
The geopolitical availability for HEMS in Europe depends on several key factors. Market players determine the supply of HEMS to the European market, while trade policies, global supply chains and the location of manufacturing operations determine geopolitical availability. The CRM in HEMS and their geopolitical availability score (in brackets) are: LREE (3), magnesium (3), germanium (1), borates (3), cobalt (2), platinum group metals (2), natural graphite (1), vanadium (2), titanium (1), gallium (3), silicon metal (1), manganese (1) and copper (1). The average score on geopolitical availability score for these CRM is 2. These materials are critical since they originate in either one or few countries, with questionable availability. Recycling HEMS could partly meet demand for new HEMS, but due to increasing pressure on these CRM from various other sectors in the economy, raw resources are likely to remain crucial to scaling this technology.
Abundance (score: 2)
There are some CRM in HEMS and the importance of these materials to the technology is high because they are required for the proper functionality of these devices. Therefore, a score of 2 is assigned. The average abundance score for the materials described in the geopolitical availability section above is 2.
Circularity (score: 2)
HEMS consist of complex electronics, often containing CRM. Recycling HEMS is therefore important to reduce dependence on CRM supply. No data could be found on the recycling rate of

HEMS, but approximately 40% of general e-waste is recycled in the EU. Regulations are being established to improve the recycle rate for e-waste.[3] The European Commission has proposed the Critical Raw Materials Act, which is a comprehensive response to the risks of CRM supply disruption and structural vulnerabilities of EU CRM supply chains. Here, circularity is a major pillar, but given the moderate e-waste recycling rate of 40%, this risk is given a score of 2.

Supply chain complexity (score: 2)

Since HEMS consisting of meters, digital infrastructure, communication networks, servers and more, there are many different supply chains involved. This introduces a certain complexity.

Two aspects: i) dependence on CRM, and ii) multiple supply chains, lead to some supply chain complexity, hence is scored 2.

Supply chain location (score: 2)

Supply chain of components such as semiconductors and microchips are dominated by players like Taiwan, South Korea, the United States and China. Since the manufacturing of HEMS is not centrally located in one part of the world, but certain components contain raw materials categorised as critical, the supply chain location risk is given a moderate score of 2.

Digital vulnerability (score: 3)

HEMS contain many digital components and are therefore vulnerable to digital threats, including theft of information and cyberattacks. Access control is also a potential risk, should unauthorised individuals gain control of HEMS. We therefore assign the highest score.

Physical vulnerability (score: 1)

Digital components are generally vulnerable to overheating and may be disrupted by electromagnetic radiation. Furthermore, radiofrequency jamming attacks can distort the wireless communication of HEMS.[4] There is no particular physical risk for this technology compared to other value chains, and the damage resulting from physical events would probably be limited. Therefore, a score of 1 is assigned.

Broader sustainability (score: 2)

HEMS play a significant role in broader sustainability efforts by helping individuals and households optimise their energy use and reduce their environmental footprint. HEMS enable users to monitor and manage their energy consumption, promoting more efficient use of electricity, heating and cooling. This contributes to energy savings and a reduction in GHG emissions.

Since this technology contains CRM, it is important to consider the extraction processes of these materials in the context of broader sustainability. There are multiple concerns over mining operations, such as human rights abuses,[5] environmental pollution[6] and high-water use.[7] The CRM used in semiconductors, electronics, batteries, etc, are vital to the energy transition, but the harmful effects of mining operations on communities and the environment remain an issue.

Affordability (score: 1)

HEMS aims to help households optimise energy use and reduce their environmental footprint, which at the same time reduces energy costs. To make this technology interesting to consumers, initial investment in HEMS should be lower than the total savings it brings over a certain payback period.

A study showed that a given HEMS with PV battery configuration could reduce electricity costs by 19.4–25.98%.[8] Another study showed that a HEMS with PV battery configuration could reduce electricity costs by 11.87% per day, and 7.94% over a 20-year lifetime.[9]

Skills (score: 2)

The successful integration of HEMS into existing energy infrastructure requires a multidisciplinary approach, involving professionals with various skills and expertise – including electrical engineering, IT, cybersecurity, data management and analysis, and regulatory knowledge. Increasing labour demand in the electrical energy sector is expected to be a limiting factor for the adoption of this technology. The EU faces a shortage of skilled workers in this industry. Other developments, such as the installation of solar PV, heat pumps, and broader electrification of homes and businesses, increase demand and put pressure on the available workforce in this sector. Since this introduces a certain risk regarding the implementation of this technology, this risk category is scored 2.

9.16.3.5. Bibliography

1 Mordor Intelligence. (2023). Mordor Intelligence. https://www.mordorintelligence.com/industry-reports/europe-home-energy-management-system-market.

2 Berg Insight (2023). https://media.berginsight.com/2023/07/04193141/bi-homeenergy1-sum.pdf

3 European Commission. (2023). Right to repair: Commission introduces new consumer rights for easy and attractive repairs. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1794

4 Balakrishnan, R., & Geetha, V. (2021). 'Review on home energy management system'. *Materials Today: Proceedings*, 47, 144-150. https://doi.org/https://doi.org/10.1016/j.matpr.2021.04.029

5 Amnesty International. (2023). Democratic Republic of the Congo: Industrial mining of cobalt and copper for rechargeable batteries is leading to grievous human rights abuses. Amnesty International. https://www.amnesty.org/en/latest/news/2023/09/drc-cobalt-and-copper-mining-for-batteries-leading-to-human-rights-abuses

6 Earth.Org. (2023). The Environmental Impacts of Cobalt Mining in Congo. https://earth.org/cobalt-mining-in-congo

7 Energy Transitions Commission. (2023). Material and Resource Requirements for the Energy Transition. Energy Transitions Commission. https://www.energy-transitions.org/wp-content/uploads/2023/08/ETC-Materials-Report_highres-1.pdf

8 Al Muala, Z. A., Bany Issa, M. A., Sansó-Rubert Pascual, D., & Bello Bugallo, P. M. (2023). 'Realistic Home Energy Management System Considering the Life Cycle of Photovoltaic and Energy Storage Systems'. *Sustainability*, 15(14).

9 Ibrahim, O., Bakare, M. S., Amosa, T. I., Otuoze, A. O., Owonikoko, W. O., Ali, E. M., Adesina, L. M., & Ogunbiyi, O. (2023). 'Development of fuzzy logic-based demand-side energy management system for hybrid energy sources'. *Energy Conversion and Management*: X, 18, 100354. https://doi.org/https://doi.org/10.1016/j.ecmx.2023.100354

9.17. Energy building and district technologies

9.17.1. Thermal energy storage – for building and district heating and cooling

Thermal energy storage (TES) works by heating or cooling a storage medium so that temporarily stored energy can be used later for heating and cooling. The main technologies used in district heating are sensible heat technologies. Sensible heating technologies store energy without changing the phase of the storage medium. Most common technologies are tank thermal energy storage (TTES) and underground thermal energy storage (UTES). In the future latent technologies could play a bigger role. Latent technologies store energy with a phase change of the storage medium. These have favourable characteristics, and in the future innovation can lead to cheaper phase change materials (PCM) meaning these technologies can be adopted on a wider scale.

9.17.1.1. Characteristics

Role in EU energy system: Energy storage. Capacity: 199 GWh globally, including TTES, UTES and solid-state TES.[1]

Primary energy source: all renewable heat and cold sources (solar, ambient, geothermal, aquathermal) can be used as primary energy source for TES, including residual heat from (industrial) processes.

TRL: 9 – TTES and UTES are in the commercial phase.

9.17.1.2. Life cycle: construction phase

Components of TTES:

- Tank: made of reinforced concrete, plastic or stainless steel and insulation material
- Heat exchanger: made of copper or stainless steel
- Pumps
- Control system

Components of UTES:

- Underground piping: boreholes are drilled deep into the ground and pipes are placed inside, made of stainless steel or HDPE.
- Heat exchanger: made of copper or stainless steel.
- Heat transfer fluid: water or antifreeze solutions.
- Distribution system: connects heat exchangers to the building or facility and includes pipes and pumps made of copper or stainless steel.
- Control and monitoring system.

9.17.1.3. Life cycle: use phase

Limited maintenance required during use phase.

9.17.1.4. Life cycle: end-of-life

The lifetime of underground TES is up to 30 years.[2]

Table C.38 Energy security indicators for thermal energy storage

Geopolitical availability (score: 1)
Since almost all technologies contain copper (as part of electronics) these materials are considered a background risk (score 1). Besides this, TES does not use materials on the EU CRM list,[3] therefore the score given is 1.
Abundance (score: 1)
Since almost all technologies contain copper (as part of electronics) these materials are considered a background risk (score 1).
Circularity (score: 2)
UTES has a relatively long lifetime, however the end-of-life treatment of the borehole components can be complex. TTES has components, such as the tank system, that are not highly complex to recycle. Overall, a score of 2 is given.
Supply chain complexity (score: 1)
Manufacturing The components needed for this technology are not highly specialised. *Operations* The complex map of stakeholders involved (developers, local authorities, utilities, consumers and housing associations) could be a barrier to implementation. However, during use phase operations are straightforward. Therefore, an overall score of 1 is given.
Supply chain location (score: 1)
Leading EU countries in storage for district heating are Denmark, Germany and Sweden, which currently account for over 60% of the world's district heating storage capacity due to extensive use of UTES.[1]
Digital vulnerability (score: 1)
No specific digital infrastructure included in the technology. Low risk of local cyberattacks at building level if the thermal storage is part of a smart building system.
Physical vulnerability (score: 1)
UTES systems have a low risk of physical attacks or disruptions. Higher risk for above-ground systems in case of major weather or climate events – however, the overall risk is low.
Broader sustainability (score: 1)
TES enables much greater application of renewable heat sources for district heating by enabling seasonal storage (e.g. storing solar heat in the summer for use in the winter). Installation of TES requires the construction of underground of piping networks, which can have an impact on neighbourhoods. However, broader sustainability impacts are generally positive, such as improving local air quality – therefore a score of 1 is given.

Affordability (score: 1)
Current TES has a levelised cost of storage (LCOS) of 0.05–0.22 USD/kWh.[4,5] Compared to other technologies this is low and therefore a score of 1 is given.

Skills (score: 2)
Although some skilled workers are needed for this value chain, no specific vulnerabilities with respect to workforce size or specific skills are foreseen, compared to other value chains. Therefore, we assign a score of 1.

9.17.1.5. Bibliography

[1] IRENA (2020). Innovation Outlook: Thermal Energy Storage. Abu Dhabi, International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Innovation_Outlook_TES_2020.pdf?rev=6950b7b9792344b5ab28d58e18209926

[2] Sarbu and Sebarchievici (2018). A Comprehensive Review of Thermal Energy Storage. *Sustainability.* Volume 10. https://www.mdpi.com/2071-1050/10/1/191

[3] Alva and Fang (2018). An overview of thermal energy storage systems. *Energy.* Volume 144 (341-378). https://www.sciencedirect.com/science/article/abs/pii/S036054421732056X

[4] Heier et al. (2015). Combining thermal energy storage with buildings – a review. *Renewable and Sustainable Energy Reviews.* Volume 42 (1305-1325). https://www.sciencedirect.com/science/article/abs/pii/S1364032114009629

[5] Guelpa and Verda (2019). Thermal energy storage in district heating and cooling systems: A review. *Applied Energy.* Volume 252. https://www.sciencedirect.com/science/article/abs/pii/S0306261919311481

[6] Odukomaiya et al. (2021). Addressing energy storage needs at lower cost via on-site thermal energy storage in buildings. *Energy & Environmental Science.* Volume 10. https://pubs.rsc.org/en/content/articlelanding/2021/ee/d1ee01992a#!

9.17.2. Combined heat and power – for building and district technology

Combined heat and power (CHP), also known as cogeneration, generates electricity and useful thermal energy (heat) from a single energy source. Currently, most CHP systems utilise fossil fuels. However, in future more CHP systems will be able to utilise biomass, solar, geothermal and hydrogen. CHP systems can be applied to buildings or on a district level to provide electricity and heating or cooling. In CHP, an energy source is connected to a generator such as a turbine to produce electricity. The unique feature of CHP is that the waste heat produced during electricity generation is recovered and used for heating. This makes it a highly efficient system. Most suitable locations for CHP systems are sites where there is a constant load requirement for space heating and hot water demand (for example hospitals, greenhouse horticulture or as part of district heating).[1,2]

9.17.2.1. Characteristics

Role in EU energy system: CHPs are currently the largest supplier of thermal energy in European district heating networks.[3]

Primary energy source: most utilised now is natural gas. Geothermal (Italy and Iceland) and biomass (Denmark).

TRL: 9 – the technology is mature and commercially available throughout the EU.[3]

9.17.2.2. Life cycle: construction phase

Main components of a CHP:[4]

- Turbine/motor
- Generator
- Semiconductors

Infrastructure:

- Connection to the grid
- Connection to a building or facility
- Network of pipes, heat exchangers, pump houses and substations carrying heat from a power plant to buildings[4]

Specific materials

- Metals (e.g. steel, aluminium, copper)
- Permanent magnets in generators

9.17.2.3. Life cycle: use phase

Maintenance and renewable energy input.

9.17.2.4. Life cycle: end-of-life

Lifetime for (small) gas CHP is approximately 10–20 years.[5] Bigger CHP installations have a longer lifetime of approximately 50 years.[6] The lifetime of renewable CHP is expected to be similar.

Table C.39 Energy security indicators for combined heat and power

Geopolitical availability (score: 1)
Since almost all technologies contain permanent magnets (as part of generators) and copper (as part of the connection to the grid) these materials are considered a background risk (score 1). Besides this, CHP's core technology uses the following materials from the EU CRM list:[2] • Copper: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Aluminium: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). Since the average score for all materials is 1, this is the overall score assigned to this indicator.
Abundance (score: 2)

Since almost all technologies contain permanent magnets (as part of generators) and copper (as part of the connection to the grid) these materials are considered a background risk (score 1).

The critical materials in the technology's core and their abundance risk are:

- Copper, which has a medium abundance risk (1 to 100 ppm, score 2).
- Aluminium, which has a low abundance risk (>10 000 ppm, score 1).

Since the average score for all materials is 2, this is the overall score assigned to this indicator.

Circularity (score: 1)

The system of pipes delivering heat to buildings is extensive and underground, making end-of-life treatment more difficult. However, copper and aluminium have good recycling rates. Therefore, a score of 1 is given.

Supply chain complexity (score: 1)

Manufacturing: CHP components of such as turbines, engines, generators and heat exchangers are also used in other technologies, meaning manufacture of these components is not highly specialised.

Supply chain location (score: 1)

Market in Europe is developed. For example, Finland has the highest share of CHP generation (75% of district heat is based on CHP generation). Therefore, a score of 1 is given.

Digital vulnerability (score: 2)

For small CHP systems there is no particular digital risk to this technology compared to other value chains, and the damage resulting from cyberattacks can probably be limited. Bigger CHP systems rely on large quantities of electricity, and as the electricity system is vulnerable to cyberattacks, this value chain is also vulnerable. Therefore, a score of 2 is assigned to this energy security indicator.

Physical vulnerability (score: 1)

Low risk (score: 1) of physical attacks or disruptions.

Broader sustainability (score: 1)

Apart from space requirements, there are no significant broader sustainability considerations for CHP systems. Therefore, a score of 1 is assigned.

Affordability (score: 1)

LCOE depends on the type of fuel used, the efficiency of the system and the size of the installation. Since this technology is already widely used and makes efficient use of coupling heat and power, we estimate this technology to be more affordable than others, giving it a score of 1.

Skills (score: 1)

Although some skilled workers are needed for this value chain, no specific vulnerabilities with respect to workforce size or specific skills are foreseen, compared to other value chains. Therefore, we assign a score of 1.

9.17.2.5. Bibliography

[1] U.S. Department of Energy (2016). CHP Technology Fact Sheet Series. https://www.energy.gov/eere/amo/articles/overview-chp-technologies-doe-chp-technology-fact-sheet-series-fact-sheet-2017

[2] European Biogas Association (2020). Categorisation of European Biogas Technologies. https://www.europeanbiogas.eu/wp-content/uploads/2021/11/BioGas_AD_Final.pdf

[3] JRC (2022). Industrial and District Heat and Cold Management in the European Union. Luxembourg: Publications Office of the European Union. https://setis.ec.europa.eu/industrial-and-district-heat-and-cold-management-european-union_en

[4] Rezaei et al. (2021). 'Biomass-fuelled combined heat and power: integration in district heating and thermal-energy storage'. *Clean Energy.* Volume 5 (44-56). https://academic.oup.com/ce/article/5/1/44/6153909

[5] Greenspec (n.d.). Combined Heat and Power (CHP) Costs. https://www.greenspec.co.uk/building-design/chp-costs/#:~:text=CHP%20systems%20based%20on%20reciprocating%20combustion%20engines%20use,and%20the%20engine%20may%20be%20rebuilt%20several%20times.

[6] CE (Delft 2023), Internal communication.

9.17.3. Advanced control technologies

In the context of energy, advanced control technologies refer to sophisticated, data-driven, and automated systems and strategies used to optimise the generation, distribution, consumption and management of energy resources. These technologies play a crucial role in enhancing the efficiency, reliability and sustainability of energy systems.

9.17.3.1. Characteristics

Role in EU energy system: Advanced control technologies are not yet widely deployed but could play an important role in the future EU energy system. One application could be in smart grids, where they can control the integration of renewable energy sources, improve reliability and enable demand response programmes that encourage consumers to adjust their energy use at peak times, thereby balancing supply and demand at a local level.

On a larger scale, advanced control technologies could enable demand response systems, where power grid operators communicate with consumers and businesses to adjust their electricity consumption based on real-time pricing or grid conditions, which helps reduce peak demand and, therefore, grid stress.

Primary energy source: electricity.

TRL: Advanced control technology hardware and underlying infrastructure are well developed, and in this regard has a TRL of 9. However, the application of advanced control technology in the EU is not widely adopted. Advanced control technology sometimes involves energy consumers or generators ceding autonomy to network operators or other parties, raising concerns over privacy and autonomy. Smart grids, an embodiment of advanced control technology, are increasingly researched and piloted. Demand response is a key feature of future smart grids. The integration and application of demand response could proceed via contractual agreements between grid operators and consumers.

9.17.3.2. Life cycle: construction phase

Advanced control technologies consist of hardware and software. The construction phase of advanced control technologies involves the installation and setup of the hardware and software components necessary to monitor and manage the energy use of a company or household. Key aspects of the construction phase include:

- Hardware installation: This involves the deployment of physical components such as smart meters, sensors and other devices that can monitor local energy consumption and generation. These devices may be installed at various points, including the electrical panel, HVAC systems, and individual processes and appliances.

- Network setup: During construction, network infrastructure is established to connect the various sensors, meters and control components. This network can be wired or wireless, depending on the design of the system. It should provide reliable communication between the various devices and an aggregator or network operator.

9.17.3.3. Life cycle: use phase

The use phase of advanced control technologies involves the ongoing operation and utilisation of the system to actively manage and optimise energy consumption within the energy (typically electricity) system. Key aspects of the use phase include:

- Real-Time monitoring: There is continuous monitoring and collection of data on energy consumption, often in real-time. This data includes information on grid status and electricity generation and usage.

- Energy optimisation: Based on collected data and grid status, advanced control technologies can automatically optimise energy generation, use and power flow by implementing strategies like load shifting, demand response and integration with renewable energy sources. This results in energy efficiency and potential cost savings.

- Smart automation: Advanced control technologies can automate various processes, in both in households and industry, to ensure efficient energy use.

The use phase of advanced control technologies is characterised by active energy management, enabling aggregators or network operators to have greater control over the energy (power) system and its operation. During the use phase, hardware components are designed to function for around 10–20 years. Regularly software updates are required for optimisation, to remove software bugs and for the general functionality of the system.

9.17.3.4. Life cycle: end-of-life

The end-of-life phase of advanced control technologies refers to the stage when the system or its components reach the end of their operational life. Key aspects of the end-of-life phase include:

- System decommissioning: At end-of-life, components including smart meters, sensors, and communication devices are decommissioned. This may involve de-installing and removing the system from a home.

- Environmental Impact: Proper disposal and recycling of components are important to minimise environmental impact. Recycling or disposing of electronic components should follow local regulations and environmental standards.

- Data Management: Careful handling of any user data and system data is crucial. Data should be securely deleted or anonymised to protect user privacy.

The end-of-life phase is an important aspect of sustainable advanced control technology implementation, as the disposal and recycling of equipment and data must be carried out in an environmentally responsible and secure manner. Since components often contain valuable semiconductor materials, with including CRM, recycling/reusing/repurposing is important to reduce dependence on raw materials. E-waste is one of the fastest growing waste streams in the EU. Members of the European Parliament want to increase product life through reusability and reparability. In March 2023, the European Commission adopted a new proposal on rules promoting the repair of goods.[1]

Table C.40 Energy security indicators for advanced control technologies

Geopolitical availability (score: 2)
The geopolitical availability risk for advanced control technologies in Europe depends on several key factors. Market players determine the supply of advanced control technologies to the European market, while trade policies, global supply chains and location of manufacturing determine geopolitical availability. The CRM and their geopolitical availability (in brackets) used in advanced control technologies are: LREE (3), magnesium (3), germanium (1), borates (3), cobalt (2), platinum group metals (2), natural graphite (1), vanadium (2), titanium (1), gallium (3), silicon metal (1), manganese (1) and copper (1). The average geopolitical availability score of these CRM is 2. These materials are critical since they originate from one or few countries, with questionable availability. Recycling advanced control technologies could partly supply the demand for new advanced control technologies, but due to growing pressure on these CRM from various other sectors in the economy, raw resources are likely to remain crucial for scaling this technology.
Abundance (score: 2)
There are some CRM in this technology, which are required for the proper functionality of these devices and therefore highly important. Therefore, a score of 2 is assigned. The average abundance score for the materials described in the geopolitical availability section above is 2.
Circularity (score: 2)
Advanced control technology equipment includes complex electronics, which often contain CRM. The recycling of advanced control technology equipment is therefore important to reduce dependence on CRM supply. No data could be found on the recycling rate of advanced control technology equipment, but approximately 40% of general e-waste is recycled in the EU. Regulations are being established to improve recycle rates of e-waste. Higher recycling rates reduce dependence of raw resources of CRM. The European Commission has proposed a Critical Raw Materials Act, which is a comprehensive response to the risks of CRM supply disruption and structural vulnerabilities of EU CRM supply chains. Here, circularity is a major pillar, but given the moderate e-waste recycling rate of 40%, this risk is given a score of 2.
Supply chain complexity (score: 2)

Since advanced control technology consists of meters, digital infrastructure, communication networks, servers and more, there are many different supply chains involved. This introduces a certain complexity.

Two aspects: i) dependence on CRM, and ii) multiple supply chains, lead to some supply chain complexity, hence is scored 2.

Supply chain location (score: 2)

Advanced control technology equipment is produced globally, with many companies in the United States and Europe.[2] The supply chain for components such as semiconductors and chips is dominated by players such as Taiwan, South Korea, the United States and China.[3] Since manufacturing of advanced control technology is not centrally located in one part of the world and there several companies in Europe are active in this sector, but the raw materials are categorised as critical, the supply chain location risk is given a moderate score of 2.

Digital vulnerability (score: 3)

Advanced control technology is particularly vulnerable to digital risks.[4] Main risks are theft of smart meter data and cyberattacks.

Stealing smart meter data

Stealing encrypted digital information from smart meters is possible – if the encryption can be compromised, which demands significant computational resources. The EU has implemented several measures to improve data protection. Besides compromising encryption, hackers could also gain access by pretending to legitimately request access to data sources.

Cyberattacks

Cyberattacks on smart meters can be classified under four categories, based on the methodology and type of attack:

- Availability attacks:
  - Dos/DDos attack: disrupts a digital system by overwhelming it with excessive (digital) traffic
  - Replay attack: maliciously inserts, fraudulently repeats, or delays, data
- Integrity attack: manipulation that compromises data integrity and causes the grid to lose power
- Confidentiality attack: breaches confidentiality of (personal) data
- Authenticity attacks: attempt to obtain (log-in) authentication

Since digital vulnerability can entirely compromise the operation of advanced control technology, the highest score is assigned for digital vulnerability.

Physical vulnerability (score: 1)

Digital components are generally vulnerable to overheating and may be disrupted by electromagnetic radiation. Furthermore, radiofrequency jamming attacks can distort the wireless communication of advance control technology.[4] There is no particular physical risk to this technology compared to other value chains, and the damage resulting from physical events would probably be limited. Therefore, a score of 1 is assigned.

Broader sustainability (score: 1)

The main function of advanced control technology is to connect energy demand and supply, optimising energy use and generation, and providing valuable insights into load forecasting and system irregularities. With the adoption of more renewables and more energy storage to distribute the energy generated over the demand profile, advanced control technologies play a critical role that could lead to lower energy use, and therefore a more sustainable system.

Since this technology contains CRM, it is important to consider their extraction processes in the context of broader sustainability. There are multiple concerns over mining operations, including human rights abuses,[5] environmental pollution[6] and high water-use.[7] The CRM used in semiconductors, electronics, batteries, etc, are vital to the energy transition, but the harmful effects of mining operations on communities and the environment remain an issue.

Affordability (score: 1)

In general, advanced control technology aims to optimise energy generation and demand, and so lower energy use and reduce costs. To make this technology interesting to consumers, initial investment in AMI should be lower than the total savings it brings over a certain payback period.

Skills (score: 2)

The successful integration of advanced control technology into existing energy infrastructure requires a multidisciplinary approach, involving professionals with various skills and expertise – including electrical engineering, IT, cybersecurity, data management and analysis, and regulatory knowledge. Increasing labour demand in the electrical energy sector is expected to be a limiting factor for the adoption of this technology. The EU faces a shortage of skilled workers in this industry. Other developments, such as the installation of solar PV, heat pumps, and broader electrification of homes and businesses, increase demand and put pressure on the available workforce in this sector. Since this introduces a certain risk regarding the implementation of this technology, this risk category is scored 2.

9.17.3.5. Bibliography

[1] European Commission. (2023). Right to repair: Commission introduces new consumer rights for easy and attractive repairs. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1794

[2] Allied Market Research. (2021). Advanced Metering Infrastructure (AMI) Market by Product Type (Smart Metering Devices, Solutions, and Services) and End User (Residential, Commercials, and Industrial): Global Opportunity Analysis and Industry Forecast, 2021-2030.

[3] Teer, J. (2023). Reaching breaking point: The semiconductor and critical raw material ecosystem at a time of great power rivalry. https://hcss.nl/wp-content/uploads/2022/10/Reaching-Breaking-Point-Full-Version-HCSS-2022.pdf

[4] Balakrishnan, R., & Geetha, V. (2021). 'Review on home energy management system'. *Materials Today: Proceedings*, 47, 144-150. https://doi.org/https://doi.org/10.1016/j.matpr.2021.04.029

[5] Amnesty International. (2023). Democratic Republic of the Congo: Industrial mining of cobalt and copper for rechargeable batteries is leading to grievous human rights abuses. Amnesty International. https://www.amnesty.org/en/latest/news/2023/09/drc-cobalt-and-copper-mining-for-batteries-leading-to-human-rights-abuses

[6] Earth.Org. (2023). The Environmental Impacts of Cobalt Mining in Congo. https://earth.org/cobalt-mining-in-congo

[7] Energy Transitions Commission. (2023). Material and Resource Requirements for the Energy Transition. Energy Transitions Commission. https://www.energy-transitions.org/wp-content/uploads/2023/08/ETC-Materials-Report_highres-1.pdf

9.18. Off-grid energy systems

9.18.1. Heating based on renewable gas: biogas tank

In a biogas tank, organic waste is transformed into biogas and effluent and digestate, which can be used as fertiliser. The tank can vary in size, from large industrial tanks used by large waste producers to small individual tanks used by households. Biomass is digested by anaerobic micro-organisms, creating biogas that can be used for heating or cooking.

9.18.1.1. Characteristics

Role in EU energy system: Energy conversion/energy distribution and infrastructure.

Biogas is seen as an important renewable energy carrier. In the EU, its use could more than triple from 15 Mtoe in 2015 to around 50 Mtoe in 2050.

Primary energy source: biogas (derived from biomass).

TRL: 9 – biogas is already commercially available and used in several applications.

9.18.1.2. Life cycle: construction phase

A biogas tank consists mainly of steel.

9.18.1.3. Life cycle: use phase

The operation of a biogas tank requires a continuous supply of biomass. The use of biogas for heating will require a relatively continuous supply of biogas, which can be stored in the tank.

9.18.1.4. Life cycle: end-of-life

Recycling of the tank might be required.

Table C.41 Energy security indicators for biogas tanks

Geopolitical availability (score: 1)
No complexity, feedstock for biogas is widely available within the EU. No geopolitical risks regarding tank materials. Therefore, the score is 1.
Abundance (score: 1)
Resources to produce biogas are abundant. There are no risks regarding abundance of materials for gas tanks, therefore, the score is 1.
Circularity (score: 1)
Biogas tanks may be subject to recycling objectives after at end-of-life, but this does not constitute a complexity – therefore, the score is 1.

Supply chain complexity (score: 1)
No complex manufacturing processes. Limited complexity to the supply chain for biogas, but this is covered in the factsheet on biomass (see above). A remote (off-grid) biogas tank does need to be supplied with biogas, either locally produced or transported by truck.
Supply chain location (score: 1)
Everywhere/ubiquitous.
Digital vulnerability (score: 1)
N/A.
Physical vulnerability (score: 1)
N/A.
Broader sustainability (score: 2)
There is a sustainability risk related to materials that might be used as feedstocks. Due to the small scale of biogas tanks, chemical waste or other waste of prohibited categories (e.g. from drug laboratories) could be loaded in the digester. This is a way to dispose of illegal waste, which would end up in the food value chain via recycling of the digestate.
Affordability (score: 1)
Depending on application and availability of feedstock, a range of 0.04 to 0.1 EUR/kWh.[1]
Skills (score: 1)
No specific skills required.

9.18.1.5. Bibliography

1 PBL (2023), Model SDE++, Den Haag: Planbureau voor de Leefomgeving. https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.pbl.nl%2Fsites%2Fdefault%2Ffiles%2Fdownloads%2Fpbl-2023-ot-model-sde-plus-plus-2023-4815_1.xlsx&wdOrigin=BROWSELINK

9.18.2. Heating based on solid biomass: pellet stove

A pellet stove is an iron stove that can create both low and high temperature heat. Used to heat the atmosphere or water, it is renewable alternative to a boiler or central heating system run on natural gas (or another fossil fuel). A major advantage of a pellet stove is that it is disconnected from the grid and therefore creates a high level of independence. A disadvantage is that a pellet stove could generate local air pollution, although this can be significantly reduced using filters. There a whole range of different types of pellet stove, with modern versions using automatic supply of pellets, creating an overall supply of heat (water, atmospheric), with high efficiency and low levels of air pollutants.[1,2]

9.18.2.1. Characteristics

Role in EU energy system: Energy conversion. Pellet stoves are not really the subject of a policy target but might play a role in local renewable heating policies.

Primary energy source: pellets (woody biomass).

TRL: 9

9.18.2.2. Life cycle: construction phase

A rather basic technology with no critical materials, only steel.

9.18.2.3. Life cycle: use phase

Supply of pellets (woody biomass) is needed.

9.18.2.4. Life cycle: end-of-life

At end-of-life, a pellet stove needs to be recycled.

Table C.42 Energy security indicators for pellet stoves

Geopolitical availability (score: 1)
No issues. Both pellets and the materials for a pellet stove are sufficiently available in EU and non-EU countries.
Abundance (score: 1)
No issues related to the stove.
Circularity (score: 1)
Pellet stoves may be subject to recollection and recycling schemes, but this is not particularly complex – therefore score of 1 is justified.
Supply chain complexity (score: 1)
Not complex: just a straightforward steel structure, which can be designed in many different ways. Therefore, a score of 1 is justified.
Supply chain location (score: 1)
Pellet stoves can be produced anywhere steel is available by a blacksmith. Therefore, a score of 1 is justified.
Digital vulnerability (score: 1)
N/A – a pellet stove is not connected to digital applications.

Physical vulnerability (score: 1)
None.
Broader sustainability (score: 2)
Local air pollution is an issue that would make extensive use of pellet stoves in a densely populated area undesirable.
Affordability (score: 1)
A pellet stove is a cheap option, with long-term prices dependent only on pellets, since stoves have a very long lifetime. 0.035 EUR/kWh.
Skills (score: 1)
Blacksmithing skills may be needed to produce a pellet stove, although mas produced pellet stoves are also abundantly available.

9.18.2.5. Bibliography

1 CE Delft (2021), Factsheet pelletketel, Delft: CE Delft. https://ce.nl/wp-content/uploads/2021/04/02_Factsheet-Pelletketel_DEF.pdf

2 PBL (2023) Model SDE++, Den Haag: Planbureau voor de Leefomgeving. https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.pbl.nl%2Fsites%2Fdefault%2Ffiles%2Fdownloads%2Fpbl-2023-ot-model-sde-plus-plus-2023-4815_1.xlsx&wdOrigin=BROWSELINK

9.18.3. Solar heating: thermal collector

Solar heating with a thermal collector uses solar radiation to heat a fluid that can be used for space heating or to heat water. Flat plate collectors are the most common type of solar thermal collector (concentrating solar collectors are the other type, discussed in 1.9). They consist of an absorber plate, which is usually mounted on the roof of a building to be exposed to sunlight. A fluid (usually water or a mixture of water and antifreeze) circulates through tubes or channels within the absorber plate. As sunlight strikes, it heats the plate. The heat is pumped or circulated to a heat exchanger or storage tank, where the thermal energy can be used for heating purposes such as domestic hot water (DHW) and space heating (SH). One of the main reasons for the weak solar thermal market is strong competition from other renewable technologies – mainly heat pumps and solar PV.[1]

9.18.3.1. Characteristics

Role in EU energy system: In 2021, the EU had overall installed capacity of 1.4 GW.[2]

Primary energy source: solar radiation.

TRL: 9 – the technology is mature and commercially available throughout the EU.

9.18.3.2. Life cycle: construction phase

Components:[2]

- Absorber plate: made of copper or aluminium, with a coating that has high solar absorptance and low thermal emittance.
- Transparent cover: glass or plastic
- Insulation: fiberglass or foam
- Heat transfer fluid system:
  - fluid: water or mixture of water and antifreeze
  - tubes or channels within the absorber plate to carry the heat transfer fluid
- Frame (to provide structure and support): steel or aluminium
- Water tank (including heat exchanger, covering, electrical resistance and inner pipes for sanitary water flow):
  - tank material: stainless steel or glass-lined steel
  - insulation: high density pure foam
  - heat exchanger: copper or stainless steel
  - magnesium or aluminium anode rod to protect against corrosion
- External support (to fasten the system to a roof)
- Other components: External HDPE pipes
- Critical materials: copper, aluminium, magnesium (optional)

9.18.3.3. Life cycle: use phase

During the use phase, only maintenance and cleaning of the thermal collector is needed.

9.18.3.4. Life cycle: end-of-life

More than 80% of components are made from metal and can be recycled.[3]

Table C.43 Energy security indicators for solar heating (thermal collectors)

Geopolitical availability (score: 1)
The critical materials for solar thermal collectors and their relative geopolitical availability are as follows:

- Copper: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1).
- Aluminium: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1).

Since the average of the materials is 1, this score is given.

Abundance (score: 2)

The critical materials in the technology and their abundance are:

- Copper, which has a medium abundance risk (1 to 100 ppm, score 2).
- Aluminium, which has a low abundance risk (>10 000 ppm, score 1).

Since the average score for all materials is 2, this is the overall score assigned to this indicator.

Circularity (score: 2)

Metal components (representing more than 80% of total mass) can most likely be recycled. However, collection and recycling systems are not yet fully established – therefore we give a score if 2.

Supply chain complexity (score: 1)

Solar thermal collectors are a relatively simple technology, and, in most countries, local manufacturers produce, install and maintain the equipment themselves. Therefore, a score of 1 is given.

Supply chain location (score: 1)

Materials: The EU has a small percentage of overall reserves.

Manufacturing: China has the highest capacity for thermal collector manufacturing, followed by Turkey, the United States and then Germany.[4] German was the lead manufacturer of flat plate collectors in 2015,[1] followed by China and then Turkey.

Operations: Solar thermal systems operate on both cloudy and sunny days, making them suitable to many European locations.[5]

Because the supply chain has an overall strong presence in Europe, a score of 1 is given.

Digital vulnerability (score: 1)

Although cyberattacks can never be excluded, there is no particular digital risk for this technology compared to other value chains, and the damage resulting from a cyberattack could probably be limited. Therefore, a score of 1 is assigned.

Physical vulnerability (score: 1)

The digital vulnerability of solar thermal collectors is similar to that of PV. They are vulnerable to mechanical damage – caused by falling objects, for example – and can be damaged by extreme weather conditions such as hailstorms or hurricanes. Accumulation of dust, dirt, bird faeces and leaves on the thermal collectors can reduce functionality. Severe air pollution can also cause reduce thermal output due to less sunlight coming in. However, compared to other technologies these represent small risks and therefore a score of 1 is assigned.

Broader sustainability (score: 1)
Thermal collectors are usually placed on the roofs of buildings, and therefore require little space. Locally, they improve air pollution by replacing gas for heating. The only low risk (score: 1) is from the transfer fluid, which in some cases (e.g. glycol-based solutions) can be toxic and environmentally harmful if leaked or improperly managed. Proper disposal and maintenance are needed to minimise this risk. To summarise, the overall sustainability risk is low, therefore a score of 1 is assigned.
Affordability (score: 2)
The exact LCOE for thermal collectors is not publicly available. Since this technology is commercially available, but less widely than solar PV, which is also more efficient (and scores a 1), we assign solar thermal collector technology a score of 2.
Skills (score: 1)
The manufacturing, installation, maintenance and recycling of thermal collectors requires skilled labour, but the necessary skills can be acquired in under a year. Therefore, we assign a score of 1.

9.18.3.5. Bibliography

[1] M. Jakubcionis (2018). Solar Thermal Heating and Cooling Market Development Report EUR 29925 EN, European Commission, Luxemburg. doi:10.2760/90387, JRC118312.
[2] Solar Thermal World (2023). Historically high growth in Europe's solar heat market in 2021. https://solarthermalworld.org/news/historically-high-growth-in-europes-solar-heat-market-in-2021/#:~:text=10.7%20million%20solar%20thermal%20systems%20are%20in%20operation,which%20corresponds%20to%20over%2053.9%20million%20m%202.
[3] Ardente et al. (2005). Life cycle assessment of solar thermal collector. *Renewable Energy.* Volume 30 (1031-1054). https://www.sciencedirect.com/science/article/abs/pii/S0960148104003714
[4] Weis and Spörk-Dür (2020). Solar Heat World Wide: Detailed Market Figures 2020. https://www.iea-shc.org/Data/Sites/1/publications/2022-IEA_SHC-Solar_Heat_Worldwide-3.pdf
[5] Energy Technology List (2020). Solar Thermal Systems and Collectors. https://assets.publishing.service.gov.uk/media/65dc416287005a1daa80f83a/Solar_Thermal_TIL_-_April_2020.pdf

9.19. Energy Transmission and Distribution Technologies

9.19.1. Hydrogen storage and transportation

Hydrogen is expected to play an increasingly important role in the energy system – and will need to be stored and transported, just as fossil fuels are in the current system. The primary method for storing hydrogen, is in the form of ammonia or hydrogen gas.

Ammonia has a high volumetric density, requires low storage pressure, and is stable over time. Ammonia is therefore considered important for transporting hydrogen overseas. However, converting ammonia back to hydrogen requires significant amounts of energy (3.2 MJ/kg ammonia).[1] Methanol, LOHC and DBT can also be used as hydrogen carriers.

Hydrogen gas can be stored in underground geological formations, such as salt caverns, aquifers or empty gas fields. This is expected to become increasingly important as the energy system becomes more and more dependent on wind and solar energy, requiring large-scale and seasonal energy storage. Absence of oxygen makes hydrogen storage underground sufficiently safe, and current availability of storage capacity makes it relatively cheap.[2] Hydrogen can also be stored in storage tanks or cylinders in the form of compressed and liquified hydrogen, liquid organic carriers, metal hydrates or methanol. Liquid hydrogen requires 800 times less volume at standard temperature and pressure but has the disadvantage of requiring very low temperatures (-253 °C).

Underground storage is efficient, stable, economically feasible and would enable hydrogen to be integrated into a hydrogen pipeline transport system.[1]

For onshore transport, stainless steel pipelines (e.g. from the old natural gas system, with minimal adaptations) can be used.

9.19.1.1. Characteristics

Role in EU energy system: Storage.

Hydrogen storage is essential in a climate neutral energy system and expected to increase in all EU 2050 climate neutral scenarios – from its current 6 Mtoe to at least 15 Mtoe, but more likely around 50 Mtoe, and up to 150 Mtoe the maximum EU 2050 scenario.[3]

Primary energy source: Hydrogen can have different energy sources (fossil and renewable) but this is not applicable for storage.

TRL: 5–8

Pilots are currently being carried out with storage in salt caverns. This option is already feasible in the short term. Large-scale storage in empty gas or oil fields might be possible from 2035 on but requires further research.[4]

9.19.1.2. Life cycle: construction phase

No specific new materials are needed to manufacture systems for hydrogen storage, compared to materials already also in use for fossil fuel storage. Underground storage will require cushion gas to pressurise (or maintain pressure of) the gas. Since this may be required in significant volumes, it makes sense to consider cheaper gases, like CO_2, CH_4 or N_2. Contamination of hydrogen with cushion gas is a problem, especially when a very high level of hydrogen purity is required.

To convert gas pipelines to pure hydrogen pipelines, more compressor stations are needed along the route and general modernisation of infrastructure may be needed.

9.19.1.3. Life cycle: use phase

Maintenance and general monitoring. Purifying hydrogen contaminated with cushion gas may be required.

9.19.1.4. Life cycle: end-of-life

At end-of-life, infrastructure (e.g. pipelines and compressors) must be recycled. Empty fields can be decommissioned and closed when no longer needed.

Table C.44 Energy security indicators for hydrogen storage and transportation

Geopolitical availability (score: 1)
Underground storage facilities are sufficiently available in the EU but located in specific areas, mainly in northern Europe. No dependence on non-EU countries is foreseen, and neither does the supply chain require any critical materials – therefore a score of 1 is given.
Abundance (score: 1)
No critical materials required, and abundance of storage facilities is covered in the previous point – therefore a score of 1.
Circularity (score: 1)
Where possible, components and equipment from decommissioned storage facilities and installations can be repurposed or relocated to new projects. For example, compressors and electrical components can find new applications in other energy storage projects or industrial settings.
Supply chain complexity (score: 2)
The realisation of the whole storage and transportation system could be complex, especially when no former natural gas transportation and storage system is available. Significant investments from governments and procedures related to spatial planning may be required.
Supply chain location (score: 1)
Materials needed for storage and transportation are widely manufactured, both in the EU and elsewhere. Underground storage facilities are sufficiently available in the EU but located in specific areas, mainly in northern Europe. southern and central Europe have significantly fewer available natural storage facilities. The highest storage scenario (150 Mtoe) in the EU 2050 climate neutral scenarios mentioned above, could in principle be accommodated using salt caverns in northern Europe (Germany, Denmark, Netherlands, UK and Poland).[5]
Digital vulnerability (score: 1)
As for other technologies directly relying on renewable energy, certain control software is needed to manage charging and discharging based on weather profiles and data from network operators. Although cyberattacks can never be excluded, there is no particular digital risk for this technology compared to other value chains, and the damage resulting from a cyberattack could probably be limited. Therefore, a score of 1 is assigned.
Physical vulnerability (score: 1)
Underground storage entails risks of contamination of hydrogen by cushion gas, as well as leakage to the surface. However, according to the literature, these risks can be mitigated through monitoring and control.[5] Other physical vulnerabilities are not relevant for this supply chain.
Broader sustainability (score: 1)
Salt caverns used for underground activities can potentially cause subsidence and seismic activity. Although soil subsidence is a natural part of cavern construction, it can be managed and

mitigated if necessary. The seismic activities measured at storage caverns are disproportionate to those measured at gas fields. While the risks associated with underground activities related to natural gas storage are well understood, the risks of hydrogen storage are relatively unknown and necessitate additional research. Furthermore, extraction of salt and underground activities frequently face resistance from local communities, primarily due to concerns over subsidence and seismic events.

Since for this value chain has limited sustainability risks, a score of 1 is assigned.

Affordability (score: 1)

Since no hydrogen storage facility is operational yet, there are no data available. Estimates from the literature point to a hydrogen storage cost of approximately 3 500 EUR/tonne (0.11 EUR/kWh).[1]

Skills (score: 1)

The exploration and application of hydrogen transportation and underground storage facilities require a specialised labour force. However, workers with knowledge of natural gas can learn expertise specific to hydrogen in approximately a week.

9.19.1.5. Bibliography

[1] Kalavasta et al. (2018), HyChain model. https://ispt.eu/projects/hychain/
[2] D. Zivar et al. (2020), Underground hydrogen storage: A comprehensive review, International Journal of Hydrogen Energy, Amsterdam: Elsevier. https://doi.org/10.1016/j.ijhydene.2020.08.138
[3] European Commission (2018), A Clean Planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, Luxembourg: Publications Office of the European Union. https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf
[4] Netbeheer Nederland (2023), Het energiesysteem van de toekomst (ii3050), Den Haag: Netbeheer Nederland. https://mcusercontent.com/fb9c662b873082575f8ba63d1/files/2c350ac0-7445-8d26-e942-c188bc934c3d/NetbeheerNL_Rapport_II3050_Scenario_s_NL_28032023_3_.pdf
[5] D.G. Caglayan et al. (2019), Technical potential of salt caverns for hydrogen storage in Europe, International Journal of Hydrogen Energy, Amsterdam: Elsevier. https://doi.org/10.1016/j.ijhydene.2019.12.161

9.19.2. High-voltage direct current transmission

High voltage direct current (HVDC) is used for more efficient long-distance transmission of electric power. Unlike conventional alternating current (AC) systems, which periodically change direction of flow, HVDC systems maintain a consistent flow of electricity in one direction. HVDC systems consist primarily of cables (over hundreds of kilometres, up to several kilometres) and equipment for conversion, switching and control of power flow. Important innovations in HVDC technologies are:[1]

- HVDC circuit breakers: voltage source converter based HVDC (VSC-HVDC) systems require fast HDVC circuit breakers to mitigate DC line short circuit faults. DC based transmission lines lack a ‘zero crossing point’, which makes it more difficult to interrupt the current.

- Gas insulated lines (GIL) DC: GI lines can be used for HV transmission. The advantages of GIL over conventional transmission lines are:

   - Reducing electromagnetic fields: GIL creates 15–20 times smaller magnetic field strengths.
   - High safety: GIL are fire resistant and do not contain flammable material.
   - Routing: 90-degree, vertical or curved sections with narrow spacing is possible.
- HVDC mass impregnated (MI) cables: MI HVDC cables are a proven and reliable technology that can be used for HV transmission.
- HVDC XLPE (cross-linked polyethylene): HVDC XLPE cables can be used for HV transmission.
- Voltage source converters: used to connect HV-AC systems to HV-DC systems.

9.19.2.1. Characteristics

Role in EU energy system: HVDC cables are already in use in Europe, mostly as interconnectors between different countries. The growing importance of electricity as energy carrier and the rise of offshore wind energy will require a further growth in HVDC transmission. The EU offshore renewable energy strategy set a target of least 60 GW of offshore wind energy and 1 GW of ocean energy by 2030, and 300 GW of offshore wind energy and 40 GW of ocean energy by 2050. Transporting and integrating this amount of energy into the grid cannot be achieved without the deployment of HVDC systems.[2]

Primary energy source: HVDC transports electrical energy over long distances, and therefore does not use primary energy, so this criterium is not relevant in this context.

TRL: HVDC power systems are already in use across Europe. Further innovations of components are being developed to improve operational and safety characteristics.

Components:[1]

- HVDC Circuit Breakers: TRL 3–6
- Gas Insulated Lines (GIL) DC:
   - 2020: TRL 4–5
   - 2025: TRL 6
   - 2030: TRL 8
- HVDC MI cables: TRL 9
- HVDC XLPE: TRL 5
- Onshore:
   - Extruded HVDC, 320 kV: TRL 9 (2019)

- Extruded HVDC, 525 kV: TRL 5 (2020)
- Extruded HVDC, 600 kV: TRL 3 (2020)

- Voltage Source Converters:
  - Monopole and bipole VSC: TRL 9
  - DC/DC converter: TRL 4
  - VSC half bridge: TRL 9
  - VSC full bridge: TRL 8

9.19.2.2. Life cycle: construction phase

The installation of convertor stations requires civil engineering and ground working. The construction of overhead lines involves constructing foundations, wireworks, tower formation and ropeway engineering. Raw construction materials are steel, aluminium, concrete, stone, bricks, ceramics, cement and mortar. For underground HVDC cables, trenches must be dug over long distances, which requires heavy excavators and a work corridor of 30–35 metres. Trucks and trains are required to transport the raw materials. Zhang et al. (2023) assumes railway transportation of the transformers and power lines.[3]

Components (ENTSO-E, 2023):

- GIL DC:
  - Outer sheath: aluminium.
  - Inner conductor: aluminium.
  - Insulator: epoxy-resin and insulation gas
- HVDC MI cables:
  - Conductor: copper or aluminium
  - Insulation: impregnated paper
  - Sheath: lead alloy
  - Protective plastic sheath: polyethylene.
  - Steel armour: steel
- HVDC XLPE
  - Conductor: copper or aluminium
  - Insulation: crosslinked polyethylene

- Voltage source converters:
    - AC/DC converter
    - Transformer (optional tapping in series/parallel)
    - DC-link capacitors
    - Passive high-pass filters
    - Phase reactors
    - DC cables
    - DC breaker (optional)

9.19.2.3. Life cycle: use phase

HVDC transmission lines require maintenance during use phase. Zhang et al. assume a 10% replacement rate during the lifetime of a HVDC transmission line.[3]

9.19.2.4. Life cycle: end-of-life

At end-of-life stage, transformer oil, SF_6, and metals such as copper, steel and aluminium must be recycled. 90% of the steel and aluminium can be recycled for secondary use.[3]

Table C.45 Energy security indicators for HVDC

Geopolitical availability (score: 1)
There are several major market players producing HVDC in Europe, which were able to meet total demand from 2015 to 2018.[4] Later data on supply and demand could not be retrieved. Regarding raw materials, there are multiple locations globally that are plentiful in these raw materials – mainly aluminium, copper and iron (steel). Besides the metals needed in HVDC, other materials like polymer compounds and semiconductors are required. Some of the most important polymers used are cross-linked polyethylene (XLPE), which offers electrical insulation, thermal resistance and mechanical strength to the cable. Alternative polymers with the same function are ethylene propylene rubber (EPR), polyethylene (PE) and polyvinyl chloride (PVC). These polymers are derived from petrochemical feedstocks. This introduces a dependence on petroleum and natural gas, which are in high demand and inherently exhaustible.5 The CRM used in HVDC and their relative geopolitical availability are as follows: • Aluminium (1) • Copper (1) Since the average score for these materials is 1, this is the overall score assigned to this indicator.
Abundance (score: 2)

The metal conductors required to produce HVDC are mainly: aluminium, copper and iron (to make steel). Aluminium is often preferred over copper for very long distances, due to its lighter weight.

Various polymer compounds, such as those used for cable insulation and jacketing, are also essential components of HVDC cables. These polymers are made from petrochemical feedstock. Therefore, oil and gas are required, which are in high demand, especially in the mobility and energy generation sector. The material requirement of petroleum or natural gas products for the manufacturing of polymer components in HVDC cables is expected to be significantly lower than for applications like mobility and energy generation. By reducing the fossil energy requirement in mobility and energy generation sectors, among others, sufficient petroleum and gas is expected to be available to manufacture HVDC. Combined with the readily available metals in HVDC cables, the abundance risk indicator is scored moderately.

There are few CRM in this technology and the importance of these materials to the technology is low to medium, because of highly abundant aluminium and moderately abundant copper. Therefore, a score of 2 is assigned.

Circularity (score: 1)

Metals such as copper, steel and aluminium can in general be recycled. Recycling of polymer compounds such as XLPE and EPR is more challenging and requires specialised processes and facilities. For example, a material such as XLPE cannot be reused due to its chemical bonds as result of the crosslinking process. Often, the polymer components in decommissioned HVDC cables is incinerated or landfilled. However, recycling is becoming more common for polymer compounds such as XLPE.[6,7]

Due to the readily recyclable metals, but somewhat harder to recycle polymers, the circularity risk is scored moderately.

Supply chain complexity (score: 1)

Since the metals used in HVDC cables are not listed as critical and the polymer compounds are made from petrochemical feedstocks, which are currently abundantly available, no particular supply chain complexity is identified.

The supply chain of HVDC consists of cable manufacturing, converter stations, supporting infrastructure and various high-voltage equipment. The supply chain for land cables differs from undersea cables, with the latter requiring specialised marine construction expertise. Growing sustainable energy generation in various parts of Europe, especially offshore, will require more HVDC transmission to bring renewably generated electricity onshore.

The materials required for HVDC technology have no particular geopolitical risk or high abundance risk. The equipment required to operate HVDC transmission requires electronics containing semiconductor materials, many of which are considered critical by the EU. However, assessing the infrastructure for HVDC specifically, the supply chain complexity risk is low.

Supply chain location (score: 1)

With regards to the material use of these cables, metals can be sourced from multiple locations. For aluminium production, the EU could source domestically from countries like Greece, Montenegro and France, or import from countries like Australia and China. Copper is also found in Europe –mainly Poland, Spain and Bulgaria – and in larger amounts globally in Chile, Peru and China. Iron, required for making steel, is abundantly available both globally and in Europe (with a concentration in Scandinavia).

The supply chain is geographically diverse. All, or almost all, elements of the value chain are covered by suppliers within the EU. Therefore, no particular risks are present and a score of 1 is assigned.

Digital vulnerability (score: 2)

HVDC are vulnerable to cyberattacks. Pan et al. simulated three types of attacks (timing attack, replay attack and false data injection attack) on an AC-HVDC system, resulting in large oscillations or unstable conditions for all three attacks.[8]

Physical vulnerability (score: 2)

Sabotage

Undersea HVDC cables are vulnerable to sabotage. In May 2023, NATO's intelligence chief stated that were increased concerns that Russia may target undersea cables and infrastructure.

Broader sustainability (score: 2)

Zhang et al. conclude that the infrastructure-induced emissions for ultra-high voltage direct current (UHVDC) transmission lines are negligible compared to the annual emissions reduction due to the delivery of renewable electricity at full load.[3] For nine UHVDC projects (in China) they estimated infrastructure-induced emissions of 16.7 Mt CO_2, while the annual reduction was estimated to be 305.2 Mt CO_2 for these projects. Considering a 40-year service lifetime, the infrastructure-induced emissions are even more negligible.

HVDC projects are typically very large in terms of CAPEX and regulatory involvement. Since large areas of land/seabed are required to build HVDC, environmental consequences must be carefully identified and assessed.

The application of HVDC transmission integrates large scale renewable energy generation in the EU. Due to the large infrastructural projects of HVDC technology, the environmental impact is carefully identified and assessed and is an integral part of the development of HVDC. Even though these individual risks are not very high, as there are various risks related to different sustainability aspects of this value chain, an overall score of 2 is assigned for broader sustainability.

Affordability (score: 1)

The affordability of HVDC cables is complex, multifaceted and influenced by a range of factors. HVDC cables are a critical component of modern electrical infrastructure, enabling efficient long-distance power transmission and the integration of renewable energy sources.[9]

In general, HVDC lines are more costly over short distances. This can be seen in the figure below. However, after a certain critical distance (where the AC and DC graphs intersect) the costs of a DC cable are less than for a similar AC line.

A review by Härtel et al. provide an overview of the cost parameters for different HVDC projects. Prices for HVDC cables in this review range from 0.32m EUR/km to 3.2m EUR/km.[10]

The affordability of the HVDC technology depends on multiple factors. Distance, power transmission, transmission voltage and onshore/offshore application all are important to consider, among other factors. Due to the cost advantage of HVDC over long distances, the affordability of HVDC is good, hence a 1.

Skills (score: 2)

HVDC technology requires extensive knowledge and expertise in electrical engineering. These skills are required to incorporate HVDC in the energy landscape, with large new volumes of sustainable energy from sources like solar and wind. In Europe, offshore HVDC applications will be especially important to transport large volumes of electrical energy from sea to land. Onshore HVDC applications will also be crucial, for instance in Germany, where they will transport energy generated from windfarms in the North to industry in the South.

Due to the large presence of credible companies active in HVDC technology, Europe has the skills required to widely adopt HVDC in energy infrastructure. These skills require relatively long, university-level education, but compared to more decentralised technologies such as heat pumps and PV, fewer installers are needed overall. To summarise, the skills needed are complex and specialised, but a relatively small workforce is needed, giving a score of 2.

9.19.2.5. Bibliography

[1] ENTSO-E. (2023). Technopedia. https://www.entsoe.eu/Technopedia/

[2] European Commission. (2022). High voltage direct current (HVDC) & direct current (DC) technologies. https://setis.ec.europa.eu/implementing-actions/high-voltage-direct-current-hvdc-direct-current-dc-technologies_en

[3] Zhang, Y., Liu, T., Yao, L., Song, Q., & Gao, C. (2023). ‘Negligible carbon costs of UHVDC infrastructure delivering renewable electricity’. *Resources, Conservation and Recycling*, 192, 106940. https://doi.org/https://doi.org/10.1016/j.resconrec.2023.106940

[4] EUROPACABLE. (2018). Demand and Capacity for HVAC and HVDC underground and submarine cables.

[5] European Commission. (2021). Implementation Plan on ‘High Voltage Direct Current (HVDC) & DC Technologies’. https://setis.ec.europa.eu/system/files/2022-02/SETPlan_HVDC_DC_Tech_ImplementationPlan_Final.pdf

[6] R. Huuva, E. R. (2019). Recycling XLPE from cable waste. https://www.jicable.org/TOUT_JICABLE_FIRST_PAGE/2019/2019-D6-2_page1.pdf

[7] Borealis Group. (2020). Unlocking the value of recycled XLPE. https://www.borealisgroup.com/storage/Polyolefins/Energy/Unlocking-the-value-of-recycled-XLPE_CaseStudy.pdf?utm_source=LinkedIn&utm_medium=social&utm_campaign=recycled%20XLPE

[8] Pan, K., Dong, J., Rakhshani, E., & Palensky, P. (2020). ‘Effects of Cyber Attacks on AC and High-Voltage DC Interconnected Power Systems with Emulated Inertia’. *Energies*, 13(21).

[9] Härtel et al (2017), Review of investment model cost parameters for VSC HVDC transmission infrastructure. https://www.sciencedirect.com/science/article/abs/pii/S0378779617302572

[10] Stan, Andrei, Sorina Costinaș, and Georgiana Ion. 2022. "Overview and Assessment of HVDC Current Applications and Future Trends" Energies 15, no. 3: 1193. https://doi.org/10.3390/en15031193

9.20. Smart cities

9.20.1. Autonomous driving

Autonomous driving, also known as self-driving or driverless technology, refers to the capability of a vehicle to navigate and operate on its own without human intervention. It is a transformative innovation in the automotive industry driven by advanced technologies such as sensors, AI, machine learning and connectivity. Autonomous vehicles can operate at various levels of automation, from basic driver assistance systems to fully autonomous, driverless cars.[1]

9.20.1.1. Characteristics

Role in EU energy system: In the context of energy, autonomous driving may reduce the energy consumption of vehicles by improving traffic flows (e.g. preventing traffic jams and reducing stationary wait times), and by reducing excessive acceleration/braking.[2]

A study by the US National Renewable Energy Laboratory in 2016 found that autonomous driving can reduce energy consumption by 7–16% due to eco-driving, 2–4% using vehicle-to-infrastructure-communication (e.g. traffic lights), and 3–5% using platooning.[3]

Primary energy source: depending on the car type: fossil fuel and/or electricity.

TRL:[1]

- Driver assistance/partial automation: TRL 9
- Conditional automation: TRL 5
- Full automation: TRL 3

9.20.1.2. Life cycle: construction phase

Autonomous driving technology obviously requires autonomous vehicles. Some cars already have self-driving capabilities, although only in specific situations and with limitations. Full application of autonomous driving technology implies autonomous vehicles fully capable of self-driving. These autonomous vehicles generally have more sensors and/or cameras to enable self-driving.

Autonomous driving technology requires electronics such as sensors and central processing units (CPUs). A study by Gawron et al. listed the following components:[2]

- Camera: plastic, electronics
- Radar: plastic, electronics
- Sonar: plastic, electronics
- Large LiDAR: cast iron, aluminium, copper, glass, plastic, REE, electronics
- Small LiDAR: cast iron, aluminium, copper, glass, plastic, REE, electronics
- GPS/INS: plastic, electronics
- Dedicated short range communication: steel, aluminium, copper, plastic, electronics
- CPU: aluminium, copper, plastic, REE, electronics

Semiconductor materials are utilised in a wide range of components within autonomous vehicles, such as microprocessors, memory devices, sensors (e.g. image sensors, LiDAR sensors), radar systems, communication devices and power electronics. These materials are integral to processing data from the vehicle's surroundings, enabling real-time decision-making and controlling various vehicle functions – all of which are essential for the safe and efficient operation of autonomous vehicles. Semiconductor technology generally contains: palladium, cobalt, gallium, germanium, silicon and REE.

Rare earth elements (REE): scandium, yttrium, lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium

9.20.1.3. Life cycle: use phase

Autonomous vehicles require fuel or electricity. We assume that during the use phase, no additional material input is required. However, we that expect maintenance of autonomous systems will be required to guarantee safety. This may include replacement of damaged/broken sensors and software updates.

9.20.1.4. Life cycle: end-of-life

In the context of autonomous driving, the end-of-life phase mainly involves recycling metals, plastics, glass and electronics. With autonomous vehicles – often electrically driven – battery recycling is a key consideration, since it contains valuable CRM like Li, Co and Ni.

Recycling of cars is well-established in the EU and regulated by the End-of-Life Vehicle (ELV) Directive, which places responsibility on vehicle manufacturers and importers to ensure that ELV vehicles are properly managed and recycled. This directive aims to minimise the environmental impact of ELVs, recover valuable materials and promote sustainable resources.

Table C.46 Energy security indicators for autonomous driving

Geopolitical availability (score: 2)
Autonomous vehicles, either electrical or conventional, mostly consist of aluminium, steel, plastics and glass. Modern vehicles contain increasing amounts of electronics and battery packs, which often include critical materials. Supplies of CRM used to manufacture semiconductors are (indirectly) imported from China and Russia, and from African countries with complicated political-economic or military contexts (see also Supply chain complexity).[4] The CRM used in autonomous driving technology and their relative geopolitical availability are as follows: • Li: 1 • Co: 2 • Mg: 3 • Cu: 1 • Ni: 1 • Al: 1 • LREE: 3 • HREE: 3 Since the average score for these materials is 2, this is the overall score assigned to this indicator.
Abundance (score: 3)
There are some CRM in this technology, which are highly important because they are required for the proper functionality of these devices. Therefore, a score of 3 is assigned.
Circularity (score: 2)

Recycling/reusing the (critical) materials in the electronics and components of autonomous vehicles can reduce the need for these raw materials. There is a general trend observed in recycling of car components, such as the aluminium frame and battery materials, especially in the design of new vehicles. A good example is the new EX30 by Volvo, which has a 75% smaller CO_2 footprint than other Volvo EV models due to using recycled aluminium (25%), steel (17%) and plastic (17%). Moreover, the EX30 is designed to be recovered to 95%, by recycling materials and recovering energy from what cannot be recovered.

Supply chain complexity (score: 3)

Bulk materials such as aluminium, steel, plastic and glass are readily available from multiple sources globally and in Europe. Besides bulk materials, electronics are also increasingly used in vehicles. A study by The Hague Centre for Strategic Studies concludes that most of the semiconductor value chain is dominated by Taiwan, South Korea, the United States, Japan and European states. However, supplies of CRM used to manufacture semiconductors are (indirectly) imported from China and Russia, and African countries with complicated political-economic or military contexts.[4] It is increasingly important to reduce dependence on these countries, making circularity a potentially crucial factor.

Tensions between the United States and China have been escalating, with the former making efforts to restrict the export of advanced semiconductor technologies to China. In July 2023, China announced stringent regulations requiring export approval for specific gallium and germanium products by Chinese exporters.[5] How these heightened tensions will impact the EU's relationship with China remains to be seen.

Relations between China and Taiwan are further deteriorating, potentially leading to a Chinese naval blockade/invasion of Taiwan in the next decade, thereby disrupting the supply chain for semiconductors or end products to the EU.[4]

Because of the complexity of the supply chain as argued above, this risk indicator is given the highest score of 3.

Supply chain location (score: 3)

China increasingly dominates the car manufacturing, especially for EVs, which are expected to replace conventional ICE vehicles. Moreover, there is critical dependence on battery materials required for EVs (see value chain for batteries containing CRM, above). The semiconductors required for electronics in autonomous vehicles are largely dominated by Taiwan, South Korea and the United States.[4]

With respect to the bulk materials for car manufacturing, namely aluminium, glass and steel, locational dependence is not considered critical.

Due to the critical dependence on semiconductor materials, which are crucial to electronics in autonomous vehicles, this risk criterium is scored 3.

Digital vulnerability (score: 3)

Autonomous driving is a digital technology that includes sensors, digital hardware and software (AI). Digital security is key to avoiding threats such as hacks, which can have life-threatening outcomes in the context of autonomous driving.

Cyberattacks

Cyberattacks on smart meters can be classified under four categories based on method and type of attack:

- Availability attacks:

    - Dos/DDos attack: disrupts a digital system by overwhelming it with excessive (digital) traffic.
    - Replay attack: maliciously inserts, fraudulently repeats, or delays, data.
- Integrity attack: data manipulation that compromises integrity of data
- Confidentiality attack: breaches confidentiality of (personal) data
- Authenticity attack: attempt to obtain (log-in) authentication, potentially leading to theft

Due to the digital vulnerability of autonomous vehicles as argued above, and the serious safety consequences if autonomous vehicles are compromised, this criterium is scored 3.

Physical vulnerability (score: 2)

Due to the various sensors and cameras required for autonomous driving vehicles, the weather plays a crucial role in the functionality of these vehicles.

The function of several sensors used in autonomous vehicles may be affected by weather conditions. Rain can affect the radar signal attenuation in RADAR sensors. LiDAR can be affected by dense smoke. Ultrasonic sensors can be disrupted by noise. Rain, fog, strong light and dense smoke pose risks to the camera, potentially leading to false detection or detection failure.[6]

The effects of weather conditions on function of autonomous vehicles are expected to be local but could be potentially life-threatening. Therefore, this criterion is scored 2.

Broader sustainability (score: 2)

Public acceptance

The algorithms that enable autonomous driving must deal with many (unknown) traffic situations and require automated decision-making. However, it is unclear how autonomous driving algorithms should deal with traffic accidents. For example, should an autonomous vehicle save a child while risking the life of an older person in case of an accident? How these ethical dilemmas are dealt with may affect how the public respond to the deployment of (fully) autonomous vehicles.

In addition, the adoption of fully autonomous vehicles is expected to result in job losses for taxi and bus drivers.

Although these individual risks are not very high, since this value chain is subject to risks related to different sustainability aspects, an overall score of 2 is assigned for broader sustainability.

Affordability (score: 2)

A study by Bosch et al. calculated that autonomous vehicles would lead to reduced costs per passenger kilometre compared to non-autonomous vehicles. For taxis and busses, this cost reduction is mainly caused by removing of the driver (i.e. the salary for the driver).[6,7]

However, costs for autonomous vehicles are correlated with safety. For example, an increasing number of sensors is associated with improved collision avoidance but will increase the total price of the vehicle.[8]

Due to the increased cost of autonomous vehicles from increased use of sensors and complex advanced software, set against the increased safety associated with autonomous vehicles, this risk criterium is scored 2.

Skills (score: 3)
Autonomous vehicles require expert knowledge for suitable hardware as well as software. The automotive industry is known to be plagued by labour shortages across most segments.[9] Therefore, this criterium is scored 3.

9.20.1.5. Bibliography

[1] European Commission. (2020). AI Watch Assessing Technology Readiness Levels for Artificial Intelligence. https://ai-watch.ec.europa.eu/publications/ai-watch-assessing-technology-readiness-levels-artificial-intelligence_en

[2] Gawron, J. H., Keoleian, G. A., De Kleine, R. D., Wallington, T. J., & Kim, H. C. (2018). 'Life Cycle Assessment of Connected and Automated Vehicles: Sensing and Computing Subsystem and Vehicle Level Effects'. *Environmental Science & Technology*, 52(5), 3249-3256. https://doi.org/10.1021/acs.est.7b04576

[3] T.S. Stephens, J. G., Y. Chen, Z. Lin, C. Liu, D.Gohlke. (2016). 'Estimated Bounds and Important Factors for Fuel Use and Consumer Costs of Connected and Automated Vehicles'. https://www.nrel.gov/docs/fy17osti/67216.pdf

[4] Joris Teer, M. B. (2023). Reaching breaking point: The semiconductor and critical raw material ecosystem at a time of great power rivalry. https://hcss.nl/wp-content/uploads/2022/10/Reaching-Breaking-Point-Full-Version-HCSS-2022.pdf

[5] Zhang, Y., Carballo, A., Yang, H., & Takeda, K. (2023). 'Perception and sensing for autonomous vehicles under adverse weather conditions': A survey. *ISPRS Journal of Photogrammetry and Remote Sensing*, 196, 146-177. https://doi.org/https://doi.org/10.1016/j.isprsjprs.2022.12.021

[6] Vargas, J., Alsweiss, S., Toker, O., Razdan, R., & Santos, J. (2021). 'An Overview of Autonomous Vehicles Sensors and Their Vulnerability to Weather Conditions'. *Sensors*, 21(16).

[7] Bösch, P. M., Becker, F., Becker, H., & Axhausen, K. W. (2018). 'Cost-based analysis of autonomous mobility services'. *Transport Policy*, 64, 76-91. https://doi.org/https://doi.org/10.1016/j.tranpol.2017.09.005

[8] Tan, H., Zhao, F., Zhang, W., & Liu, Z. (2023). 'An Evaluation of the Safety Effectiveness and Cost of Autonomous Vehicles Based on Multivariable Coupling'. *Sensors*, 23(3).

[9] EURES. (2022). Report on labour shortages and surpluses. https://www.ela.europa.eu/sites/default/files/2023-03/eures-labour-shortages-report-2022.pdf

9.21. Electricity and heat storage: other

9.21.1. Compressed air energy storage (CAES)

Compressed air energy storage (CAES) is a technique used for medium-term electricity storage. Electricity drives a compressor to compress air, which is then injected at high pressure into substantial underground areas such as depleted gas fields, salt caverns, or potentially aquifers – as well as above-ground vessels. When electrical power is needed, the stored compressed air is heated and subsequently expanded through a turbine to drive a generator. TNO provides a schematic overview of a CAES installation in their report.[1]

9.21.1.1. Characteristics

Role in EU energy system: CAES can be used to store surplus renewable energy, particularly electricity. When electricity demand surpasses supply, the compressed air can be converted into electricity with a round-trip efficiency of 60–70%. For a viable business case, it is most likely that CAES will charge and discharge between 6 and 12 hours.

Primary energy source: The primary energy source for CAES as a clean energy technology will most likely be solar and wind energy. Currently, fossil fuels are used to heat the compressed air, but this method is not further discussed here, as we focus on clean energy technologies.

TRL: A CAES system can be diabatic or adiabatic, depending on how the heat created during compression is dealt with. Operational CAES systems around the world are all diabatic. Therefore, the TRL of diabatic CAES is 9. For every new installation, the underground storage facility must be explored beforehand and made operational. This process takes time, meaning there is uncertainty over whether a storage facility is suited to CAES.[1]

Adiabatic CAES, a more advanced form of CAES with higher efficiency, has a TRL of 5. This technique is not yet operational, but operational facilities are expected in the next few years. Recent developments around CAES systems have successfully focused on efficiency improvement.

9.21.1.2. Life cycle: construction phase

A CAES installation requires a large (underground) space – most likely a salt cavern – to store compressed air, as well as an above-ground installation where the air is compressed, expanded and let through a generator to create electricity. The compression and expansion system's engine can be powered by the grid or a nearby solar or wind farm – the latter ensuring that a local surplus of electricity can be stored right away in the CAES system. The generator is most likely directly connected to high-voltage grids.[2]

The capital goods in case of CAES are the compressor and expansion system, heat exchanger, above-ground storage tanks for compressed before it is injected into underground storage, an electric generator and motor to generate electricity, and a system to control pressure in the storage space. These parts are mostly made of (stainless) steel, copper, aluminium, iron, (reinforced) concrete and alloys to withstand high pressures and temperatures. Also, insulation and sealing materials may be needed to maintain temperature and pressure conditions in the system.

For grid connections and electrical distribution, copper cables, aluminium conductors, insulators, transformers, switchgears and various other materials may be used.

Locations for CAES installations are limited by the availability storage spaces, which might alternatively be used to store hydrogen. Therefore, CAES is in competition with hydrogen for underground infrastructure.[3]

9.21.1.3. Life cycle: use phase

The compressed air for diabatic CAES is heated by an external heating source. Diabatic CAES will use solar and wind energy in the future. Minimal input is required for adiabatic CAES since the heat produced during compression is stored and later used as an input to expand the air. In general, a CAES installation needs maintenance.

9.21.1.4. Life cycle: end-of-life

The lifetime of a CAES installation is at least 35 years. The end-of-life stage involves decommissioning, site restoration, material disposal and cavern closure (sealed or repurposed for other uses). It is likely that parts, and especially materials such as steel, can be reused.

Table C.47 Energy security indicators for CAES

Geopolitical availability (score: 1)
The critical materials for CAES and their relative geopolitical availability are as follows: • Copper: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Aluminium: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). Since the average score for all materials is 1, this is the overall score assigned to this indicator
Abundance (score: 2)
The critical materials in this technology and their abundance risk are: • Copper, which has a medium abundance risk (1 to 100 ppm, score 2). • Aluminium, which has a low abundance risk (>10 000 ppm, score 1). Since the average score for all materials is 2, this is the overall score assigned to this indicator.
Circularity (score: 1)
Where possible, components and equipment from decommissioned CAES installations can be repurposed or relocated to new projects. For example, compressors, turbines, and electrical components can find new applications in other energy storage projects or industrial settings. Materials mostly used for CAES such as steel, concrete and metals can often be recycled, as is already done now – therefore, the score of 1 is assigned.
Supply chain complexity (score: 2)
The necessary components to install CAES are not novel and have been produced for many years. The exploration of underground storage space can be complex, time-intensive, and involves potentially lengthy legal and security procedures. It is largely for this reason that the supply chain is seen as complex.[4] Extensive exploration for underground storage space adds complexity to construction phase, and therefore the total supply chain – therefore a score of 2 is assigned.
Supply chain location (score: 2)
The materials needed for CAES are widely manufactured both in the EU and globally. Specialised parts – in electrical components, air compressors and turbines, for example – may not be produced in the EU. However, CAES is limited to specific locations for underground storage. Salt caverns occur naturally in some regions. However, not all salt caverns are suitable for CAES. Therefore each salt cavern (new or old) must undergo an exploration phase. How many locations are suitable for CAES is currently uncertain, and finding suitable locations can be a lengthy and complex process.[3] Although the geographical limitations of the technology are not considered an energy security risk in themselves, as per our methodology, extensive exploration needed may pose a risk, therefore a score of 2 is assigned.
Digital vulnerability (score: 1)

As for other technologies relying directly on renewable energy, certain control software is needed to manage charging and discharging based on weather profiles and data from network operators. Although cyberattacks can never be excluded, there is no particular digital risk for this technology compared to other value chains, and the damage resulting from a cyberattack could probably be limited. Therefore, a score of 1 is assigned.

Physical vulnerability (score: 2)

CAES itself is not inherently physical vulnerable. The above-ground facilities such as the compressor, expansion unit and power generator are as physically vulnerable as other energy infrastructure and can be protected. The underground storage facility is vulnerable in the event of earthquakes or landslides. Therefore, geological stability should be monitored to maintain safe and reliable operation and prevent cracks and leaks. The technique is somewhat vulnerable to physical disruptions, therefore a score of 2 is assigned.

Broader sustainability (score: 3)

Salt caverns used for underground activities can potentially cause subsidence and seismic activity. Although soil subsidence is a natural part of cavern construction, it can be managed and mitigated if necessary. The seismic activities measured at storage caverns are disproportionate to those measured at gas fields. While the risks associated with underground activities related to natural gas storage are well understood, the risks of compressed air storage are relatively unknown and necessitate additional research. Extraction of salt and underground activities frequently encounter resistance from local communities, primarily due to concerns over subsidence and seismic events.[4]

Storage areas suitable for CAES could alternatively store hydrogen. As it is uncertain whether there will be enough appropriate storage space for hydrogen, CAES is likely to be in competition with hydrogen for underground storage. Hydrogen is expected to have a more predominant role in the energy system, and therefore may be prioritised over CAES.[4]

Since for this value chain faces various risks exist related to different sustainability aspects, an overall score of 3 is assigned.

Affordability (score: 2)

Estimated LCOS are around 150 EUR/kWh and are not expected to drop significantly over time.[1]

Skills (score: 2)

Further development of adiabatic CAES and implementation of renewable energy (instead of the fossil fuels currently used) requires a highly skilled labour force. Exploration and application of new underground storage facilities also requires specialised labour force. However, expertise from underground gas storage can be partly used for storage of compressed air in salt caverns. Once operational, CAES does not require extensive maintenance as the technique is established. Since the development phase in particular requires a highly skilled labour force, a score of 2 is assigned.

9.21.1.5. Bibliography

[1] NP RES & CE Delft (2022). Factsheet Opslag van elektriciteit, Den Haag: NP RES. https://ce.nl/wp-content/uploads/2023/01/CE_Delft_220271_RES-Factsheet-Opslag_elektriciteit-2022.pdf

[2] TNO. (2020). Large-Scale Energy Storage in Salt Caverns and Depleted Fields: Project Findings. https://publications.tno.nl/publication/34637700/8sBxDu/TNO-2020-R12006.pdf

[3] TNO (2021). Ondergrondse Energieopslag in Nederland 2030-2050: Technische evaluatie van vraag en aanbod. https://www.ebn.nl/wp-content/uploads/2022/10/Ondergrondse-energieopslag-in-Nederland-2030-%E2%80%93-2050-%E2%80%93-Technische-evaluatie-van-vraag-en-aanbod-2.pdf

[4] TNO (2020). Inventory of risks associated with underground storage of compressed air (CAES) and hydrogen (UHS), and qualitative comparison of risks of UHS versus. underground storage of natural gas (UGS). https://publications.tno.nl/publication/34637695/1RqPrg/TNO-2020-R12005.pdf.

9.21.2. Flywheels

A flywheel is a wheel with large mass that stores energy in the form of rotational energy. The flywheel is driven by an electric motor at times surplus of energy, bringing it to a high speed. Designed to have almost no friction, the wheel can keep on spinning. The rotational energy in the flywheel can later be converted into electricity by slowing the wheel with the electric motor, which can also work as a generator.[1]

9.21.2.1. Characteristics

Role in EU energy system: Flywheels can be used for energy storage for short durations only (seconds to minutes). They are well suited to processes that require a lot of power in a short time, due to their fast reaction time. In addition, flywheels can be used to support the stability of the power system. Flywheels can store relatively little energy store (1 MW/30 kWh), due to the limited size of the wheel. Efficiency is very high (92–98%).[1]

Primary energy source: the primary energy source for flywheels as a clean energy technology is most likely solar and wind energy.

TRL: Flywheels are a long-standing component of various motor systems. For energy storage, flywheels can be distinguished in two categories: low-rpm and high-rpm (rotation per minute):

- Low-rpm have a lot in common with existing flywheels and have a TRL of 9, as they are commercially available for energy storage on a small scale.[1]
- High-rpm is a new advanced generation of flywheels based on lightweight materials such as carbon or composites with (superconducting) magnets or bearings. Within this category there many variations in materials and development. The TRL is therefore 5–8. Due to the wide range of materials, and uncertainties over further developments of specific techniques, this category is not further discussed here, and this factsheet focuses on low-rpm flywheels.

9.21.2.2. Life cycle: construction phase

Low-rpm flywheels primarily comprise steel, which is made of iron. Some copper is used in the motor and a fraction of silicon is used in propulsion.[2] Flywheels must be connected to the grid.

9.21.2.3. Life cycle: use phase

Little to no maintenance is needed for flywheels. Flywheels need (renewable) electricity.

9.21.2.4. Life cycle: end-of-life

Flywheels have a lifespan of 20 years.[2] Flywheels consist mainly of steel, which can be recycled.

Table C.48 Energy security indicators for flywheels

Geopolitical availability (score: 1)
The critical materials needed for flywheels and their relative geopolitical availability are as follows:[2] • Copper: available in more than three EU or global countries. Supply risk relatively low. Supply not concentrated in one country (score: 1). • Silicon: available in more than three EU or global countries. Supply risk relatively low. Supply concentrated in one country but supply risk relatively low (score: 1). Since the average score for all materials is 1, this is the overall score assigned to this indicator.
Abundance (score: 1)
The critical materials in the technology and their abundance risk are: • Copper, which has a medium abundance risk (1 to 100 ppm, score 2). • Silicon, which has a low abundance risk (>10 000 ppm, score 1). Since relatively small quantities of copper and silicon are used for flywheels, the average overall score is 1. The segment of new-generation flywheels examined here uses superconducting magnets or bearings. Superconducting materials often use materials such as niobium, titanium and tin. Depending on developments and commercialisation, this may potentially pose a long-term risk.
Circularity (score: 1)
Lifetime is relatively long, and the main component (steel) is recyclable.[2] Therefore, a score of 1 is assigned.
Supply chain complexity (score: 1)
The supply chain for flywheels is relatively simple and does not consist of a large number of steps or require highly specialised knowledge of components.[2] Therefore, a score of 1 is assigned.
Supply chain location (score: 1)
For the extraction phase, most materials are available in the EU. The manufacturing and operations phase can take place in the EU. Therefore, a score of 1 is given.
Digital vulnerability (score: 1)

Although cyberattacks can never be excluded, there is no particular digital risk for this technology compared to other value chains, and the damage resulting from a cyberattack could probably be limited. Therefore, a score of 1 is assigned.

Physical vulnerability (score: 1)

Although sabotage and extreme weather events can never be excluded, there is no particular physical risk for this technology compared to other value chains, and the damage resulting from physical events will probably be limited. Therefore, a score of 1 is assigned.

Broader sustainability (score: 1)

Limited land use and no other significant sustainability risks. Therefore, a score of 1 is assigned.

Affordability (score: 2)

Expected LCOS is 200–250 EUR/kWh.[1]

Skills (score: 1)

Although some skilled workers are needed for this value chain, no specific vulnerabilities with respect to workforce size or specific skills are foreseen, compared to other value chains. Therefore, we assign a score of 1.

9.21.2.5. Bibliography

[1] NP RES & CE Delft (2022). Factsheet Opslag van elektriciteit, Den Haag: NP RES. https://ce.nl/wp-content/uploads/2023/01/CE_Delft_220271_RES-Factsheet-Opslag_elektriciteit-2022.pdf
[2] CE Delft, S4 Energy and QuinteQ (October 2023), Personal communication.

ANNEX D: HEATMAP AND CRITICALITIES

The longlisted energy security criticalities that did not make the shortlist, along with reasons they weren't included, are presented in Table D.1.

The criticalities were longlisted using a heatmap, which shows how many scenarios each criticality was longlisted within (see methodology in Annex A, Section 6). Tables D.2 and D.3 indicate whether each value chain and each energy security indicator was longlisted as a criticality in 1, 2 or 3 scenarios (or 0, which means not longlisted as a criticality), for both 2030 and 2050. Tables D.3 and D.4 show the same for 'to-be-discussed' criticalities.

Table D.1 Value chain analysis: longlisted criticalities that were not shortlisted

Technology area	Criticalities not shortlisted	Considerations
Advanced biofuels	Physical vulnerability	Longlisted only for one value chain (algae-based) and through one scenario. Risks relate to physical impacts on harvest and are expected to be mitigated as the value chain is further developed.
Bioenergy	Supply chain complexity	Longlisted for only one value chain (crop-based) and through only one scenario, only for 2030. Linked to need for measurement, reporting and verification (MRV) but expected to be addressed sufficiently by regulation.
	Broader sustainability	Longlisted for only one value chain (crop-based) and through only one scenario, only for 2030. Linked to need for sustainability criteria for feedstock but expected to be addressed sufficiently by regulation.
Concentrated solar power	Physical vulnerability	Longlisted through only one scenario. There are several smaller risks in this category that are not related, therefore physical vulnerability itself was not considered a key criticality.
	Supply chain location	Longlisted through only one scenario and only for 2030. Risk relates to small number of manufacturers globally, but most are in the EU, so not considered a key criticality.
Geothermal energy	Supply chain location	Longlisted through only one scenario and only for 2030. Major manufacturers for geothermal power generation are located outside the EU, but mainly in countries with politically friendly relationships with the EU.
	Broader sustainability	Longlisted through only one scenario and only for 2030. Risks of contamination exist, but technological solutions are

		available. Within the EU, regulation is deemed sufficient to address these risks.
	Skills	Longlisted through only one scenario and only for 2050. Shortages may pose a risk, but in general the technology is well-established, and labour supply is hard to project for 2050.
Hydropower	Supply chain complexity	Longlisted through only one scenario and only for 2030. Risk is mainly related to complex and long process for both building and decommissioning a dam, but with adequate planning, and development of alternative sources of renewable electricity, this risk is considered manageable.
Ocean energy	Digital vulnerability	Digital risks are relatively uncertain due to the technology still being under development. Risks are deemed similar to those associated with wind energy, where digital vulnerability was not shortlisted either.
	Physical vulnerability	Longlisted mainly for OTEC, which is not applicable within the EU due to the temperature difference needed, hence this is not considered a key criticality.
	Supply chain complexity	Longlisted mainly for OTEC and wave energy. OTEC cannot be deployed in the EU, and for wave energy technological solutions are deemed sufficient to address the complexities, mainly because the technology is still being developed.
	Supply chain location	Longlisted mainly for OTEC, which is not applicable within the EU due to the temperature difference needed, hence this is not considered a key criticality.
	Skills	Longlisted mainly for salinity gradient value chain, where high R&D skills are needed to further develop the technology. As thermal and wave energy are already at a higher stage of development, this is not considered a key criticality for the entire technology category. Validation workshop participants indicated that skills are not considered a key criticality as the sector can draw from declining offshore industries.
Photovoltaics	Supply chain complexity	Longlisted through only one scenario and only for 2030. Solar PV supply chains consist of many elements and involve high-tech processes such as stacking of thin layers. However, because many supply chain elements are produced or manufactured outside the EU (such as the raw materials needed and ingots/wafers), the shortlisted criticalities of CRM and supply chain location are considered dominant over the risks associated with supply chain complexity, which is why this criticality was not shortlisted separately.
	Broader sustainability	Longlisted through only one scenario and only for 2030. This criticality is associated with several different, unrelated

		risks in the field of sustainability, hence it was not considered a key criticality.
Wind energy	Digital vulnerability[1]	Digital attacks may cause significant damage to wind turbines. On the other hand, the technology is less dependent on digital connections than other value chains, which is why this criticality was not shortlisted. Validation workshop participants assessed cybersecurity for wind energy as medium risk – medium preparedness.
	Supply chain complexity	Longlisted for only one value chain (offshore), through only one scenario and only for 2030.
	Broader sustainability	Longlisted through only one scenario and only for 2030. This risk covers several non-related issues under this indicator, including impact on wildlife and the sustainability of a certain type of wood used. Compared to other value chains, sustainability risks are considered manageable.
	Skills	Longlisted through only one scenario and only for 2050. Shortage of labour may be a risk, but wind energy value chains are quite well established compared to other value chains. Also, there is an overlap in skills with the offshore sector, providing a possible new source of labour as offshore extraction of fossil fuels is reduced. Labour supply is hard to project for 2050.
Renewable and solar fuels	Supply chain location	Longlisted through only one scenario. This risk is mainly related the EU not having a leading role in research to further develop this technology. However, EU research is taking place and has a good track record, therefore this criticality was not deemed key.
	Broader sustainability	Longlisted for only one value chain (thermochemical) and through only one scenario. Risks are related to land and water use, but relatively limited compared to other value chains.
	Affordability	As this technology is in a very early phase, current costs are not considered representative of a future commercially available value chain. Although costs are also considered a risk in the future due to uncertainty over whether the technology will be cost-competitive, it is deemed premature to state that affordability is a key energy security risk for this technology.
CCUS	Digital vulnerability	CCS is not used for energy generation or distribution. Therefore, the risk from cyberattacks is considered less pronounced than for technologies with other roles in the energy system.

[1] While this was initially discounted, validation workshop participants disagreed with the assessment and placed it as a high-risk criticality. Therefore, an R&I action for this criticality was included in the final R&I action plan.

	Physical vulnerability	Longlisted through only one scenario. Risks are mainly related to the possibility of malicious threats (sabotage), but as with digital vulnerability, these risks are deemed less pronounced for CCS than for technologies with other roles in the energy system.
	Affordability	Costs are high, but as CCS is considered a transition technology for industry to meet its emission reduction targets, state subsidies are available. In future, CCS is projected to play a large role in carbon removal, but in financing modes are also expected to be made available this context (e.g. through certification or inclusion of carbon removal in the ETS).
	Skills	Longlisted through only one scenario, only for 2050. For the above reasons, the technology is expected to be well established by 2050. Also, labour supply is hard to project for 2050.
Batteries	Digital vulnerability	Cyberattacks may lead to significant damage, but this technology is less dependent on digital connections than other, smart technologies, therefore this criticality was not shortlisted.
	Supply chain complexity	Longlisted through only one scenario, only for 2030. Risks are different for different value chains and mostly linked to supply chain location and CRM, which are anyway shortlisted.
	Skills	Longlisted through only one scenario, only for 2050. Labour shortage may pose a challenge, but less so than in some other value chains. Labour supply is hard to project for 2050.
Hydrogen	Digital vulnerability	Digital vulnerability is elevated because of high dependence on the supply of (renewable) electricity, which makes the technology vulnerable to grid disruptions. This risk is indirect and less pronounced than for other, smart technologies, which is why this criticality was not shortlisted.
	Supply chain complexity	Longlisted through only one scenario, only for 2030. Risks mainly relate to some of the value chains still being set up.
	Supply chain location	Longlisted only for one value chain (PEM), through only one scenario and only for 2030.
	Skills	Longlisted through only one scenario, only for 2050. Labour shortage may pose a challenge, but less so than in some other value chains. Labour supply is hard to project for 2050.
RFNBOs	Digital vulnerability	Risks are mainly linked to the supply chain for renewable hydrogen, where digital vulnerability was not shortlisted either.

	Broader sustainability	Risks identified in the assessment are mainly linked to the need for renewable electricity and the associated sustainability issues there. However, this is more of a systemic criticality and not specific for RFNBOs.
Heat pumps	Digital vulnerability	Risks mostly associated with high dependence on supply of (renewable) electricity and vulnerability of the grid. As this is an indirect (and more systemic) risk, it was not shortlisted.
	Supply chain complexity	Longlisted through only one scenario and only for 2030. Risks are mainly related to tailored design for industrial heat pumps, therefore not deemed a key criticality for the entire technology. Validation participants noted that developing standards for heat pumps would mitigate this criticality (as well as the risks related to skills).
	Supply chain location	Longlisted through only one scenario and only for 2030. Risks mainly linked to a relatively small number of manufacturers of key components, but as these include EU parties this is not considered a key criticality.
	Broader sustainability	Longlisted through only one scenario and only for 2030. Main issue concerns recent stricter regulation on the use of F-gases. This is expected to be addressed by industry and therefore was not considered a key criticality.
Smart energy grids	Broader sustainability	Longlisted for two out of three value chains, through only one scenario and only for 2030. Risks are related to the mining of certain critical materials. These risks are similar to those identified for batteries, where they are shortlisted. Therefore, this criticality was not shortlisted separately for smart energy grid technologies.
	Skills	Longlisted through only one scenario, only for 2050. Labour shortage may pose a challenge, but less so than in some other value chains. Labour supply is hard to project for 2050.
Energy building & district technologies	Skills	Longlisted for only one value chain (ACT), through only one scenario and only for 2050.
Energy transmission & distribution technologies	Supply chain complexity	Longlisted for only one value chain (hydrogen storage), through only one scenario and only for 2030. Risks mainly concern new infrastructure, but repurposing of existing gas infrastructure can limit need for new infrastructure.
	Broader sustainability	Longlisted for only one value chain (HVDC), through only one scenario and only for 2030. Risks mainly linked to construction in marine environments but considered less pronounced compared to other value chains that operate entirely offshore (such as wind energy or ocean energy).

	Skills	Longlisted for only one value chain (HVDC), through only one scenario and only for 2050. Demand for offshore skills can be partly met by downscaling fossil exploitation towards 2050.
Smart cities	Physical vulnerability	Longlisted through only one scenario. Risks are linked to the vulnerability of key components of the technology, such as sensors. Therefore, risks for energy security are indirect as they mainly concern safety issues. As the technology is still in development, these risks are expected to be mitigated.
	Broader sustainability	Longlisted through only one scenario. Risks run mainly through public opinion, which may be critical towards autonomous driving, but as the technology is still in development it is deemed too early to state that this is a key criticality for energy security.
Other energy storage (CAES)	Physical vulnerability	Longlisted for only one value chain (CAES) and through only one scenario. Risks mainly relate to geological stability of underground locations. This risk is deemed manageable through proper monitoring.
	Supply chain location	Risks mainly relate to specific requirements for CAES locations, and the extensive exploration phase needed. However, geographical limitations of the technology itself are not considered an energy security risk but rather a systemic limitation.
	Skills	Longlisted for only one value chain (CAES), through only one scenario and only for 2050.

Table D.2 Heatmap of longlisted energy security criticalities, showing the number of scenarios through which they were longlisted, for 2030

		2030									
		Geopolitical availability	Abundance	Circularity	Digital vulnerability	Physical vulnerability	Supply chain complexity	Supply chain location	Broader sustainability	Affordability	Skills
Wind energy	Onshore	0	2	0	1	1	0	0	1	0	0
	Offshore	0	2	0	1	3	1	0	1	0	0
	Airborne wind system	0	2	0	1	3	0	0	0	0	0
	Downwind rotor	0	2	0	1	3	0	0	1	0	0
Advanced biofuels	Algae-based	0	0	0	0	1	3	0	1	0	0
	Crop-based	0	0	0	0	0	1	0	0	0	0
	Waste-based	0	2	0	0	0	1	0	0	0	0
Photovoltaics	Silicon-based	3	2	0	1	0	1	3	1	0	0
	CIGS	0	2	0	1	0	1	3	1	0	3
	CdTe	0	2	0	1	0	1	3	1	0	3
	Perovskite	0	0	0	1	0	1	3	1	0	3
Ocean energy	Tidal	0	2	0	1	0	1	1	1	3	0
	Wave	0	2	0	1	0	3	1	1	3	0
	Thermal	0	0	0	1	3	3	3	1	3	0
	Salinity gradient	0	2	0	0	1	1	1	1	3	3
Geothermal energy	Geothermal plant	0	2	0	0	0	0	1	1	0	0
Hydropower	Hydropower plant	0	2	0	0	3	1	0	3	0	0
Hydrogen	Alkaline electrolysis	0	2	0	1	0	0	0	1	3	0
	PEM electrolysis	0	3	0	1	0	1	1	1	3	0

	Solid oxide electrolysis	3	2	0	1	0	1	0	1	0	0
	AEM electrolysis	0	2	0	0	0	1	0	1	0	0
Batteries	Containing CRM	3	2	0	1	0	1	3	3	0	0
	Not containing CRM	0	0	0	1	0	1	0	0	0	0
	Redox flow	0	0	0	1	0	1	3	0	0	0
	Molten salt	0	0	0	0	0	0	0	0	0	0
Other electricity and heat storage	Compressed air storage	0	2	0	0	1	1	1	3	0	0
	Flywheels	0	0	0	0	0	0	0	0	0	0
Bioenergy	Primary crop-based	0	2	0	0	0	1	0	1	0	0
	Waste-based	0	2	0	0	0	0	0	0	0	0
Concentrated solar energy	Concentrated solar energy plant	0	0	0	0	1	0	1	1	0	0
Renewable fuels of non-biological origin	Synthetic kerosene	0	0	0	1	1	1	0	1	3	0
Carbon capture, utilisation and storage	Capture and storage infrastructure	0	0	0	1	1	0	0	3	3	0
Heat pumps	Industrial	0	2	0	1	1	1	1	1	0	3
	Domestic	0	2	0	1	1	1	1	1	0	3
Smart energy grid technologies	Electric vehicle smart charging	0	0	0	3	0	0	0	0	0	0
	Advanced meter infrastructure	0	2	0	3	0	1	1	1	0	0
	Home energy management systems	0	2	0	3	0	1	1	1	0	0
Energy building and district technologies	Advanced control technologies	0	2	0	3	0	1	1	0	0	0
	Thermal energy storage	0	0	0	0	0	0	0	0	0	0
	Combined heat and power	0	2	0	1	0	0	0	0	0	0
Off-grid energy systems	Biogas tank	0	0	0	0	0	0	0	1	0	0
	Pellet stove	0	0	0	0	0	0	0	1	0	0

	Solar heat: thermal collector	0	2	0	0	0	0	0	0	0	0
Energy transmission and distribution technologies	**Hydrogen storage and transportation**	0	0	0	0	0	1	0	0	0	0
	High-voltage direct current transmission	0	2	0	1	1	0	0	1	0	0
Smart cities	**Autonomous driving**	0	3	0	3	1	3	3	1	0	3
Direct solar fuels	**Photochemical/photobiological**	0	2	0	0	0	3	1	0	3	3
	Thermochemical	0	0	0	0	0	1	1	1	3	3

Table D.3 Heatmap of longlisted energy security criticalities, showing the number of scenarios through which they were longlisted, for 2050

		2050									
		Geopolitical availability	Abundance	Circularity	Digital vulnerability	Physical vulnerability	Supply chain complexity	Supply chain location	Broader sustainability	Affordability	Skills
Wind energy	**Onshore**	1	1	0	2	1	0	0	0	0	1
	Offshore	1	1	0	2	3	0	0	0	0	1
	Airborne wind system	1	1	0	2	3	0	0	0	0	1
	Downwind rotor	1	1	0	2	3	0	0	0	0	1
Advanced biofuels	**Algae-based**	0	0	0	0	1	3	0	0	0	0
	Crop-based	0	0	0	0	0	0	0	0	0	0
	Waste-based	0	1	0	0	0	0	0	0	0	0
Photovoltaics	**Silicon-based**	3	1	0	2	0	0	3	0	0	1
	CIGS	1	1	0	2	0	0	3	0	0	3
	CdTe	0	1	0	2	0	0	3	0	0	3
	Perovskite	0	0	0	2	0	0	3	0	0	3
Ocean energy	**Tidal**	1	1	0	2	0	0	0	0	3	1
	Wave	1	1	0	2	0	3	0	0	3	1
	Thermal	0	0	0	2	3	3	3	0	3	1
	Salinity gradient	1	1	0	0	1	0	0	0	3	3
Geothermal energy	**Geothermal plant**	0	1	0	0	0	0	0	0	0	1
Hydropower	**Hydropower plant**	1	1	0	0	3	0	0	3	0	0
Hydrogen	**Alkaline electrolysis**	0	1	0	2	0	0	0	0	3	1
	PEM electrolysis	1	3	0	2	0	0	0	0	3	1
	Solid oxide electrolysis	3	1	0	2	0	0	0	0	0	1
	AEM electrolysis	0	1	0	0	0	0	0	0	0	1

Batteries	**Containing CRM**	3	1	0	2	0	0	3	3	0	1
	Not containing CRM	0	0	0	2	0	0	0	0	0	1
	Redox flow	1	0	0	2	0	0	3	0	0	1
	Molten salt	0	0	0	0	0	0	0	0	0	1
Other electricity and heat storage	**Compressed air storage**	0	1	0	0	1	0	0	3	0	1
	Fly wheels	0	0	0	0	0	0	0	0	0	0
Bioenergy	**Primary crop-based**	0	1	0	0	0	0	0	0	0	0
	Waste-based	0	1	0	0	0	0	0	0	0	0
Concentrated solar energy	**Concentrated solar energy plant**	0	0	0	0	1	0	0	0	0	0
Renewable fuels of non biological origin	**Synthetic kerosene**	0	0	0	2	1	0	0	0	3	0
Carbon capture, utilisation and storage	**Capture and storage infrastructure**	0	0	0	2	1	0	0	3	3	1
Heat pumps	**Industrial**	0	1	0	2	1	0	0	0	0	3
	Domestic	0	1	0	2	1	0	0	0	0	3
Smart energy grid technologies	**EV smart charging**	0	0	0	3	0	0	0	0	0	1
	Advanced meter infrastructure	1	1	0	3	0	0	0	0	0	1
	Home energy management systems	1	1	0	3	0	0	0	0	0	1
Energy building and district technologies	**Advanced control technologies**	1	1	0	3	0	0	0	0	0	1
	Thermal energy storage	0	0	0	0	0	0	0	0	0	0
	Combined heat and power	0	1	0	2	0	0	0	0	0	0
Off-grid energy systems	**Biogas tank**	0	0	0	0	0	0	0	0	0	0
	Pellet stove	0	0	0	0	0	0	0	0	0	0
	Solar heat: thermal collector	0	1	0	0	0	0	0	0	0	0
Energy transmission and distribution technologies	**Hydrogen storage and transportation**	0	0	0	0	0	0	0	0	0	0

	High-voltage direct current transmission	0	1	0	2	1	0	0	0	0	1
Smart Cities	**Autonomous driving**	1	3	0	3	1	3	3	1	0	3
Direct solar fuels	**Photochemical/photobiological**	0	1	0	0	0	3	1	0	3	3
	Thermochemical	0	0	0	0	0	0	1	1	3	3

Table D.4 Heatmap of items on 'to-be-discussed' list, showing the number of scenarios through which they entered the list, for 2030

		2030									
		Geopolitical availability	Abundance	Circularity	Digital vulnerability	Physical vulnerability	Supply chain complexity	Supply chain location	Broader sustainability	Affordability	Skills
Wind energy	Onshore	2	0	0	0	0	1	1	0	0	2
	Offshore	2	0	0	0	0	0	1	0	3	2
	Airborne wind system	2	0	2	0	0	1	1	1	0	2
	Downwind rotor	2	0	0	0	0	1	1	0	3	2
Advanced biofuels	Algae-based	0	2	0	1	0	0	1	0	3	0
	Crop-based	0	2	0	1	1	0	1	1	0	0
	Waste-based	0	0	0	1	1	0	1	1	3	0
Photovoltaics	Silicon-based	0	0	2	0	1	0	0	0	0	2
	CIGS	2	0	2	0	1	0	0	0	0	0
	CdTe	0	0	2	0	1	0	0	0	0	0
	Perovskite	0	2	2	0	1	0	0	0	0	0
Ocean energy	Tidal	2	0	2	0	1	0	1	0	0	2
	Wave	2	0	2	0	1	0	1	0	0	2
	Thermal	0	2	2	0	0	0	0	0	0	2
	Salinity gradient	2	0	0	1	0	0	1	0	0	0
Geothermal energy	Geothermal plant	0	0	0	1	1	1	1	0	0	2
Hydropower	Hydropower plant	2	0	2	1	0	0	1	0	0	0
Hydrogen	Alkaline electrolysis	0	0	0	0	1	1	1	0	0	2
	PEM electrolysis	2	0	0	0	1	0	1	0	0	2
	Solid oxide electrolysis	0	0	0	0	1	0	1	0	3	2

	AEM electrolysis	0	0	0	1	1	0	1	0	3	2
Batteries	**Containing CRM**	0	0	2	0	1	0	0	0	0	2
	Not containing CRM	0	2	2	0	1	0	1	1	3	2
	Redox flow	2	2	0	0	1	0	0	1	3	2
	Molten salt	0	2	0	1	1	1	1	1	3	2
Other electricity and heat storage	**Compressed air storage**	0	0	0	1	0	0	1	0	3	2
	Fly wheels	0	2	0	1	1	1	1	1	3	0
Bioenergy	**Primary crop-based**	0	0	0	1	1	0	1	0	0	0
	Waste-based	0	0	0	1	1	1	1	1	0	0
Concentrated solar energy	**Concentrated solar energy plant**	0	2	2	1	0	1	1	0	3	0
Renewable fuels of non-biological origin	**Synthetic kerosene**	0	2	0	0	0	0	1	0	0	0
Carbon capture, utilisation and storage	**Capture and storage infrastructure**	0	2	0	0	0	1	1	0	0	2
Heat pumps	**Industrial**	0	0	0	0	0	0	1	0	3	0
	Domestic	0	0	0	0	0	0	1	0	0	0
Smart energy grid technologies	**Electric vehicle smart charging**	0	2	2	0	1	1	1	1	0	2
	Advanced meter infrastructure	2	0	2	0	1	0	1	0	0	2
	Home energy management systems	2	0	2	0	1	0	1	0	0	2
Energy building and district technologies	**Advanced control technologies**	2	0	2	0	1	0	1	1	0	2
	Thermal energy storage	0	2	2	1	1	1	1	1	0	0
	Combined heat and power	0	0	0	0	1	1	1	1	0	0
Off-grid energy systems	**Biogas tank**	0	2	0	1	1	1	1	0	0	0
	Pellet stove	0	2	0	1	1	1	1	0	0	0
	Solar heat: thermal collector	0	0	2	1	1	1	1	1	3	0

Energy transmission and distribution technologies	**Hydrogen storage and transportation**	0	2	0	1	1	0	1	1	0	0
	High-voltage direct current transmission	0	0	2	0	0	1	1	0	0	2
Smart cities	**Autonomous driving**	2	0	1	0	0	0	0	1	2	0
Direct solar fuels	**Photochemical/photobiological**	0	0	0	0	0	0	2	0	0	0
	Thermochemical	0	1	0	0	0	0	2	1	0	0

Table D.5 Heatmap of items on ‘to-be-discussed’ list, showing the number of scenarios through which they entered the list, for 2050

		2050									
		Geopolitic al	Abundanc	Circularity	Digital	Physical	Supply	Supply	Broader	Affordabili	Skills
Wind energy	Onshore	0	0	0	0	1	0	0	2	0	0
	Offshore	0	0	0	0	0	2	0	2	2	0
	Airborne wind system	0	0	0	0	0	0	0	0	0	0
	Downwind rotor	0	0	0	0	0	0	0	2	2	0
Advanced biofuels	Algae-based	1	1	0	2	1	0	0	2	2	1
	Crop-based	1	1	0	2	1	2	0	0	0	1
	Waste-based	1	0	0	2	1	2	0	0	2	1
Photovoltaics	Silicon-based	0	0	0	0	1	2	0	2	0	0
	CIGS	0	0	0	0	1	2	0	2	0	0
	CdTe	1	0	0	0	1	2	0	2	0	0
	Perovskite	1	1	0	0	1	2	0	2	0	0
Ocean energy	Tidal	0	0	0	0	1	2	2	2	0	0
	Wave	0	0	0	0	1	0	2	2	0	0
	Thermal	1	1	0	0	0	0	0	2	0	0
	Salinity gradient	0	0	0	2	1	2	2	2	0	0
Geothermal energy	Geothermal plant	1	0	0	2	1	0	2	2	0	0
Hydropower	Hydropower plant	0	0	0	2	0	2	0	0	0	1
Hydrogen	Alkaline electrolysis	1	0	0	0	1	0	0	2	0	0
	PEM electrolysis	0	0	0	0	1	2	2	2	0	0
	Solid oxide electrolysis	0	0	0	0	1	2	0	2	2	0

	AEM electrolysis	1	0	0	2	1	2	0	2	2	0
Batteries	Containing CRM	0	0	0	0	1	2	0	0	0	0
	Not containing CRM	1	1	0	0	1	2	0	0	2	0
	Redox flow	0	1	0	0	1	2	0	0	2	0
	Molten salt	1	1	0	2	1	0	0	0	2	0
Other electricity and heat storage	Compressed air storage	1	0	0	2	1	2	2	0	2	0
	Fly wheels	1	1	0	2	1	0	0	0	2	1
Bioenergy	Primary crop-based	1	0	0	2	1	2	0	2	0	1
	Waste-based	1	0	0	2	1	0	0	0	0	1
Concentrated solar energy	Concentrated solar energy plant	1	1	0	2	1	0	2	2	2	1
Renewable fuels of non biological origin	Synthetic kerosene	1	1	0	0	1	2	0	2	0	1
Carbon capture, utilisation and storage	Capture and storage infrastructure	1	1	0	0	1	0	0	0	0	0
Heat pumps	Industrial	1	0	0	0	1	2	2	2	2	0
	Domestic	1	0	0	0	1	2	2	2	0	0
Smart energy grid technologies	EV smart charging	1	1	0	0	1	0	0	0	0	0
	Advanced meter infrastructure	0	0	0	0	1	2	2	2	0	0
	Home energy management systems	0	0	0	0	1	2	2	2	0	0
Energy building and district technologies	Advanced control technologies	0	0	0	0	1	2	2	0	0	0
	Thermal energy storage	1	1	0	2	1	0	0	0	0	1
	Combined heat and power	1	0	0	0	1	0	0	0	0	1
Off-grid energy systems	Biogas tank	1	1	0	2	1	0	0	2	0	1
	Pellet stove	1	1	0	2	1	0	0	2	0	1
	Solar heat: thermal collector	1	0	0	2	1	0	0	0	2	1
Energy transmission and distribution technologies	Hydrogen storage and transportation	1	1	0	2	1	2	0	0	0	1
	High-voltage direct current transmission	1	0	0	0	1	0	0	2	0	0
Smart cities	Autonomous driving	1	0	0	0	2	0	0	1	1	0
Direct solar fuels	Photochemical/photobiological	0	1	0	1	0	0	2	0	0	0

	Thermochemical	0	0	0	1	0	2	2	1	0	0

ANNEX E: SUMMARY OF THE VALIDATION WORKSHOP

10. Workshop approach and participants

The workshop brought together 50 participants, 41 online and 9 in person. Participants were invited based on their expertise and experience in the technologies in scope or key criticalities (e.g. CRM and cybersecurity). Participants represented countries across the EU and non-EU countries, and were predominantly from research organisations (12%), academia (18%), trade bodies (26%) and think tanks (4%). A small number of industry participants were in attendance (16%), nominated by relevant ETIPs. Several experts from the European Commission (DG RTD, DG ENER and JRC) were also present (24%).

Participants brought expertise in the following technologies: bioenergy, advanced biofuels, hydropower, ocean energy, wind energy, PV, concentrated solar energy, renewable and solar fuels, batteries, hydrogen, CCUS, geothermal energy, heat pumps, energy systems, grids and transmission/distribution. In addition to technology-specific expertise, workshop participants included experts on CRM, sustainability, international trade, energy policy and climate adaptation.

The workshop approach is described in detail in Annex A, Section 8. The workshop consisted of several interactive activities drawing on participants' expert knowledge to:

- Validate the study methodology.
- Validate the energy security assessment of clean energy technology value chains.
- Validate and refine the proposed R&I challenges and corresponding R&I interventions for the action plan.

Inputs from in-person participants are summarised below as accurately as possible. Comments left on the online Mural boards have been pasted below with minor revisions for clarity. For example, where participants used 'we' statements, the study team noted whether this refers to participants or to the EU (e.g. 'we are at risk' becomes '[the EU] is at risk'). These study team did not inform any of the inputs below and only guided the participants through the activities.

11. Study methodology

The study team presented a high-level overview of the study approach and methodology. The participants submitted the following questions and feedback:

- Will the results feed into the SET Plan and the R&D roadmaps developed by the EERA JPs and ETIPs?
- For bioenergy, the categories are based on feedstock but not on the technological route and final product. For RFNBOs, only e-kerosene is mentioned. Why are other molecules not part of the list (e.g. synthetic diesel or other)?
- Hydro energy is also a bit coarse: run-of-river, dam hydro and pump storage have different issues. To this [the workshop participant] would also add 'hidden hydro' – i.e. hydropower in water and wastewater distribution networks mainly (including also hydro

in existing pipes). Yes, it is important to distinguish between a) run-of-river, b) storage (reservoir) hydropower and c) pumped-storage hydropower. Storage hydropower for example is very resilient against climate change, the larger the reservoir is (transfer of water of long wet periods to long dry periods).

- How can the value chains for immature technologies be assessed?

- It is not clear how the scenarios were developed.

- The criticality of value chains is closely related to the quantity of a given technology. Onshore wind cannot be compared to airborne wind.

- One workshop participant noted they would find it helpful to understand how the background scenarios for stress-tests were developed and what they aim to cover/represent.

- Clean energy value chain: clear approach to which single aspects where considered. Question: Where and how did you consider the overall energy system/the interaction of impacts among these single technologies?

The questions were answered by the study team in the workshop, informing where more clarity might be beneficial in presenting of the study methodology in the final report

12. Validation of the energy security assessment of clean energy value chains

12.1. Pre-workshop exercise

Participants were provided with the shortlist of key energy security criticalities. With the information provided, participants were invited to answer the following questions for the technologies in which they had expertise and experience:

For the technology value chain you have knowledge of, are these the main risks to the energy security of the value chain? If not, what is missing?

Participant inputs were incorporated into the findings described in Chapters 7–9 of the main report.

12.2. Activity 1: energy security criticalities, risk and EU preparedness

12.2.1. Discussion and validation of energy security criticalities

Participants were put in groups and given a selection of energy security criticalities to discuss. Using the lens of a risk-preparedness matrix, participants were invited to consider what level of risk each energy security criticality presented, and how prepared the EU is to mitigate the risk. The classification of risks provided a mechanism to identify which criticalities may not be severe enough to include on the shortlist, validate the assessment of the criticalities and identify gaps or opportunities for further prioritisation.

The **missing criticalities** identified by participants were:

- **Heat pumps – semiconductors:** Heat pumps require a significant quantity of low technology semiconductor chips to operate, and disruption to global semiconductor value chains has resulted in delivery delays for heat pumps. The EU Chips Act focuses on high-end chips – low tech chips for clean energy technologies might be a gap to address.

- **Photovoltaics – semiconductors:** for inverters – similar to above.

- **Skills**: Across all value chains, skills were highlighted as a key criticality for manufacturing and installation. The current skills shortage has prompted poaching across clean energy technology sectors and the United States is attracting workers away from the EU. In the heat pump sector, training for installation is relatively quick (a few weeks for a boiler installer) but the issue is around attracting people into the industry – the currently range of initiatives is ineffective. Ocean energy is drawing labour from declining maritime oil and gas and industries, and skills are not viewed as a key criticality for this technology. One break-out group placed skills and expertise as medium risk – medium preparedness, and another as high risk – medium preparedness.

- **Geothermal energy – permits and expert skills:** Skills within regulatory and permitting agencies were viewed as an important criticality. In particular, geological knowledge and expertise is important – and lacking – among those issuing permits to the geothermal energy sector.

- **Biofuels:** Chemical catalysts could become an issue in future.

- **Batteries – availability of CRM and recycling:** Issues with recycling CRM were highlighted. There are many recycling initiatives, but currently few recycling facilities in Europe to do this. With the growing need for recycling in future (e.g. batteries can be recycled after 10–15 years, implying that recycling capacity for around 40–60% of battery materials will be needed in 2050), the number of recycling facilities is a limiting factor.

- **Hydropower: Public opposition to hydropower** is the biggest risk to hydropower development. Participants did not view the public as having good awareness of the benefits and impacts of hydropower, meaning opposition is not based on evidence.

- **Hydropower – storage needs:** Existing plants must be prepared to serve a storage function.

- **Hydropower – costs:** Although hydropower has the highest energy/economic return on investment in the long term, there are large upfront investment costs. For reservoirs, additional services (e.g. flexibility, flood control) are not adequately remunerated and so hydropower operators are not incentivised to exploit their reservoirs for other uses (e.g. for environmental and societal purposes). For existing hydropower plants, solutions to environmental impacts exist but these are expensive.

- **Wind – supply chains:** placed as medium/high risk – medium/high preparedness (post it on the boundary between levels).

- **Batteries – public opinion:** Social acceptability of battery production and mining is also a risk.

- **CRM:** An overarching issue with all energy technologies is demand for aluminium, copper, manganese and nickel. Cu for all electric devices, Mn for steels, Ni for any stainless steel, and Al for various structures where steel is not used. Also, for any value chain, there are several types of electronics including several CRM, such as silicon metal, germanium, gallium or arsenic.

- **Wind energy – digital vulnerability and cybersecurity:** placed as medium risk – medium preparedness.

- **Hydropower and wind energy – regulation and approvals process**: placed as high risk – low preparedness.

- **Hydropower – market conditions:** placed as medium/high risk – medium preparedness.

- **Hydropower – investor risk and timelines:** placed as medium/high risk – medium/low preparedness.

- **Smart energy grid, energy transmission and distribution tech, smart cities**: resilience to solar storms?

Criticalities where participants **disagreed or added specifics** to our assessment:

- **Ocean energy – broader sustainability**: One stakeholder noted that sustainability impacts of ocean energy are well understood, and local populations are supportive, especially when the technology is submerged and not visible. Remaining uncertainties include how scale of deployment may change sustainability impacts, and comparison to floating photovoltaics and offshore wind.

- **Ocean energy – affordability:** Complexity was not considered a factor affecting affordability, but rather pre-commercial TRL. The cost of ocean energy is expected to fall with economies of scale and deployment, following similar trends to offshore wind, and aims for a competitive levelised cost of energy.

- **Photovoltaics – availability and abundance of CRM** was not viewed as a key criticality, except for silver. The value chain for refining was highlighted as a concern due to high concentration in a small number of countries.

- **Heat pumps – availability and abundance of CRM** was not viewed as a key criticality, as many are available in the EU and recycling initiatives are at play. This was, however, debated by other participants who highlighted the expected scale of increased demand for CRM as a concern, even if the materials are currently available in the EU.

- **CCUS – broader sustainability and environmental impact:** One participant noted that there was little risk regarding CO_2 leaks in particular, although they did not comment on the other environmental impacts highlighted in the study.

- **RFNBOs:** The study assumed that RFNBOs are produced with sustainably sourced feedstocks, because its focus is on clean energy technologies. However, one participant noted that the RFNBO value chain is especially risky due to requirement for sustainably produced hydrogen and sustainably sourced CO_2.

- **Biofuels – biomass availability:** Although participants agreed with the criticality, it was considered medium risk.

- **Batteries – availability of CRM:** While availability of CRM and supply chain location were both highlighted as key criticalities in the study, discussion around ‘access to CRM’ was proposed as perhaps a better phrase, as it encompasses both criticalities and the option of recycling CRM.

- **Hydropower – sustainability and environmental impacts of hydropower:** There was a general consensus that there are solutions to the environmental impacts of hydropower (e.g. modernising existing hydropower, developing hidden hydro in existing infrastructures, new pumped hydro using existing reservoirs, abandoned mine closed-loop hydropower), but varying views on the importance of this criticality. Some participants did not see sustainability as really an issue, because hydropower has a very high sustainability index (in terms of pay-back factor and CO_2-equivalent emissions) compared to other renewables. They said the only issue might be reservoir sedimentation, which reduces the useful storage volume for hydropower and other uses.

- **Hydropower – physical vulnerability to climate change:** Glacier loss is not reducing water long-term availability in absolute terms, but rather changing inflow to reservoirs over time (more snowmelt in spring, compared to glacier melt in summer). Glacier retreat presents an opportunity for new multipurpose reservoirs at dangerous new glacier lakes. It was noted that several projects in the Alps are on high priority list for new reservoirs to ensure safe energy transition in winter. Climate change impacts such as floods and drought can be mitigated by reservoirs. The need for reservoirs in newly arid zones in Europe will be of vital interest to mitigate floods and droughts, in combination with hydropower use. R&I should therefore also focus on the role of innovative multipurpose reservoirs in mitigating climate change effects. Other stakeholders highlighted environmental impact as a key issue, with reference to an EEA study on climate adaptation and impacts on various technologies (2019)[1]. According to the findings, hydropower is highly sensitive to climate impacts.

- **Hydropower/pumped storage – sustainability and physical vulnerability:** placed as low risk – high preparedness.

- **Wind energy – physical vulnerability to climate change:** It was noted that this was rather low risk, and that the overarching issue was CRM criticality (as with all technologies), and specifically demand for aluminium, copper, manganese and nickel. Cu for all electric devices, Mn for steels, Ni for any stainless steel, and Al for various structures where steel is not used. For any value chain, there are several types of electronics, including several CRM, such as silicon metal, germanium, gallium or arsenic.

- **Hydrogen – vulnerability to the wider energy system:** It is important to differentiate by scale: large scale projects >100MW can be expected to have direct connections to renewable energy plants. Small, decentralised electrolysis may run on own power or local surplus.

- **Bioenergy – availability of feedstock**: Bioenergy feedstock will compete with other bioeconomy products, but also with the need to increase the carbon sinks, which could have an impact on the level of forest harvests, for example. Competition for biomass feedstock remains poorly understood and discussion is on a theoretical level, without considering a) TRL of pathways, b) compatibility of different feedstocks with technologies, c) market volume demand for different products. Risks for different bioenergy feedstocks can be very different, so more detailed separation of feedstock + technology would be useful. See results of recent study on industry capacity for advanced biofuels (funded by European Commission). Biomass cascading is not yet part of policy (included in RED III, but only as a general principle). Great potential but deployment needs clarity on policy, financing and a level playing field.

[1] European Environment Agency (April 2019), "Adaptation challenges and opportunities for the European energy system".

- **Concentrated solar energy – sustainability and environmental impact:** rates as low risk – high preparedness.

Some criticalities were discussed in more than one break-out group and placed differently, with the following **divergences**:

- **CRM:** A key discussion point that affected how the criticality was placed was consideration of future demand. Some stakeholders did not view CRM as a key criticality, while other sectors such as wind are already moving away from CRM (permanent magnets) due to the anticipated increase in demand as a result of the global clean energy transition. Stakeholders noted that Europe is currently dependent on CRM to produce batteries and hydrogen (e.g. platinum and iridium from South Africa for hydrogen production). It was noted that Europe has many projects and initiatives looking into recycling and mining operations in Europe to meet this demand in future.

- **Hydropower and wind energy:** Public opposition was viewed as the biggest risk to hydropower development, and depends on region/country. Many stakeholders noted that the public have poor awareness of hydropower benefits and impacts, and therefore opposition to hydropower is not based on knowledge. In contrast, other stakeholders noted that new hydropower projects in Europe are almost never contested by local communities – who are given concession fees and other incentives – and opposition is driven mostly by regional environmental NGOs. On the other hand, wind farms are mainly contested by local communities because of visual and aural impact.

- **Advanced biofuels – feedstock:** assessment varied between groups, with agreement on medium preparedness from the EU, but risk level viewed as medium or high.

- **Batteries – supply chain:** EU preparedness was viewed as low, with varying views on the level of risk being medium or high.

- **PV – CRM:** assessment varied significantly between groups. One group assigned low risk – high preparedness, highlighting that only silver is a concern, while another group assigned high risk – low preparedness.

- **Ocean energy – sustainability:** Both groups agreed that risk is low. One group suggested that EU preparedness was high, with environmental impacts well understood and the public supportive. The other grouped viewed EU preparedness as low, potentially with regards to permitting challenges.

- **Ocean energy – affordability:** Both groups agreed medium risk, but assessment of EU preparedness varied between medium and low. The group that assigned medium preparedness highlighted estimated cost reduction curves, drawing on lessons from offshore wind and examples from countries now providing revenue support and commercial contracts (e.g. France).

Key points highlighted in discussion included:

- **Critical raw materials:** Discussion highlighted that availability of the materials is not the only concern, as significant energy is needed to turn raw materials into usable feedstock. Another key question raised was the stage at which CRM are key in the value chain: installation or throughout energy generation. If required during generation, for example, the energy security implications may be starker than a delay in installation, depending on the technology and its importance to the energy system. Where CRM are critical for installation, extending the life of technologies with repairability enabled by modular design would strengthen the energy security of the value chain.

- **Affordability** is linked to the characteristics of the value chain. For example, in PV, the innovation-commercialisation cycle is very short and new developments can reach market in six months to a year. In contrast, heat pumps will always have an affordability challenge due to upfront costs. Policy interventions are necessary to enable households, particularly low-income households, to adopt the technology. Support varies by country and was viewed as a political problem. Affordability was also linked to TRL, with less developed technologies facing high costs and cost reduction uncertainties. For example, CCU and CCS have distinct maturity levels and affordability, with some types of technology (e.g. mineralisation for long-term storage with CCS) more reliable than others. One participant noted that hydrogen would always be more affordable than RFNBOs.

- **Protection of intellectual property** was not viewed as a major concern. The EU is currently at the forefront of innovation; the challenge is not access to knowledge but other countries manufacturing more cheaply than the EU.

- There were no alternatives to some criticalities and technology solutions and therefore these were place higher on the risk–preparedness matrix (e.g. platinum, iridium and PFAS used in hydrogen production). For PFAS usage in electrolysis, for example, stakeholders noted that future policy developments and PFAS regulations would likely impact the innovation of products for hydrogen production, and regulations would come in phases, targeting different PFAS in each phase. This would mean future policy developments in hydrogen production would need to anticipate policy developments and distinguish between types of PFAS used and when they would be banned, to ensure hydrogen production is not impacted without a suitable alternative to PFAS having been developed.

- Stakeholders mentioned that some criticalities were dependent on the specific value chains within a technology category. Mobile and stationary batteries have differing needs, as do new versus existing hydropower plants. One criticality or solution does not necessarily address all types of batteries or hydropower plants.

- **Ocean energy** has not been deployed at sufficient scale yet, with potential challenges unknown. As a result, one group viewed EU preparedness as low.

- **Decision-making and policies** affecting technologies are a cross-cutting challenge. Authorities and regulators have an important role to play in enabling deployment of clean energy technology with their decision-making. They need competencies and knowledge or skills to make decisions in a timely manner, and for knowledge sharing.

- The risk carried by each technology is not the same for the **energy system** as a whole: for example, wind is higher risk due its significant role in energy supply.

- **Biofuels:** Policy uncertainty was highlighted as a significant risk, including for R&I.

- Advanced chips were assigned intermediate risk and low preparedness, but copper is fine.

- Cybersecurity considerations for PV inverters are a topic of focus for the sector. One participant highlighted IEA-PVPS Task 14 on cybersecurity of PV inverters.

- **Batteries:** The middle part of the battery value is a key risk. With regards to CRM, flexibility in the value chains can and should be prepared for.

12.2.2. Activity 1: scenarios and implications for energy security criticalities

Participants were invited to consider the scenarios developed in this study and what these plausible futures might mean for the energy security criticalities discussed in their groups.

Points that apply across all scenarios include:

- **Energy security** will evolve in future. Energy supply might be better anticipated than currently, with fewer sudden shocks. Cyberattacks or active disruption will become the primary source of sudden disruption. Will the energy grid be resilient enough with electricity coming from many sources, growing production, cyberattacks and solar storms?

- **CRM usage** must decrease in any scenario and across technologies. A key challenge is low confidence in new emerging technologies that make less use of CRM; this will have to be addressed moving forward. One stakeholder noted that some in industry are turning towards locally sourced materials to reduce dependence.

- In any scenario where energy cost increases, this will impact the affordability of all covered technologies.

- **Risk identification** is challenging.

- With temperature increases, it is assumed that technology development will have to continue to grow to address climate challenges. For example, **advanced biofuels**: food production will need to shift from places that become impossible to grow food in, to places further north where food production is still possible. There will be impacts on food security due to warming, making agriculture a priority concern.

12.2.3. Scenario 1

General comments about scenario outlook and impact on technologies:

- Does EU decarbonisation mean that imported products also have zero carbon footprint? Otherwise production and industry will just move outside the EU.

- If the whole world continues with climate change: more climate impacts and disruptions are to be expected.

- Right now, [the EU] needs some technologies, like PV, a lot – so its absence would impact [the EU] a lot. Other technologies, like hydrogen, will play a greater role in 2030 and 2040, so short-term impact is low but long-term impact high. Risk is higher in 2050 as [the EU] will rely on it more.

- **Critical raw materials**: CRM value chains are already starting to diversify, for example in Australia, and if this trend continues the supply chain risk from concentration may be reduced. A key question is whether there are enough natural CRM resources available to achieve the transition. For example, silver is not naturally abundant enough to meet the anticipated scale of PV deployment. In the case of PV, the first wave of technology is reaching end-of-life, creating an opportunity for recycling and reuse of key materials, where the EU has an advantage due to its larger deployment of clean energy technologies compared to other countries. The challenge is to develop processes for recycling, as raw materials are cheaper than recycled materials and with small margins, industry does not have an incentive to invest and deploy with recycled materials.

- **Recycling** was viewed as a huge opportunity for the EU, with a comparative advantage from the scale of installed clean energy capacity. Technical challenges remain to developing effective, efficient and high-quality recycling processes. Policy is also currently misaligned: for example, recycling targets are defined by a weight requirement, and in PV only 3% of the weight is important but the recycling target is met with lower-value recycling of glass.

(a) Criticalities for which the risk reduced and/or preparedness increased (compared to 2023 assessment):

- **PV – supply chain location:** moved from high risk – low preparedness, to low risk – high preparedness.

- **Advanced biofuels and bioenergy – abundance of feedstock:** moved from high risk – low preparedness, to medium risk – medium preparedness.

- **Batteries – availability and abundance of CRM:** moved from high risk – low preparedness, to medium risk –medium preparedness.

- **Hydrogen – availability and abundance of CRM:** moved from high risk – low preparedness, to medium risk – medium preparedness.

- **Hydrogen – vulnerability to wider energy system disruption:** moved from high risk – low preparedness, to low risk – high preparedness.

- **Batteries – supply chain location:** moved from high risk – low preparedness, to medium risk – medium preparedness.

- **PV – digital vulnerability**: moved to higher preparedness.

- **PV – availability and abundance of CRM:** moved to lower risk and higher preparedness.

- **Bioenergy/Advanced Biofuels – biomass availability**: moved from high risk – low/medium preparedness, to medium risk – medium preparedness. The impacts of climate change (e.g. droughts, forest fires, etc) can create a risk for biomass feedstock availability (valid for Scenario 3 as well).

- **Wind energy – CRM:** moved up to high EU preparedness in this scenario.

- **Wind energy – physical vulnerability:** if [the EU is] seeking net zero at any cost then it has been solved. Some risk of supply chain disruption would remain, but preparedness is very high. Physical vulnerability is low risk – high preparedness.

- **CCUS – affordability:** risk decreases with improved technology development. Some technologies, such as DAC, will play an important role in this scenario. At the moment, DAC technology is not yet ready, despite many initiatives globally, and needs to develop further. Development of this technology also depends on the degree of electrification. Price is also important aspect to consider. Hydrogen will also be more important, with an impact on the supply chain complexity criticality. The more DAC and other technologies are applied, the lower the cost.

- **PV – supply chain location:** moved from high risk – low preparedness, to low risk – high preparedness. If the EU meets its ambitions, this will mean [the EU has] implemented renewable energies effectively. PV supply chain would have been implemented and production can take place in Europe, and components can also be made in Europe. Countries have their own interests at heart: the point of CRM protectionism versus abundance. This would apply to all renewable energies. If [the EU] wants to reach the net zero, all renewable technologies will have to be implemented. Caveat: Production capability and production line: production capability in 2023 grew more in China than in Europe. So [the EU is] already behind, and [is] going to be even further behind.

- **PV – availability and abundance of CRM:** from high risk – low preparedness, to medium risk – medium/high preparedness. Regarding copper: no big supply issues now, however, if the energy transition proceeds in line with even the 2.5 degree target, global demand will increase a lot, while there is little new additional production in view and especially not within Europe, which already needs more copper than it produces from mining and recycling => a major supply issue on the horizon.

(b) Criticalities for which risk increased and/or preparedness reduced:

- **Renewable solar fuels – availability and abundance of CRM**: moved to higher risk and slightly lower preparedness. The EU has companies in this sector, but production is low at least 10% under where [it] would want to be.[2-3] Installation capacity is an issue. Since the United States implemented the Inflation Reduction Act and stopped importing Asian modules, the EU market is being flooded with cheap modules. A question to address is how to argue that EU products are better quality and address competition.

- **Ocean energy – affordability** is a key issue. If [the EU] moves to a scenario with lower energy costs this is less of an issue.

- **Hydropower – sustainability and environmental impacts:** modified from low risk – high preparedness, to mix of low risk – high preparedness (pumped storage HP) and medium risk – medium preparedness (other storage HP). The plant licensing process is very long. A different approach could be to adjust the regulatory framework. But [hydropower] needs a clear monitoring and adaptive management programme, for example a 'green label' (some hydropower plants have to show x, y, z species are being monitored). The tools are available but there is no money or incentive to implement. Many studies exist but there is no programme to monitor implementation. Study outcomes detect but don't transfer directly to other hydropower plants: the monitoring is case-specific. [The EU] will have to accept trade-offs in solutions; this is also a resourcing question. Impacts from hydropower are less than impacts from other technologies. [The EU] must define what is optimal in a local/regional context, and ranking of best choices is not quite there in technology rollout. Sustainability will move up as [the EU] will understand the technology by this time [the EU] has processes for consent in place, and will be aware of the environmental impacts.

- **Hydropower – physical vulnerability to climate impacts:** moved from low risk – high preparedness (pumped storage hydropower) and medium risk – low preparedness (run of river hydropower), to high risk – medium preparedness (run of river hydropower). The scenario increases the physical vulnerability and environmental impact criticality risks, but EU preparedness increases for pumped-storage HP. The impacts of climate change vary depending on the technology: for example, open loop hydropower is more vulnerable to climate change risks, while closed loop is less vulnerable. Electricity generation from run-of-river hydropower is much more affected by climate change.

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[2] PV Magazine. 2003. Europe to add 58 GW of solar in 2023. https://www.pv-magazine.com/2023/10/30/europe-to-add-58-gw-of-solar-in-2023/

[3] SolarPower Europe. EU Solar Manufacturing Map. https://www.solarpowereurope.org/insights/interactive-data/solar-manufacturing-map

Electricity generation from storage-hydropower much less affected, but the functionality of reservoirs is affected a lot by climatic changes. Pump storage hydropower has a low vulnerability to climate change. Continuous study is being conducted on this and preparedness is high. Distinguish between run of river – water flow can be affected by climate change. Storage hydropower is far less affected as it can mitigate the effects. Closed loop versus hydrostorage. Potential sites for closed loops around the world. Most are not really closed loop. Need to distinguish closed loop for storage. Some are used for batteries.

- **Off-grid energy**: under this scenario, the risks will be understood better. Risks of climate change may increase.

- **PV – digital vulnerability:** moved from medium/high risk – medium preparedness, to high risk – high preparedness.

- **Renewable and solar fuels – CRM:** moved from medium risk – medium preparedness to high risk – low/medium preparedness.

- **Batteries – CRM:** moved from medium risk – medium/low preparedness to medium risk – high/medium preparedness.

Technology-specific comments from the discussion to consider for this scenario:

- **Heat pumps – cyber security:** Closer collaboration with the United States may provide opportunities. For heat pumps, major companies are based in the United States and investing significantly. The risk of IP theft was also viewed as lower with the United States than China, in particular as the United States uses different types of heat pump from the EU. Collaboration within the EU will also be key to increasing preparedness – in particular initiatives that target positive effects on the cost (lower costs).

- **PV:** For PV, [the EU is] currently in a good manufacturing position, ranking well in terms of manufacturing operations and maintenance companies. For the rest, [the EU] ranks 3rd and 4th in relation to other countries. China has bigger companies, [Europe has] smaller companies. So [the EU is] not so badly placed, but looking at cost of production, large Chinese companies are able to decrease costs and can rely more on raw material.

- **Bioenergy/advanced biofuels:** Cost of energy might be higher, but the competitiveness of sustainable energy is high. Biomass availability risk will depend on how other technologies develop. Some sectors such as aviation do not have other alternatives. How [has Europe] reached net zero? Has [the EU] reduced the emissions to close to zero or do [they] rely on LULUCF sinks and carbon dioxide removal (CDR)? If [Europe] needs high sinks and significant amounts of nature-based CDR, this can affect biomass availability in the EU (relevant for all scenarios). Related study referenced.[4]

12.2.4. Scenario 2

General comments about scenario outlook and impact on technologies:

- **Cybersecurity** was viewed as a key threat across different futures and in particular in a highly digitised energy system. All technologies and manufacturing are smart in this

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[4] NEGEM Project EU. Quantitative assessments of NEGEM scenarios with TIMES-VTT. Horizon 2020, Grant Agreement no. 869192. https://www.negemproject.eu/wp-content/uploads/2023/11/NEGEM_D8.2_NEGEM-scenarios.pdf

scenario (and to varying degrees in other scenarios). The responsibility for cybersecurity is however unclear, especially at the boundaries in the value chain. Manufacturers are currently only focusing on their piece, and not how it connects with other systems. For example, in PV and other technologies, digital vulnerability is relevant for all components. It will all be linked through larger IT networks. Also true for inverters where China is important in the supply chain. Digital solutions are already studied and funded by Horizon projects and hydropower is expected to reach high levels of digitalisation.

- **Digitalisation** improves EU preparedness drastically, and the risk of studied criticalities (ocean energy, hydropower, wind), namely supply chain complexity, wind CRM and hydropower public awareness reduce.

- More generally for the energy system, PV can't be removed specifically because it is connected to everything. This vulnerability must be considered for everything.

- **Preparedness** is an awareness problem. Some stakeholders noted that awareness of the digital vulnerability is perhaps not as high as it should be in this scenario. Awareness of vulnerability in some countries (e.g. Netherlands). cropped up specifically. It was noted that it would not be hard to address technically, but just hasn't been addressed so far. Inverter and PV value chain: [Europe has] a few companies that are European, US, Israeli, and there the situation is different.

- **Reliance on global value chains** was viewed as a risk for quality. Quality already varies significantly in the wind industry, with low quality resulting in more frequent malfunction and repairs. The structure of current value chains means parts are sourced from multiple suppliers for the same price but varying quality. Overconcentration is also a significant risk, especially if value chains are entirely driven by cost.

- **Lower cost of energy** prompted a range of discussions. Low energy cost for consumers may reduce incentives for efficiency measures or create a push for efficiencies to increase profitability. Low cost of energy would make EU production cheaper, which is currently a competitive challenge for EU manufacturing compared to other countries. The grid was assumed to be more distributed in this scenario, contributing to reducing the cost of energy to consumers. A distributed grid has potential to increase the resilience through flexibility. A distributed grid and diversity of suppliers in renewable energy also makes the system more resilient compared to the non-renewable energy system, where energy production is concentrated and more vulnerable.

- Stakeholders identified there would be a large amount of global innovation and collaboration. Significant R&I and global efforts would be needed to achieve this scenario.

- Stakeholders thought that the scenario would lead to pressure on carbon feedstocks and reliance on political goodwill for CRM.

- Stakeholders considered that a huge increase in renewable electricity production would be required to enable both the hydrogen economy and CDR with DACCS, as well as electrification of many industrial processes and transport.

- Trade-offs will be needed in LULUCF, NBS and biomass availability.

- Negative emissions will also be needed (e.g. DAC with CCS)

(a) Criticalities for which the risk reduced and/or preparedness increased:

- **Renewable solar fuels – availability and abundance of CRM:** moved to slightly lower risk than Scenario 1.

- **Hydropower – all criticalities:** The EU is the main global exporter of hydropower equipment, so supply chain is a strength for hydropower. In this scenario, agreement on how environmental risks are handled for hydropower is expected – more societal agreement and similar with climate change resilience.

- **Wind energy – CRM:** Risks seem to be reduced. Moved up to medium risk – high preparedness.

- **Wind energy – physical vulnerability:** moved to low risk – high preparedness.

- **Ocean energy – sustainability and environmental impacts:** moved to low risk – high preparedness. Deployments and preparedness increase.

- **Off-grid energy:** moved to low risk – high preparedness. More widely embraced in this scenario as more resources available for it.

(b) Criticalities for which the risk increased and/or preparedness reduced:

- **PV – availability and abundance of CRM:** Moved to lower preparedness and slightly lower risk than Scenario 1. In Scenario 2, stakeholders noted that it sounds like risks for raw materials would still be there, and equally high as today [2023]. Although the situation sounds positive in some respects, thinking ahead, [the PV industry/Europe] may also have to plan for a less collaborative world at that point in time. Availability of CRM is also linked to industrial policy.

- **PV – supply chain location:** moved to lower preparedness compared to Scenario 1. A certain independence in supply chain is a cost. Russia and gas: [Europe] should work to not to replicate this mistake.

- **Smart energy and grid technology – digital vulnerability:** moved to lower preparedness compared to 2023 scenario.

- **Advanced biofuels and bioenergy – abundance of feedstock:** risk increased, so moved up to medium risk – high preparedness.

- **Hydrogen – availability and abundance of CRM:** risk increased, so moved up to medium risk – high preparedness.

- **Hydrogen – vulnerability to wider energy system disruption:** risk increased, so moved up to low risk – high preparedness.

- **Ocean energy – affordability:** remains an issue, medium risk – medium preparedness.

- **Batteries – CRM:** global demand will peak – risk is high in this scenario, but efficient circular economy established.

12.2.5. Scenario 3

General comments about scenario outlook and impact on technologies:

- With severe supply chain disruption, good maintenance will play an important role. It may be valuable to consider maintenance as part of design and skills development to ensure repairability of clean energy technologies.

- Climate adaptation raised a number of challenges and many knowledge gaps:

  - Water scarcity is a major issue due to the use of water in the production of many clean energy technologies. Water scarcity will also raise energy demand for desalination.

  - For PV, hail is a major issue and mega events such as storms seen in Italy can cause severe local disruption. Technical adaptation and repairability are key considerations for continued operation or mitigation of disruption. Energy supply predictions may be completely different compared to now, with risk of climactic events happening in different locations simultaneously and affecting the wider EU energy grid.

  - A warming climate will increase demand for cooling, technology for heating and cooling, circular heat and cold, and technologies that produce less waste heat will be important to develop.

  - Clean energy technologies may also provide adaptation solutions for other sectors. For example, PV could be used to shade crops and prevent water loss with example deployments in strawberry fields in the Netherlands and vineyards in France.

  - Uncertainty over the evolution of the climate is a challenge, as decisions on the location of clean energy technologies are being made now and may no longer be optimal in future for certain technologies. For example, wind speeds are changing.

  - Climate change migration may provide an opportunity for skills.

- **Trade wars:** It might be more expensive, but autonomy will be important in this scenario with the development of local capacity to reduce reliance on imports. The economy here in EU must invest in all capacity.

- Europe does have reserves of **raw materials**, but they are not being exploited right now for different reasons. This scenario could remove some objections and make [Europe] more ready to exploit what [it] already [has] (e.g. lithium for batteries).

- Participants assumed that in general the EU is prepared for all criticalities but one could be more pessimistic – i.e. that we even don't prepare, so more boxes may get into the red lower right [high risk – low preparedness] area.

- **Energy security:** Energy security and autonomy will be key. Systems should be robust/fail-proof, with a backup/insurance policy. Energy efficiency can help. Basic needs and security aspects would trump environmental considerations. Would not move this down as a threat. This scenario highlights areas where the EU needs insurances. There are fewer R&I investments, so more reliance on existing technologies and regional autonomy (short supply chains).

- **Fossil fuel/renewable fuel access:** Fossil fuels may become scarce due to conflict in this scenario. Focus will increase on local resources and domestic production (e.g. hydrogen).

- **Biomass**: With conflict elsewhere, immigration is likely to increase to EU. This will increase need for more food production in the EU, meaning less land available for bioenergy?

- Cyber warfare is already happening or being prepared. The EU must prepare for this.

(a) Criticalities for which the risk reduced and/or preparedness increased:

- **Renewable solar fuels – availability and abundance of CRM:** Moved to slightly lower risk than in Scenario 2. Still using a lot of fossil fuels, etc. The stakeholder wouldn't be confident in the renewable market in this scenario – in a world where we just accept climate change and go ahead blindly. In the larger system, even coal is not cheaper, just more available than solar.

- **Wind energy and hydropower:** Key risks in this scenario relate to physical vulnerability (wind, hydro) and environmental impact (wind) – although environmental impact of hydro is low risk.

- **Hydropower – sustainability** would remain independent from the scenario. Any energy source must be sustainable in any scenario.

- **CCUS**: Availability of geological CO_2 storage for CCS in this type of world is a question, creating further challenges for decarbonisation.

(b) Criticalities for which the risk increased and/or preparedness reduced:

- **Concentrated solar energy – sustainability and environmental impact:** Slightly lower preparedness, but continued low risk compared to baseline scenario. Difference between scenarios – but still little impact on the overall map. The situation is similar, but the impact is stronger. In such a world, the European value chain becomes even more important than in a peaceful world.

- **PV – supply chain location:** Moved to higher risk and lower preparedness than Scenario 2. If the economy is in recession, investment is low. High risk and low preparedness, because [investment would recede]. Companies that are still in the market would not be able to survive, so fewer companies in this aspect. If we keep the level of investment, we would not be in a good place. In this scenario, we would have a very different market situation. The intrinsic low-cost potential of PV would create a lot of business opportunities. Even halfway-good PV production would open up opportunities as a consequence of resilience strategy. On preparedness: all the necessary know-how to build a supply chain would still be there. What we miss is the risk of losing the supply chain, which is possible, but an unattractive business opportunity. The CRM are there. Risk is low, but we would start with higher cost and we would be independent from other countries.

- **PV – digital vulnerability:** Moved to higher risk and lower preparedness than Scenario 2.

- **Smart energy and grid technology – digital vulnerability:** Moved to higher risk and lower preparedness than Scenario 2. In Scenario 3, we would be more autonomous, and therefore more prepared on some of these items so they can shift upwards – digital vulnerabilities, for example: we might be better off with our own autonomy on these things. The risk remains high, but the preparedness may also be higher if we are more autonomous. This scenario wouldn't come over night. If we move towards this, we will get our supply chain more in order. We still have learning power in terms of seeing what will happen.

- **Bioenergy/advanced biofuels – biomass availability:** Moved to higher risk – low preparedness. Recession scenario – tree cutting and biomass burning.

- **Hydropower run off river – physical vulnerability:** Moved to high risk. How can we be prepared with climate change impacts – highly vulnerable. Stakeholders agree that the vulnerability should remain in this position – the reservoir is highly impacted by climate change. But the reservoir would be the means to mitigate risk. It's a question from where we are looking. In flowing to reservoir but larger reservoir risk that no water available. Also depends on geographical context – some countries have more water available than others. Hydrological availability – will it increase in the future? Will there be floods or draughts? Study at JRC: understanding how hydrological factors will change in the future. Difficult to give precise answer. This is a hot topic. Hydropower plants are already being shut down due to droughts – will become more relevant. Water availability will decrease – even if we build new reservoirs will not solve the problem. We have to save water rather than building new reservoirs. Maybe both? Will have periods with lots/small amounts of water.

- **Advanced biofuels and bioenergy – abundance of feedstock:** moved down to high risk – low preparedness.

- **Hydrogen – availability and abundance of CRM:** moved down to high risk – low preparedness.

- **Batteries – availability and abundance of CRM:** moved down to high risk – low preparedness.

- **Batteries – supply chain location:** moved down to high risk – low preparedness.

- **Hydrogen – vulnerability to wider energy system disruption:** moved down to medium risk – medium preparedness.

- **Wind energy – CRM:** risk is high for wind in terms of CRM disruptions.

- **Wind energy – physical vulnerability:** risk has increased.

- **Hydropower – physical vulnerability:** Would increase in risk, moving towards 3 °C. Incentives: EU is missing its targets – less hydro overall with lower end use. Some types of hydropower would be less attractive than others. Moving to 3 °C would require large reservoirs. There would be a trend of large reservoirs, which fulfil several functions. Affordability split on access to off-grid energy tech by economic status. Interplay with risks around water availability, which will impact reservoirs and climate instability. Will differ by region, depending on climate impacts.

- **Ocean energy**: Energy security benefit in a scenario like this is significant – likely to reduce overall risk but investment is lower, need for security is higher. These are conflicting scenarios.

- **CRM**: Much more mining in EU, and recycling – also for RES, electrolysers, etc.

13. Validation and development of the R&I action plan

13.1. Pre-workshop exercise

Participants were provided with the shortlist of key energy security criticalities. With the information provided, participants were invited to answer the following questions for the technologies in which they have expertise and experience:

In your view, are the corresponding R&I challenges [to the key energy security criticalities] correct? What potential solutions are you aware of?

Participant inputs are incorporated into in Chapters 7–9 of the main report.

13.2. Activity 2a: feasibility and impact of proposed R&I actions

Participants were invited to place proposed R&I interventions on a feasibility-impact matrix and to suggest practical considerations or alternatives that might both address the energy security criticalities and increase feasibility and impact.

13.2.1. Feedback on suggested R&I interventions

Ocean energy – research on public perceptions: One stakeholder did not view this as an area for R&I, while another noted that the challenge is to do this until we know exactly what it is we put in the ocean. The research would need to be broad and high-level at the moment but would support improving public perceptions.

Ocean energy – affordability: addressed to some extent by existing programmes. Deployment pilot projects combined with finance mechanisms (e.g. revenue support in UK, commercial tenders in France) would support the demonstration of cost-reducing technologies and enable wider deployment.

Ocean energy/hydropower – climate impacts – hybridisation: for example, supporting pumped hydro in an ocean context. It was noted that so far there are only a few case studies on this, but the stakeholder was not sure if should be on EU research agenda. There could also be environmental issues caused by salt water on topography with this solution, but there are ongoing tidal height projects (e.g. Alpheus). Similarly, cross-cutting work on biodiversity mentioned as a solution across technologies, not only marine energy.

Wind energy – CRM: not only about magnets, but also about recycling/reuse/reduction of all material inputs. Circularity in general for wind should be further researched.

Advanced biofuels – biomass abundance – conversion technologies: Stakeholders agreed that feedstocks will remain important, but might not be the most important criticality, and conversion technology is probably more relevant. R&I challenges to address this are key.

- **Heat pumps – CRM:** Open calls that specify the desired outcome rather than the approach would encourage looking at criticalities and developing solutions.

- **Hydrogen – broader sustainability and environmental impact:** Material use of, for example, PFAS could be lowered. There are companies that develop membranes without PFAS. The material decomposition during use-phase, recycling stage and over whole lifetime, should be a focus. Solid oxide electrolysis is always more efficient, but the TRL is lower than for PEM and alkaline electrolysis. SOE should be a focus, where heat requirement is paramount.

- **Hydrogen – supply chain complexity:** Standardisation of testing would be extremely important. With this, we can compare upcoming technologies and alterations on the same level playing field. This could improve trust and acceptance of industry in new emerging technologies. The testing should be on components of the electrolyser.

- **Batteries – availability and abundance of CRM:** Opportunities for developments in other battery materials, following a distinction between mobile and stationary batteries that should be considered when developing supply chain and recycling aspects, as these are very different ecosystems. Alternative battery configurations, like Na-ion, should be promoted (Li-ion still dominates most markets). Separately, MNC (nickel manganese cobalt) currently dominates car industry.

- **Wind energy – physical vulnerability:** Opportunity for a futures-focused call involving EU OEMs and researchers to ensure adaptation to extreme weather events in different scenarios was viewed favourably, and it was noted that this may be required for all technologies, not only wind.

- **Batteries – CRM – package to build EU supply chain for batteries completely without CRM.** For low- and no-CRM batteries, the stationary storage market is easily accessible to get a foothold and critical mass. Later, these technologies might find their way into mobility applications. A clearly regulated electricity market that rewards stationary storage accordingly will be a further boost. Additional policy research would be valuable. Policy on ownership of stationary storage (batteries etc.) needs to be addressed, as well as stacking of energy services.

- **Batteries – CRM – package to build EU supply chain of batteries completely without CRM & R&I for cost efficient battery manufacturing in EU:** Opportunities to use our competitive advantage in digitalisation to accelerate materials research and manufacturing. What about skills necessary? It's a bottleneck for both developing batteries without CRM and programmes to improve cost-effectiveness of battery manufacturing processes. Especially if you want to solve supply chain criticality through acquisition.

- **Batteries – CRM – acquisition** is more effective than R&I: you need to build local competence for onshoring through acquisition to work, otherwise you will remain dependent on foreign expertise and/or supply chains. This competence needs to be built through R&I and education efforts. Local acceptance is necessary – perhaps SSH R&I action is needed on this.

13.2.2. Alternative or additional R&I interventions suggested:

- **Ocean energy – broader sustainability:** Support for regulators may be valuable. Projects have explored adaptive management with regulators and innovative companies. Adaptive management includes the retirement of risks once sufficient evidence is available, reducing the burden on companies aiming to deploy. Data transferability, from one demonstration to the next, would also be valuable to ensure lessons learnt in one location can form part of the evidence for the next.

- **Thermal storage:** R&I was identified as a cross-cutting challenge across technologies for waste heat and cold recovery, looking at how technologies could work together. This could be address through research on what a standardised net zero building looks like and how standardisation could support cost cutting and installation.

- **Heat pumps – affordability:** Standardising industrial heat pumps is a current challenge where EU R&I funding would accelerate the development of solutions. A programme bringing together a major industry partner and heat pump developers could aim to identify standardisation opportunities that would then be available across industry consumers, without the first consumer bearing the cost and time impacts.

- **Heat pumps:** Support for regulators may also be beneficial, for example around the regulation of historical buildings, to develop working solutions.

- **Batteries – availability and abundance of CRM:** opportunities to develop recycling of batteries, as this is not yet a developed market. Strong policy support is needed to promote recycling. However, the supply chain will remain largely depended on primary raw materials from outside EU, so the recovery of materials will be important, and R&I has a role to play here.

- **Carbon capture, utilisation and storage:** More public funding should be promoted as well as reducing regulatory ambiguity. R&I studies into political science may be able to provide insights into these issues, or consultations with market parties.

- **Hydrogen and RFNBOs – affordability and vulnerability to energy system disruption:** Getting technology out in the market, policy labs, research or regulatory sandboxes can be used to ensure affordability. This would be high feasibility, high impact.

- **Energy grids, transmission and distribution:** Additional research on cable types and where to place transmission lines (some ongoing work but more is needed). This should involve coordination between countries, which is lacking.

13.2.3. Opportunities and technology-wide R&I needs highlighted in discussion with regards to feasibility and impact:

- **Cybersecurity** is an important research issue, in particular with regards to determining how to best proceed and agree standards. Efforts are currently disparate and convening the various stakeholders to discuss a proposed approach would be valuable.

- **Skills:** A recent call is looking at how to attract more people. One gap identified is a systems view of the whole clean energy sector and skills requirements, in particular to mitigate risk of competing demands between different clean energy value chains. These capacity building programmes could help people understand technologies and their interactions. This type of capacity building programme could be beneficial.

- Opportunities for **international collaboration** are numerous. Japan sees the EU as a model to follow. Australia, the UK, South Korea and Canada would also be potential collaborators. Ukraine has developed interesting technology and reconstruction will provide an opportunity to develop and deploy innovative technologies. Collaboration with African countries would also be valuable, in line with support for sustainable development and shared challenges.

- **Hybridisation** was a theme: co-location of wave and wind projects; PV and hydropower; grid solutions to combine energy technologies and best grid set ups (on and offshore). Combining clean energy technologies may help resolve key performance issues or criticalities. For example, heat pumps could provide a solution to battery performance in cold climates, which would support the use of EVs in colder regions. A targeted EU programme would create incentives for the automotive sector to be involved. Another potential combination with efficiency opportunities is combining ocean energy and wind energy, sharing some of the infrastructure and producing more energy from the same area. Wave energy, for example, is complementary to wind and tends to produce energy for longer after wind reduces.

- **Grids**: European optimised deployment of wind technologies. Linking national profiles for wind (and PV). Reduce flexibility needs by linking countries in particular ways for maximum complementarity. And think about complementarity with other technologies. Relevant for storage as well as generation. EEA-ACER joint report on flexibility shows the need to support decarbonisation – i.e. showing that complementarity effects for wind and PV can be improved via grids and better planning.

- Opportunities for **digitalisation** and qualified personnel are important cross-cutting issues.

13.2.4. Concerns were highlighted in discussion with regards to feasibility and impact

- SMEs facing bureaucracy: Small and innovative companies view EU programmes as presenting significant barriers, in particular bureaucracy and are reluctant to participate in Horizon programmes. For ocean energy, regional funds have been important sources of R&I funding, with Wales, the Basque country and Brittany investing.

- **Ocean energy – affordability:** A key element necessary to support development and deployment programmes are complementary finance mechanisms, whether zero interest loans or commercial revenue support. Capital costs are high and as a developing technology, investment risk remains a challenge for developers. Visibility with private investment would be better supported, with policy setting out deployment targets increasing certainty.

- **Ocean energy:** Global R&I is very competitive with a race to commercialisation. China and the United States are key competitors, with China pushing deployment and the United States is investing USD 100 million a year in R&I. EU leadership in this technology is under threat. Previous experience highlighted that EU companies will leave for markets where revenue support is available (e.g. Canada – however deployment was blocked). Support for demonstration and deployment of novel ocean energy technologies: there is already well-funded a programme of support for demonstration and deployment that just needs the time to deliver.

- **Grids:** low coordination between countries.

- **Hydropower – biodiversity:** Tools are available (e.g. monitoring) but no money to implement them. There is not a lack of methodologies or tools.

- **Advanced biofuels and bioenergy – feedstock abundance:** Bioenergy as part of the bioeconomy (connection with bioproduct developments). Not just an energy issue.

- **PV – CRM – R&I package for perovskites:** Perovskite is relatively new and companies are trying to ramp up production. Availability of silicon is a high concern and [the EU is] out... [The EU has] the raw materials but do[es]n't have the industry to turn materials into silicon. [The EU is] geopolitically hemmed in.

13.3. Activity 2b: futureproofing R&I actions

Considerations to ensure the R&I interventions are future-proofed, maximising their potential for impact, were discussed.

13.3.1. Scenario 1

Challenges this scenario poses to proposed R&I interventions:

- There is no raw material in Europe, so we will be dependent on other countries. Opportunity: this could help motivate government to put in place policies to enforce this, making funding available, etc.

- Solution-specific technical difficulties:

    - Multipurpose reservoirs: conflicts over water uses/priorities and sharing benefits and costs among users and stakeholders. Multi-purpose reservoirs are generally larger and need larger water volumes and civil structures. In these systems, hydropower is a benefit rather than a source of impact, because it also adds energy and economic value.

    - Floating PV: water level variation, ice in winter

- Without international collaboration, the EU is reliant on the battery sector outside the EU. This leads to losing EU talent (e.g. to the United States) as it becomes difficult to compete on pay. Most of the challenge is about talent and **maintaining skills, knowledge and leadership** in the EU. Similarly, the EU must respond to the US IRA as it is resulting in brain drain and financial drain.

Opportunities for ensuring R&I interventions are futureproofed:

- In this scenario, Europe is probably leading in most of these technologies, and it has long experience in all of them (e.g. EU hydropower industries are leaders in export of hydropower electromechanical equipment and in design, operation and consultancy). As long as you can have exchange within Europe, [Europe] should be OK. It would be different for PV. However, if international exchange is outside Europe, we have a serious problem to overcome. It is relatively self-sustained, and [the EU] benefits from collaborating with others. For example, hydropower sustainability must be addressed on an international level, so international research collaboration should be maintained.

- **CRM:** The EU needs to invest in its own mining ability to ensure [the EU] can provide the materials [it] require[s] – for every sector, not just the battery sector.

- There is a lot of innovation space for new materials, beyond silicon, and this space is well filled by actors in Europe that are well connected. What we do need in policy discussion, is to extend the research portfolio. Instead of a slow, complicated lab experiment in Europe, you could do something on preindustrial scale in China. This is connected to discussions [the participant's organisation has] had before. [The EU] would have to invest highly in R&I.

Proposed solutions to ensure R&I interventions are futureproofed:

- **Batteries – CRM:** R&I actions to reduce emissions in processing, manufacturing and recycling to make permitting easier.

- **Hydropower** and water reservoirs could be developed for multiple uses and to improve biodiversity. Digital and real-time control in reservoirs can be used to improve environmental performance[5].

- **Batteries – maintaining skills:** Rewards for jobs in Europe might rise as a compensation for lack of skilled foreign workers.

- **International collaboration** must be addressed on an international level for some specific technologies, as these are projects of mutual interest. For example:

  - **Hydropower – sustainability:** international research collaboration should be maintained.

  - **Batteries – CRM:** collaboration on manufacturing and recycling (where possible).

- **Reassure industrial actors** to expand the research portfolio and innovate at scale.

- Faster pace of technology commercialisation is needed within Europe, as well as more investigations into lower and higher TRLs.

13.3.2. Scenario 2

Challenges this scenario poses to proposed R&I interventions:

- **Less market for opportunities:** Not all countries are in the same position. Large countries with traditionally strong range of resources, more so than smaller countries.

- **Staff and expertise:** Exchange programmes for students will be limited, as will recruitment of researchers, as well as maintaining good research output and impact.

- **Competition:** Several technologies have companies that are competing with each other, and it is different from finding sustainability solutions which are in everybody's interests.

Opportunities to ensure R&I interventions are future-proofed:

- Technology development: Opportunities for technology R&I will expand massively. We do not have the same overall similar research R&I needed. The scale of things would be different and the scope for PV would be larger.

- Many technologies are at an earlier stage of development.

- **Wind and Hydropower**: considered well-developed technologies. They already work – forgotten that further R&D is needed, especially for wind. Competitive solutions already exist but there still needs to be ongoing R&D. They will be the backbone of the future energy system. [The EU] still need[s] to invest and lots of things to address (particularly with new role alongside other technologies). See now very low R&D support for wind versus. importance in energy system.

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[5] Quaranta et al. (2023), 'Digitalization and real-time control to mitigate environmental impacts along rivers: Focus on artificial barriers, hydropower systems and European priorities'. *Science of the Total Environment* 875, 162489. https://linkinghub.elsevier.com/retrieve/pii/S0048969723011051

- **Competition**: increase in competition drives innovation.

- **Different regions provide different assets** to the energy transition (e.g. Scandinavian countries can provide long-energy storage), southern Europe provides solar PV, northern Europe provides wind energy, Alpine regions provide hydropower and short/middle-term storage. This is an opportunity if considered.

- Most **biomass** comes from the EU – strong point. Although it is always better to reach out internationally – [the EU] still need[s] tech developments and deployment of early market tech – helps if this is proven in other regions. Investors also look globally at how technologies are proven. If [the EU] do[es]n't look at this, we would have to do it on our own – could be risky.

- **Hydrogen** will be produced where energy is the most abundant and cost-effective. There are conditions for EU production and in the long term, we will import less energy than now in the de-fossilised world, but [the EU] will nevertheless import large amounts of energy in terms of hydrogen or derivatives.

- **Challenge and opportunity:** Companies are frontrunners in biofuels – for guarding the status quo, it wouldn't harm if the exchange is limited – guarding preservation we always need the best brains for the job – challenge and opportunity?

Proposed solutions to ensure R&I interventions are futureproofed:

- According to Worman et al., by virtually interconnecting hydropower plants in Europe (not EU, but Europe) as an interconnected grid (<3 000 km), 140 TWh of energy storage could be provided by spatial-temporal coordination, similar to the current maximum theoretical storage capacity of hydropower reservoirs in Europe. So, **international collaboration is of high importance**.

- **Cooperation**: Many issues requiree cooperation, for example spatial planning, defining best interventions and solutions.

- **EU for electrolysis** – Chinese have PV already. China deployed wind turbines domestically. EU producers are yet to meet targets over the next 3–4 years. If not hit, [Europe] will need to import from China to meet EU targets. This could be the same for hydrogen.

- **Regional focus creates local value chains** which reduce CO_2 emissions in the long run. [Europe] shouldn't transport materials halfway across the world as it is environmentally costly. [Europe] should be very aware of this. This also depends on the volume transporting - there is a cost/benefit. International shipping needs to decarbonise. Long-distance transport – how can this happen?

13.3.3. Scenario 3

Challenges that scenario poses to proposed R&I interventions:

- If there is **limited investment**, there is little opportunity.
    - If we miss the boat now, it will be harder and harder to catch up. But it's not impossible. But if we leave production for another 10 years, it can be impossible. Risks will get bigger and bigger.

- At a critical point for ocean energy where we don't really have a viable product. Huge long-term impact if we don't have investment now. Same for airborne wind – need investment now or it won't be ready.

- **Competition**:

  - If EU doesn't collaborate, China and the US will be the biggest competitor in the future.

  - Risk of brain drain though competition.

- **Risks around trust** and not wanting to lose advantage – risk to manage (e.g. China collaboration).

- **Leadership risk**, with the EU depending more on expertise and resources outside of the EU.

Opportunities for ensuring R&I interventions are futureproofed:

- The funding is important, but the technologies could be invested that can run on their own. An opportunity for companies to catch foot and do something completely different to the rest. Push for innovation.

- **International collaboration**:

  - All countries are trying to address sustainability issues. More like developing methodologies and approaches to solve that.

  - **Ocean energy**: US is the big opportunity. Recently put a huge amount of funding into ocean energy, big programme at DoE.

- **Learning opportunity:** for example, hydropower. In the US: enormous efforts into pump storage and modernisation of existing hydropower. But also several Asian countries and Australia (to a smaller degree). Not so much about developing a certain type of turbine. European turbine manufacturers and US, both excellently positioned. Large market share. Defending their advantage. Also start producing certain components in China. Already a lot of international collaboration – sustainability criteria, models.

Proposed solutions to ensure R&I interventions are futureproofed:

- **Focused investment** on certain technologies – more targeted prioritisation.

- This will sound optimistic, but it could give a push to cooperation mechanisms.

- Push for **hybridisation** of technologies.

- The opportunities bring [participants] back to the point that at some point investment must come back. Optimistic points are true, but they can only bring you back to the interest to invest, but if investment doesn't come up again there will be a doom and gloom scenario.

- **Circularity**: Consider what happens at end-of-life. Specific examples – airborne wind has an advantage. Not looked at from the system level, often just one component. Consider different technology options. Consider material input rather than just outputs. Restrictions on some materials may trigger research and better solutions.

- Look at the **multiple benefits** that can be generated, especially in the long term. Try to quantify and generate additional benefits not just energy.

- Finding ways to reward local communities so they are not stranded with impacts. Equity consideration – benefit sharing. Inclusive and fair transition is part of this. Developments going on. People in vicinity – lower value of surroundings (housing, tourism) while they are not really benefitting from the electricity. How do we compensate them?

- Regulatory framework and public acceptance (for hydropower). Societal agreement to move ahead would drive adjustments in regulatory framework. Increasing understanding on clean energy technologies amongst the public.

ANNEX F: R&I ACTIONS NOT INCLUDED IN SHORTLIST

14. Shortlisting R&I challenges for the action plan

We identified 54 R&I interventions across the clean energy technology value chains. Where the R&I challenge and proposed intervention are the same, we have presented them as one. In some cases, more than one R&I intervention is proposed per challenge.

14.1. R&I challenges already addressed in EU programmes

The first step in prioritisation was to discount R&I challenges for which targeted R&I programmes are already in place and no further action is currently required. In these cases, it will be valuable to review the need for further or continued R&I upon completion of the R&I programmes, or if the external context changes.

As such, the following R&I challenges were not included on the shortlist:

- **Concentrated solar energy – how can environmental requirements and impacts be reduced or mitigated?** The EU is supporting targeted R&I for this R&I challenge. An additional R&I intervention is not proposed at this stage, and a follow-up call to existing R&I programmes may be valuable if gaps are identified or further research is needed.

- **Ocean energy – how can the environmental impact be reduced or mitigated?** This challenge is well addressed in existing European R&I interventions. The study does not recommend further R&I interventions. However, as this is a shared international challenge, it would be beneficial for the EU to ensure this is resolved with support for knowledge exchange and collaboration, whether through research partnerships or exchange in international fora such as the IEA.

- **Carbon capture, utilisation and storage – how can the environmental impact be reduced or mitigated?** The EU is supporting R&I targeted at this challenge. A follow-up to existing R&I programmes may be valuable if gaps are identified or further research is needed.

- **Wind energy – how can performance be maintained or managed with a changing climate?** Climate change impacts on wind energy were considered well understood, with workshop participants viewing further R&I as unnecessary at this stage.

- **Concentrated solar energy – how can the cost be reduced to levels competitive with other clean energy technologies?** The EU is supporting targeted R&I for this R&I challenge. An additional R&I intervention is not proposed at this stage. A follow-up call to existing R&I programmes may be valuable if gaps are identified or further research is needed.

- **Solar fuels – how can the cost be reduced to competitive levels?** The EU is supporting R&I targeted at this challenge. A follow-up to existing R&I programmes may be valuable if gaps are identified or further research is needed.

- **Hydrogen – how can the cost be reduced to competitive levels?** Existing EU programmes are addressing this challenge. A follow-up to existing R&I programmes may be valuable if gaps are identified or further research is needed.

- **Geothermal energy/batteries – how can the supply of CRM be secured?** Geothermal energy may contribute solutions to support the security of supply of certain CRM, such as lithium. The EU is supporting targeted R&I for this challenge. An additional R&I intervention is not proposed at this stage, and a follow-up call to existing R&I programmes may be valuable if gaps are identified or further research is needed.

- **Hydrogen – how can the use of CRM be reduced?** With existing programmes already addressing this issue, additional R&I intervention is not considered necessary at this stage.

- **Heat pumps – how can the use of CRM be reduced?** Recycling initiatives are in development and further R&I was not deemed necessary by validation workshop participants at this stage.

- **Photovoltaics – how can the digital vulnerability of the inverter be reduced or mitigated?** The solar power sector is working on this challenge. It would be beneficial to keep these activities under review and ensure ongoing cybersecurity research programmes are pursued, including specific research on threats relevant to solar PV inverters and their effective mitigation.

- **Carbon capture, utilisation and storage – what factors influence public opinion?** The EU is supporting R&I targeted at this challenge. A follow-up to existing R&I programmes may be valuable if gaps are identified or further research is needed.

- **Hydrogen and RFNBOs – how can the energy efficiency of production be increased?** A number of Horizon Europe calls include addressing energy efficiency challenges in these technologies. This is a shared challenge, with targeted research in the United States and potential opportunities for collaboration.

- **Storage (CAES) – how can the supply chain be more resilient?** Pending the outputs of relevant Horizon projects, additional R&I may be beneficial if CAES was not covered in the scope.

- **Solar fuels – how can the availability of skilled R&D talent be ensured?** With existing and upcoming R&I programmes contributing to developing a skilled workforce, specific R&I intervention is not recommended at this stage. However, this should remain a point of attention to ensure a continued pipeline of specialised talent is developed and incentivised to remain in the EU. Other policy actions may also support the retention of talent in the EU or attract international talent.

14.2. R&I challenges where policy or regulation may have more impact

The second step was to consider whether R&I presents an effective solution to the challenge – or if other interventions would be more impactful. In some cases, complementary R&I interventions addressing the challenge are included in the action plan. In the case of RFNBOs and hydrogen (affordability and vulnerability to the wider energy system), workshop participants suggested a policy lab or regulatory sandbox to bring technologies to market.

As such, the following R&I challenges were not included on the shortlist:

- **Advanced biofuels – how can the security and availability of feedstocks be improved?** Two technology-focused R&I actions were proposed to address this action. However, policy and regulatory action to increase certainty and resolve risks around the abundance of feedstocks was identified by validation workshop participants as high impact and high feasibility. Policy intervention is crucial to resolve this challenge, with R&I intervention potentially complementary.

- **Bioenergy – how can the security and availability of feedstocks be improved?** Policy and regulatory action to increase certainty and resolve risks around the abundance of feedstocks was identified by validation workshop participants as high impact and high feasibility. Policy intervention is crucial to resolve this challenge, with R&I intervention potentially complementary.

- **Photovoltaics – how can the supply chain be on-shored to the EU?** Acquisition of a supply chain might be the most cost-effective solution to on-shore photovoltaic supply chains. Complementary R&I interventions would be beneficial to ensure the supply chain remains globally competitive. An alternative challenge to the PV supply chain criticality is proposed (see main report, Section 9).

- **Smart energy grid technologies, smart cities, energy building and district technologies, energy transmission and distribution – how can the supply of semiconductors and electronics be secured?** Policy intervention, for example as part of the EU Chips Act, should ensure that these technologies are considered in their remit.

- **Carbon capture, storage and utilisation – how can cost be reduced to competitive levels?** The affordability of carbon capture is largely determined by the price of carbon. Policy interventions to ensure economically sustainable business models for carbon capture are the primary mechanism to address this challenge. R&I intervention may be complementary, with a number of programmes already supported by the EU.

- **Photovoltaics – how can perovskite R&I and manufacturing skills be developed and maintained in the EU?** Developing technical installation skills is not considered an R&I challenge. Existing and continued R&I programmes will contribute to ensuring a skilled workforce pipeline in the EU. Part of the challenge identified in the validation workshop includes facilitating strong connections between industry and research, which could be encouraged through collaborative R&I activities and networking across industry and academia. Non-R&I interventions that may be relevant to consider include policy interventions to facilitate and incentivise mobility of skilled talent to the EU.

14.3. R&I challenges with no existing or known solution

Four R&I challenges had no currently known solution. In these cases, a discovery research programme is proposed – however, discovery research carries high risk and is likely to take a number of years before a solution is developed to application. As such, these challenges were not prioritised for inclusion in the action plan due to uncertainty over their potential impact.

- **Storage (fly wheels & CAES)** – how can the use of CRM be reduced?
- **Off-grid energy technologies** – how can the use of CRM be reduced?
- **Solar fuels** – how can the use of CRM be reduced?
- **Smart energy grid technologies, smart cities, energy building and district technologies, energy transmission and distribution** – how can the use of CRM be reduced?

14.4. R&I challenges best addressed with alternative interventions

The following R&I interventions are not included in the action plan due to their potential to be addressed through other R&I interventions, as described in the least regrets review (Main report, Section 9.3).

- **Hydropower** – how can the use of CRM be reduced?
- **Ocean energy** – how can the use of CRM be reduced?
- **Photovoltaics** – how can R&I skills be developed and maintained in the EU?

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