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OVERALL STRATEGIC ANALYSIS OF CLEAN ENERGY TECHNOLOGY IN THE EUROPEAN UNION

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Contents

Abstract

Clean Energy Technology Observatory (CETO) provides an evidence-based analysis feeding the policy making process and hence increasing the effectiveness of R&I policies for clean energy technologies and solutions. It monitors EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal; and assesses the competitiveness of the EU clean energy sector and its positioning in the global energy market. This overall strategic assessment highlights various aspects of the clean energy technology sector in the EU, including the increase in energy consumption and carbon intensity due to economic recovery, the decrease in greenhouse gas intensity, the growth of the renewable energy sector, the deployment of carbon pricing, the investment in research and innovation, the increase in employment in the renewable energy sector, the challenges in the manufacturing industry, the need for upskilling and digitalization, and the need for improved public data.

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faced character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal
- assess the competitiveness of the EU clean energy sector and its positioning in the global energy market
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020)
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and inventive technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation of and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis
- Clean Energy Outlooks: Analysis and Critical Review
- System Modelling for Clean Energy Technology Scenarios
- Overall Strategic Analysis of Clean Energy Technology Sector

More details are available on the CETO web pages

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Executive Summary

- The economic recovery resulted in increased energy consumption, as well as energy and carbon intensity globally, with energy demand higher than 2019 levels and emission increases offsetting the 2020 drop. Compared to the year before, in 2021, both final energy consumption and final energy intensity in the EU increased. As a result, both energy and electricity per capita also increased by 6 % and 4 % respectively. Nonetheless, greenhouse gas (GHG) intensity in the EU continued to decrease, both in terms of the energy sector and the overall economy, and in 2022 GHG emissions in the EU remained below pre-COVID-19 levels and 27% below the 1990 levels. The share of renewables in final energy consumption remained at just over 20%, the achieved 2020 target, while import dependency decreased.
- In the current context of extreme energy prices and weather events, a comprehensive government response is essential to safeguard public health in the face of energy crises. During the last year, price caps, windfall taxes and handouts have helped reduce costs for consumers in the EU. Along with the national budgetary policy measures to reduce the impact of energy price hikes on citizens' public health, targeted policies and interventions aiming to expand energy assistance programs and promote energy-efficient housing can be pivotal in mitigating energy poverty and collectively alleviate the burden of excess mortality linked to it. In that respect, deployment of clean energy technologies, which inherently reduces fuel import dependence and thus the vulnerability to spikes in energy costs, is an essential step to increase EU competitiveness, when viewing the latter within its definition of providing wider benefits to society as a whole.
- In 2021, the EU renewable energy sector turnover and gross value added grew 13% on 2020 values, outperforming the overall economy – gross value added grew 7% in the same timeframe. Heat pumps and solid biofuels overtook wind as the main contributor to gross value added, while solar energy (PV and thermal) grew the most at 39%. In 2022, the EU production value of most clean energy technologies continued growing but at a slower pace compared to the previous year. However, the monitored values are affected by the high energy prices and the price fluctuations. Most of the clean energy technologies had a trade deficit that increased in 2022. The biggest deficit was registered for solar PV (EUR 22 billion) and batteries (EUR 15 billion). In almost all the technologies, China was amongst the biggest exporters to the EU, and the US and the UK were amongst the top importers from the EU.
- More jurisdictions are deploying carbon pricing, either through taxes or emission trading schemes. Carbon pricing covers 23% of global greenhouse gas emissions, up from 7% a decade ago. Still, less than 5% of global emissions are covered by a direct carbon price aligned with reaching the Paris climate agreement. Moreover, indirect pricing policies, such as fuel excise taxes, fossil fuel subsidies, and differentiated tax schemes, also play a role in determining the overall strength of the signalling effect, and may erode a positive carbon price signal.
- In 2021, for the first time, EU public R&I investment in the Energy Union R&I priorities was higher, in current prices, than a decade ago, with investments of more than EUR 5.4 billion reported this far. Nonetheless, it was still lower as a share of GDP, not only for the EU but for all five major economies. Since 2020, Horizon funds add over EUR 2 billion annually to the expenditure of the Member States, providing a vital boost to research and innovation in the EU. When added together, the EU ranks first in public R&I investment among major economies in absolute spending (EUR 8.2 billion, ahead of the US with EUR 7.7 billion) and second as a share of GDP behind Japan.
- It is estimated that respective private R&I investments have also been increasing across all major economies. In 2020 the EU private sector continued to invest comparable amounts – in absolute terms – with the US and Japan, and accounted for around 80% of the total R&I funding. In terms of private R&I investment per GDP, this still positions the EU in front of the US but behind the major Asian economies
- In 2022, rising inflation, higher interest rates, bank failures and the Russia's invasion of Ukraine leading, negatively affected global VC funding. Amidst the global funding slowdown, EU-based start-ups and scale-ups have attracted an increasing share of global VC investment. Moreover, clean energy technologies performed better than other VC segments and VC investment in the clean energy domain proved to be more resilient in the EU than in the rest of the world increasing by 42% compared to 2021.
- Since 2014, EU patenting output in the Energy Union R&I priorities has been increasing by an average 5% per year. Globally the EU maintains the strong position in internationally protected inventions that was highlighted in previous reports. It remains second to Japan in international patent filings (22% vs 24%, respectively in the period 2014-2020), while leading in renewables (29%) and energy efficiency (24%).

- EU total employment in the renewable energy sector totalled 1.5 million in 2021, growing 12% on 2020 values, which is notable after a stagnation during 2015-2020. The growth is driven by heat pumps, solid biofuels and solar PV. Since 2020, the heat pump sector has become the biggest employer, overtaking solid biofuels and accounting for 26% of all jobs in renewables. In 2021, solar PV jobs grew 35% on 2020 values and became the third biggest employer ahead of wind energy. Employment in the broader clean energy sector (including energy efficiency and e-mobility), was 2 million in 2020.
- Approximately a third of broader clean energy jobs are in the manufacturing segment, which has increased by 12% since 2015 as compared to the overall manufacturing jobs, which have increased by only 4% in the same timeframe. This confirms that clean energy sector has an enormous potential to create medium-skilled and decent jobs. Creation of decent jobs, especially in areas where jobs are disappearing is central to ensuring the just green transition.
- The supply chain difficulties and employment shortages observed in the manufacturing industry and cited by the previous CETO Overall Strategic Analysis report persist. However, whereas material shortages were easing towards the third quarter of 2023, labour shortages remain at the same level, with nearly 25% of businesses in manufacture of electrical equipment in the EU experiencing shortages. The job vacancy rate in energy supply sector, keeps increasing after the pandemic., whereas it is stabilising in the overall industry and in manufacturing. It has increased to an extremely high level, significantly above an overall industry average, in some countries pointing to an acute need for skilled workers, to be able to achieve more ambitious deployment targets.
- The majority of people working in the energy supply sector need some up/reskilling. Energy and manufacturing are among the sectors with the highest upskilling needs in terms of technical and job-specific skills, with over half of workers in need of upskilling, highlighting the importance of developing skills in partnership with the industry. Digitalisation will change how jobs will be performed and create completely new positions at the forefront of the data and AI economy, as well as new roles in engineering, cloud computing and product development. Manufacturing and energy supply are among the sectors already deploying digital technologies and automation to a higher degree than other sectors. Nonetheless, 13% of workers have an acute need to develop their digital skills further. Digital upskilling needs are particularly needed in high-skilled occupations, such as professionals and managers, to avoid skill obsolescence. Digitalisation can facilitate improvement of gender balance, which is of particular concern to energy sector, including clean energy, where women continue to be under-represented. Addressing the gender gap is crucial to deal both with current imbalances, as well as expected labour shortages due to the ageing population.
- While EU strategic autonomy and the Green deal industrial plans have seen major policy proposals the CETO reports highlight that the current market for the manufacturing sector is generally extremely challenging.
- The CETO analyses of sustainability performance for clean energy technologies have highlighted the heterogeneous and limited nature of available methods and data. For the environmental dimension, the EU's Product Environmental Footprint requirements can be directly applied for some products and the European Platform on Life cycle Assessment offers reference methods and data for applying LCA. On the other hand Social Life Cycle Assessment requires further development for clean energy technology analyses. For 2024 the JRC is proposing a new framework with security, environmental and social aspects organized based on a driver-pressure-state-impact-response (DPSIR) approach. Also by focusing on a limited set of parameters, this should be more straightforward to apply that the existing indicator scheme.
- The studies and analyses performed for CETO in 2023 have again underlined the need to improve the quality and timeliness of public data for clean energy technology sector, in particular regarding investments and socio-environmental aspects. This can be bring benefits to policy makers, prospective investors and sector participants.

1 Introduction

This report is part of an annual series from the Clean Energy Technology Observatory that address the status of technology development and trends, value chains and markets in the European Union and internationally. It aims to provide an overall integrated analysis of the clean energy technology and system integration, to complement the individual technology and system integration reports (listed in Annex 1). As set out in the CETO terms of reference, it addresses two main aspects:

a) Consolidated data on the competitiveness of the EU clean energy sector, addressing

- Energy and Resources Trends (including energy intensity, share of renewables, trade balance, electricity, carbon and fuel prices, and turnover)
- Human Capital and Skills
- Research and Innovation Trends (investments, patents)

b) Strategic analysis, addressing:

- Critical industrial value chain relationships
- Sustainability (status for environmental, social, economic and governance aspects, integrated assessment needs and roadmap for further assessments)
- SWOT analysis for global competitiveness, technology independence and sustainability

The report makes use of the analysis performed for the European climate Neutral Industry Competitiveness Scoreboard (CINDECS)[1], the work on EU Industrial Ecosystems[2] and associated transition pathways, as well as that for the proposed Net Zero Industry Act. **Table 1** shows the relationships between the CETO technologies and system integration topics and these related activities.

Concerning part b), for this first annual report focus is restricted to critical materials and industrial value chains, to sustainability and the SWOT analysis. The status of clean energy technology investments in the RRPs is summarised in section 2.2.3 – at this stage it is premature to assess specific impacts. and the EnTEC Report[3] on supply chain risks for the NZIA technologies.

Table 1. Coverage of clean energy technologies in the Clean Energy Technology Observatory, the European Climate Neutral Industry Competitiveness Scoreboard, the EU Industrial Ecosystems and the proposed Net Zero Industry Act.

CETO technology and system integration areas	**CINDECS topics**	**EU Industrial Ecosystems & Transition Pathways**	**NZIA Proposed Strategic Technologies**
Advanced biofuels		Renewable energy	Sustainable Biogas/Biomethane technologies
Batteries	Yes (Li-ion only)	Mobility, Transport, Automotive	Battery/storage technologies
Bioenergy (solid biomass and biogas for heat and power and for intermediate carriers)		Renewable energy	No
Carbon Capture Utilisation and Storage	Yes (decarbonisation of cement)	Energy Intensive Industries	Carbon Capture and Storage (CCS) technologies

[1] Kuokkanen A. et al, European Climate Neutral Industry Competitiveness Scoreboard (CINDECS) – Annual Report 2022, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/959357, JRC134499.

[2] European Commission SWD(2021)351 Updating the 2020 New Industrial Strategy: Building a Stronger single Market for Europe's Recovery. See also https://single-market-economy.ec.europa.eu/industry/transition-pathways_en#overview-of-transition-pathway-progress-per-ecosystem

[3] Energy Transition Expertise Centre (EnTEC), Report: Supply chain risks in the EU's clean energy technologies, 2023, doi 10.2833/413910

CETO technology and system integration areas	**CINDECS topics**	**EU Industrial Ecosystems & Transition Pathways**	**NZIA Proposed Strategic Technologies**
Concentrated Solar Power and Heat	-	Renewable energy	Solar photovoltaic and solar thermal technologies
Geothermal heat and power	-	Renewable energy	Heat pumps and geothermal energy technologies
Heat Pumps	Yes	Renewable energy	Heat pumps and geothermal energy technologies
Hydropower & Pumped Hydropower Storage	Yes	Renewable energy	No
Novel Electricity and Heat Storage technologies	-		Battery/storage technologies
Ocean energy	Yes (offshore operations for RE installations)	Renewable energy	Onshore and offshore renewable technologies
Photovoltaics	Yes (only panels)	Renewable energy	Solar photovoltaic and solar thermal technologies
Renewable Fuels of non-biological origin (other)	Yes (ammonia as a fuel)	Renewable energy	No
Renewable Hydrogen (water	-		Electrolysers and fuel cells
Solar Fuels (direct)	-	Renewable energy	No
Wind (offshore and onshore)	Yes (wind rotors, offshore operations for RE installations)	Renewable energy	Onshore and offshore renewable technologies
Building-related clean energy technologies	Yes: Pre-fabricated buildings, superinsulation materials, building envelope technologies, cooling and air conditioning	Construction	No
Digital infrastructure for smart energy system	Yes, EV charging infrastructure	Digital	Grid technologies

CETO technology and system integration areas	**CINDECS topics**	**EU Industrial Ecosystems & Transition Pathways**	**NZIA Proposed Strategic Technologies**
Industrial and District Heat & Cold Management	Yes, Heating and cooling networks	Energy Intensive Industries	No
Off-grid energy systems (including islands)		Digital	No
Transmission and Distribution related technologies	Yes, EMS for grids	Digital Electronics	No
Smart Cities	Yes, EV charging infrastructure		No
Innovative energy carriers and energy supply for transport	No	Mobility-transport-automotive	No

Source: JRC, 2023

2 Overall competitiveness of the EU clean energy sector

2.1 Energy and resource trends

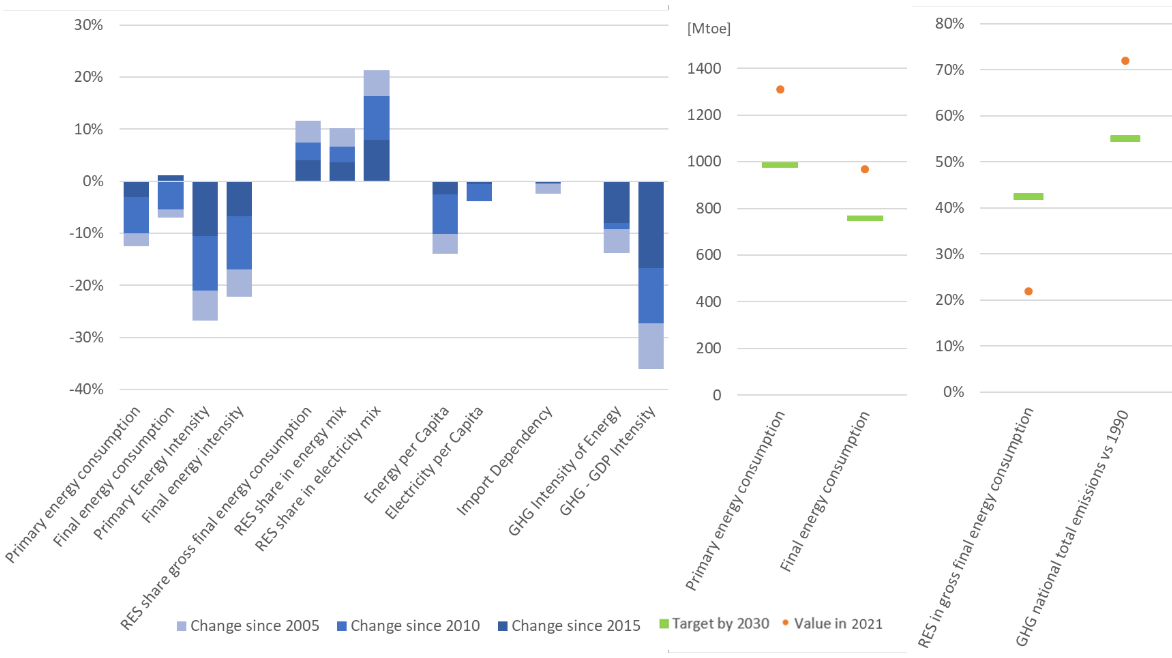
Figure 1 provides an update of the overarching indicators that are dependent on the progress of the clean energy sector but can also equally affect its prosperity as they impact the competitiveness of the EU industry and economy as a whole. In the previous edition of this report we anticipated that the economic recovery would bring increases in energy consumption, as well as energy and carbon intensity globally, with energy demand higher than 2019 levels and emission increases offsetting the 2020 drop. Indeed in 2021, final energy consumption increased by 6.9 % and final energy intensity increased by 1.4 %, as EU economies recovered from the impact of the COVID-19 crisis. As a result, both energy and electricity per capita also increased by 6.1 % and 4.1 % respectively.

Nonetheless, greenhouse gas (GHG) intensity in the EU continued to decrease, both in terms of the energy sector and the overall economy. JRC data shows that, despite the 2021 rebound, in 2022 GHG emissions in the EU remained below pre-COVID-19 levels. EU GHG emissions were 27 % lower than in 1990 having decreased in all sectors but power and transport. The EU accounted for 6.7 % of global emissions, remaining one of the least emitting, per GDP, among major global economies.[4]

There was very little change in the share of renewables in the energy and electricity mix. In 2020, the EU exceeded the target for renewable share in gross final energy consumption by 2 %, achieving one of the milestones towards climate neutrality. While the share was maintained in 2021, it has not increased further towards the increased ambition of achieving 42.5 % by 2030. .

Russia's unprovoked aggression in Ukraine, highlighted the need to reduce import dependency in general, and end the EU's reliance on Russian fossil fuels in particular. In 2021, imports of energy products decreased further form the peak reached in 2019, and returned to 51.1 %, just below 2010 levels.

Figure 1: Evolution of main indicators for energy consumption, GHG intensity and renewable energy contribution to the energy system, along with the 2021 value and 2030 targets.



Source: JRC based on EU energy statistical pocketbook and country datasheets[5]

[4] Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf E., Becker, W., Monforti-Ferrario, F., Quadrelli, R., Risquez Martin, A., Taghavi-Moharamli, P., Köykkä, J., Grassi, G., Rossi, S., Brandao De Melo, J., Oom, D., Branco, A., San-Miguel, J., Vignati, E., GHG emissions of all world countries, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/953322, JRC134504.

[5] European Commission, DG Energy, Energy Statistics, EU energy statistical pocketbook and country datasheets, 18 August 2023

2.1.1 Production and trade

In 2022, the EU production value of most clean energy technologies continued growing, at a slower pace compared to the previous year, except for wind, hydropower and CCUS, which shrank by around 10%. The production of heat pumps and bioenergy (mainly pellets and woodchips) increased by around 50%, while biofuels (mainly biodiesel) grew by 17%. Ocean and solar PV had the smallest growth (8%), while batteries (mainly Li-ion) remained stable even though Germany increased its production value by 50%. The production of hydrogen[6] had a record year as it almost tripled in value, but when it comes to volumes, it shrank by 8%.

Production and trade monitored in value are affected by price fluctuations. Especially in 2022, energy prices in the EU reached record-high levels, impacting several sectors, including manufacturing. The reason was a combination of factors, including increased demand in the "post-pandemic" economic recovery, a drop in renewable power generation due to low wind speeds and drought, and an increase in gas and coal prices due to Russia's invasion of Ukraine[7].

Compared to 2021 the value of imports increased in all the aforementioned technologies, except for hydropower (mainly parts) which shrank by 13%. The greatest increase was in hydrogen (also in volume), Li-ion batteries and solar PV (mainly assembled cells), for which the value of imports doubled. Imports for ocean energy (mainly electric conductors) grew by 85%, for heat pumps by 61% and CCU by 53%, while biofuels (mainly biodiesel) and bioenergy (mainly wood pellets) increased by 43%. After the value of imports doubled in 2021, wind rotors had the smallest increase in 2022 (+10%). All the technologies also increased the value of exports, except for wind and solar PV, which shrank by around 60%. The greatest increase was noted in CCUS (+44%) followed by Li-ion batteries (+36%). Bioenergy, biofuels and heat pumps increased their exports by around one-fifth, while hydrogen, hydropower and ocean grew by less than 10%.

However, the increase in exports was lower than the increased in imports. As a result, the trade balance worsened in all of the technologies, except for hydropower whose surplus increased by 9%, reaching EUR 230 million. Wind, ocean and hydrogen also had a trade surplus in 2022 but it decreased compared to previous years. All the other technologies experienced an increase in their trade deficit. The biggest deficit was registered for solar PV, where it doubled in 2022 reaching EUR 22 billion, followed by batteries whose deficit tripled reaching EUR 15 billion. China was amongst the biggest exporters to the EU in all of the technologies, apart from bioenergy, CCUS (US) and hydrogen (UK). The US and the UK were amongst the top importers from the EU in all the technologies except for hydropower.

2.1.2 Levelised cost of electricity

Figure 3 provides a snapshot of levelised costs of electricity (LCOE) calculations for the year 2022 for a range of representative conditions across the EU. The results indicate that in 2022 technology fleets with low variable costs (incl. variable operational costs and fuel costs) such as renewable energy generation, have been more cost competitive compared to generation technologies with high variable costs, as has been the case for fossil fuel fired generation.

This above finding is most robust for solar- and onshore wind-powered generation with LCOE in the range of 40 to 70 Euro per MWh, highlighting the high cost-competitiveness of clean energy technologies. This is despite rising prices for the critical raw materials needed for these clean energy technologies, primarily driven by a combination of rising demand and (concerns) about disrupted supply chains. The latter trend is most pronounced for offshore wind-powered generation, with a pronounced increase in LCOE compared to the previous CETO Overall Strategic Analysis report[8].

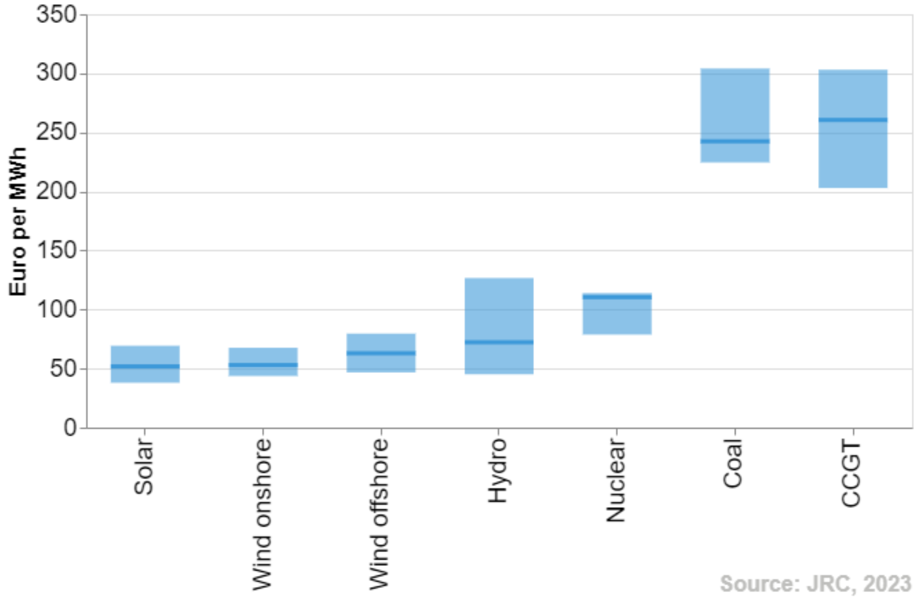
Due to the increase in commodity prices in 2022, variable costs have increased for the Combined Cycle Gas Turbine (CCGT) fleet and Coal fleet, reflected in higher LCOEs compared to last year. Indeed, gas-to-coal fuel switching occurred in EU electricity markets, in 2022 as coal-fired generation became more cost-competitive than gas-fired generation, primarily driven by the sharp increase in natural gas prices and lowering capacity factors for gas-fired generation. The fuel switch was reversed only by the end of 2022, determined by higher coal and carbon prices, and has been maintained in 2023 supported by, on average, lower gas prices.

6 Referring to all hydrogen, irrespective of production route.

7 Directorate-General for Energy, Market analysis (accessed on 04-08-2023)

8 Georgakaki, A., Letout, S., Kuokkanen, K., Mountraki, A., Ince, E., Shtjefni, D., Taylor, N., Schmitz, A., Vazquez Dias, A., Christou, M., Pennington, D., Mathieux, F., Clean Energy Technology Observatory: Overall Strategic Analysis of Clean Energy Technology in the European Union – 2022 Status Report, European Commission, 2022, doi:10.2760/12921, JRC131001

Figure 2 Snapshot of technology-fleet specific levelised costs of electricity (LCOE) for the year 2022. The light blue bars display a range across the EU and the solid blue lines denote median.



Source: JRC METIS model simulation, 2023[9]

2.1.3 Carbon Pricing

Carbon pricing continues to make gradual progress globally. In 2023, carbon pricing schemes, either via carbon taxes or emissions trading systems, cover 23% of global greenhouse gas emissions, up from 7% a decade ago[10]. In 2023 emission trading systems[11] covered about 17% of global greenhouse gas emissions. However, less than 5% of global emissions are covered by a direct carbon price at or above the range of around EUR 50-100/tCO2, which is deemed to be the minimum range to maintain global temperature increase to 2°C[12]. The EU Emissions Trading System (EU ETS), which remains the largest carbon market by traded value, falls within this range, with an average price of around EUR 80/tCO2 in 2022. For comparison, allowances in the Chinese ETS, which is the largest carbon market by emissions[13], are priced around EUR 5-10/tCO2[14].

Increasing interest towards applying direct carbon pricing policies around the globe is a positive sign. Nevertheless, progress towards imposing a global carbon price or alignment of policies in this regard has been limited[15]. Moreover, while an increasing amount of emissions are covered by direct carbon pricing, the indirect pricing policies, such as fuel excise taxes, fossil fuel subsidies, and differentiated tax schemes, that are simultaneously in place also play a role in determining the overall strength of the signalling effect. It is important to pay attention especially at fossil fuel subsidies, which dampen the price signal and in the worst case, may erode the positive carbon price altogether. Quantifying the combined impact of direct and indirect pricing is not straightforward, yet a first attempt by OECD shows that in some countries, including some EU Member States, the effective carbon prices in 2018 were negative[16]. In 2022, worldwide fossil fuel subsidies surged to an all-time high of EUR 1 trillion, as a result of governments' policy interventions to protect vulnerable consumers[17]. In addition to this, in Europe alone, about EUR 350 billion was spent to bring down energy bills. While these measures may have been necessary in the short-term, in the long-term the focus should be on

9 Gasparella, A., Koolen, D. and Zucker, A., The Merit Order and Price Setting Dynamics in European Electricity Markets, Publications Office of the European Union, 2023, JRC134300.
Computation based on annualised costs for the year 2022. Capex and Opex based on the 2022 PRIMES scenario, annualised by technical lifetimes and weighted average cost of capital. Annualised costs are levelised using capacity factors derived from the METIS model. Variable costs are based on 2022 commodity prices, variable OPEX and the dispatch in the METIS simulation.

10 The World Bank. 2023. "State and Trends of Carbon Pricing 2023" Washington, DC: World Bank. DOI:10.1596/978-1-4648-2006-9.

11 ICAP. Emissions Trading Worldwide: 2023 ICAP Status Report. Berlin: International Carbon Action Partnership.

12 Value defined according to the Report of the High-Level Commission on Carbon Prices (2017). More recent analysis, also due to the evolution of the geopolitical instability points to carbon prices in the range of EUR 50-250 /tCO2.

13 It covers so far only power sector emissions, which is equivalent to over 30% of China's total GHG emissions.

14 ICAP. Emissions Trading Worldwide: 2023 ICAP Status Report. Berlin: International Carbon Action Partnership.

15 The World Bank. 2023. "State and Trends of Carbon Pricing 2023" Washington, DC: World Bank. DOI:10.1596/978-1-4648-2006-9.

16 OECD. 2023. Net Effective Carbon Rates. OECD Taxation Working Papers.

17 IEA. 2023. Fossil Fuels Consumption Subsidies 2022.

promoting structural changes that can provide a lasting resolution to volatile prices and fuel dependency, and anchoring market-based prices coherently throughout different policies to enable clean energy choices by households and businesses.

2.1.4 Energy poverty and well-being

The intersection of health and energy poverty presents an important challenge with profound implications for public welfare. Excess mortality, resulting from inadequate access to reliable and affordable energy sources is a well-documented phenomenon as there is a direct link between energy poverty and increased mortality rates, particularly among vulnerable populations such as the elderly, infants, and individuals with pre-existing health conditions. These groups are disproportionately affected by extreme temperatures due to insufficient heating or cooling, limited access to proper medical care, and compromised living conditions.

Indoor air pollution is one dimension of energy poverty related with high health risks. Access to clean, sustainable energy in the home is essential to protect people's health from indoor air pollution caused by the use of polluting stoves and fuels such as coal and biomass. In poorly ventilated homes, indoor smoke can have fine particulate levels way higher than acceptable and exposure levels are particularly high in women and children, who spend the most time near home fireplaces.[18]

However, in Europe, the aspect of energy poverty that requires more attention is the inability to maintain indoor thermal comfort. Epidemiological research indicates that cold and heat stress can cause cardiovascular issues and excess deaths as well as exacerbate mental health conditions triggered by the stress of energy insecurity.[19] Based on the available information, some of the mortality increase in July and August 2022 compared with the same month of the past two years may be due to the heatwaves that affected parts of Europe during the reference period with around 58,000 additional deaths in the EU in July 2022.[20-21] Similarly, during the winter 2022-2023 EU recorded a distinct wave of excess mortality, with peak in December (20 %) more deaths than the baseline period. This lead to a data-backed widespread hypothesis that the hike on energy prices may cause more deaths than the Covid-19 pandemic in Europe last winter and that budgetary policy measures (price caps, windfall taxes and handouts) to mitigate energy costs for consumers helped reduce the effect.[22]

While the challenges of maintaining a home warm during the winter are well documented, the cooling deficiency and heat risk requires more attention. In a Europe heat waves become much more common as projected, thus mortality risk is expected to increase as numbers of older adults in the population will increase as well given Europe's demographic trends.[23] There are mixed evidence based on different countries and methodologies regarding the year-by-year trends on heat risk. While in some cases excess deaths remain high, especially during extreme weather events, in others there is a reduction in heat risk attributed to implementation of prevention plans, a higher level of adaptation of the local population and greater awareness of the population about exposure to heat.[24] Moreover, the increased availability of cooling systems can be an explanatory factor for heat stress reduction. Air Conditioning systems ownership is relatively low in Europe however there is an increasing trend while in Italy, Spain, Greece and southern France had already been rising rapidly for the past decade.[25] This increase in cooling systems adoption though can pose an extra challenge to the EU's climate and energy targets as it will lead to increased energy demand during the summer months.

Given the above, and the current context of extreme energy prices and weather events it is evident that a comprehensive government response is essential to safeguarding public health in the face of energy crises. During the last year, price caps, windfall taxes and handouts have helped reduce costs for consumers in the EU. Along with the national budgetary policy measures to reduce the impact of energy price hikes on citizens' public health, targeted policies and interventions aiming to expand energy assistance programs and promote energy-efficient housing can be pivotal in mitigating energy poverty and collectively alleviate the burden of excess mortality linked to it.

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18 WHO Newsroom, Factsheets 28 November 2022, Household air pollution

19 Jessel S, Sawyer S and Hernández D (2019) Energy, Poverty, and Health in Climate Change: A Comprehensive Review of an Emerging Literature. Front. Public Health 7:357. doi: 10.3389/fpubh.2019.00357

20 Ballester, J., Quijal-Zamorano, M., Méndez Turrubiates, R.F. et al. Heat-related mortality in Europe during the summer of 2022. Nat Med 29, 1857–1866 (2023).

21 Eurostat, Statistics Explained, Excess mortality – statistics : Excess mortality in the EU between January 2020 and June 2023

22 The Economist, May 10th 2023 - Expensive energy may have killed more Europeans than covid-19 last winter

23 EEA/JRC/WHO, 2008. Impacts of Europe's changing climate— 2008 indicator-based assessment, EEA Report

24 Heat and health in the WHO European Region: updated evidence for effective prevention. Copenhagen: WHO Regional Office for Europe; 2021.

25 IEA (2018) The Future of Cooling. Opportunities for energy efficient air conditioning.

In that respect, deployment of clean energy technologies, which inherently reduces fuel import dependence and thus the vulnerability to spikes in energy costs, is an essential step to increase EU competitiveness, when viewing the latter within its definition of providing wider benefits to society as a whole.

2.2 Research and innovation trends

2.2.1 Public and private R&I spending

The previous CETO Overall Strategic Analysis report highlighted that, while public R&I spending in the Energy Union R&I priorities[26] had been steadily increasing since 2016, it still had not yet recovered to the levels seen before the financial crisis. What is more, it had not been keeping pace with increases in GDP or increases in R&I investment in other sectors. In 2021, for the first time, the respective EU public R&I investment was higher, in current prices, than a decade ago. Nonetheless, it was still lower as a share of GDP, not only for the EU but for all five major economies.

More than half of EU Member States that provide data, increased their respective public R&I expenditure in 2021 in comparison to 2020, with investments of more than EUR 5.4 billion reported this far. While significant part of the year-on-year increase was induced by a change in the reporting for Spain (see methodology note), there were also significant increases for other Member States, such as the Netherlands, Denmark, and Austria that supported the trend. Nonetheless, even though over half of the reporting countries have increased expenditure, measured as a share of GPD, investment in public R&I, both at Member States and EU level, remains below the levels observed prior to 2016 (Figure 3).

The previous CETO Overall Strategic Analysis report, stressed the important role of EU funds in supporting R&I in the Energy Union R&I priorities. Since 2020, Horizon funds supporting Energy Union R&I priorities have been adding over EUR 2 billion annually to the expenditure of the Member States national programmes, providing a vital boost to research and innovation in the EU (Figure 4). While national contributions alone remain low among major economies, if Member States and Horizon funds are added together, the EU ranks first in public R&I investment among major economies (Figure 5)[27] in absolute spending (EUR 8.2 billion, ahead of the US with EUR 7.7 billion); and second as share of GDP (0.056%, behind Japan 0.057%[28]).

Figure 6 shows the evolution of Government Budget Allocations for R&D (GBARD) in the socioeconomic objective of energy in the EU Member States vs that of the public R&I investments in the Energy Union R&I Priorities discussed in the above. The two converged over the period 2012-2017, with the latter seemingly more affected by the economic downturn, and remained comparable between 2017 and 2020. In 2021 GBARD in the socioeconomic objective of energy were just over EUR 5 billion, representing 4.5 % of total GBARD[29], having decreased slightly in overall share in GBARD compared to the two previous years. This shows that, while increasing in absolute terms, public R&I support in the technologies needed to innovate the energy sector is perhaps not prioritised as much as that for other topics. In contrast, Public R&I investment in the Energy Union R&I Priorities, which represents a broader, different (if somewhat overlapping), grouping than the socioeconomic objective of energy, as defined in GBARD, have increased more in comparison between 2020-2021.

JRC estimates show that private R&I investment in technologies relevant to the Energy Union R&I priorities have also been increasing across all major economies. Consistent with the findings of the previous report, in 2020 the EU private sector continued to invest comparable amounts – in absolute terms – with the US and Japan, and accounted for around 80% of the total EU R&I funding in the Energy Union R&I Priorities. The investment is estimated at 0.18% of EU GDP and 12% of the business enterprise expenditure on R&D[30] for the EU, placing it in front of the US but behind the major Asian economies (Figure 5) for these indicators.

[26] COM(2015)80; renewables, smart system, efficient systems, sustainable transport, CCUS and nuclear safety

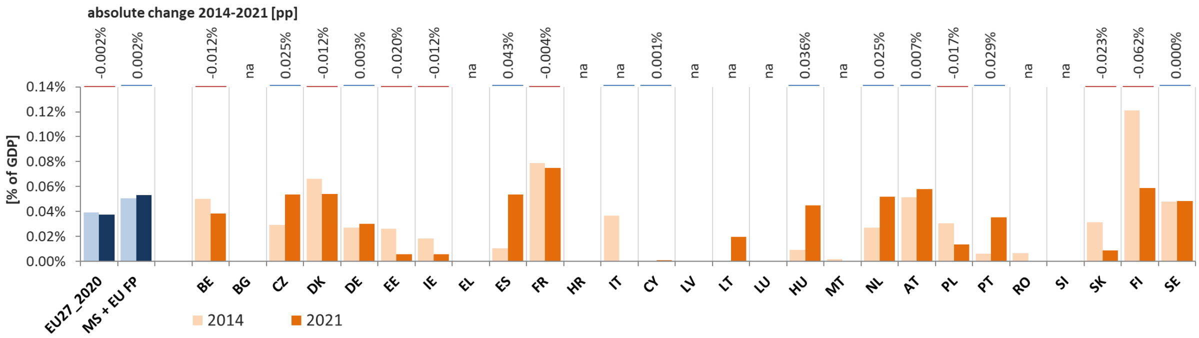
[27] The graph overlaps the first two categories of Figure 3 for the EU. The values in the two figures are slightly different, as this figure includes an estimate for Italy, which has yet to report for 2020 and 2021.

[28] These figures include MS and EU Framework Programme funds. MS funds alone, which are also shown in the same figure, remain below other major economies as a share of GDP.

[29] Eurostat, Total GBAORD by NABS 2007 socio-economic objectives [gba_nabsfin07]. The energy socioeconomic objective includes R&I in the field of conventional energy. The Energy Union R&I priorities would also fall under other socioeconomic objectives.

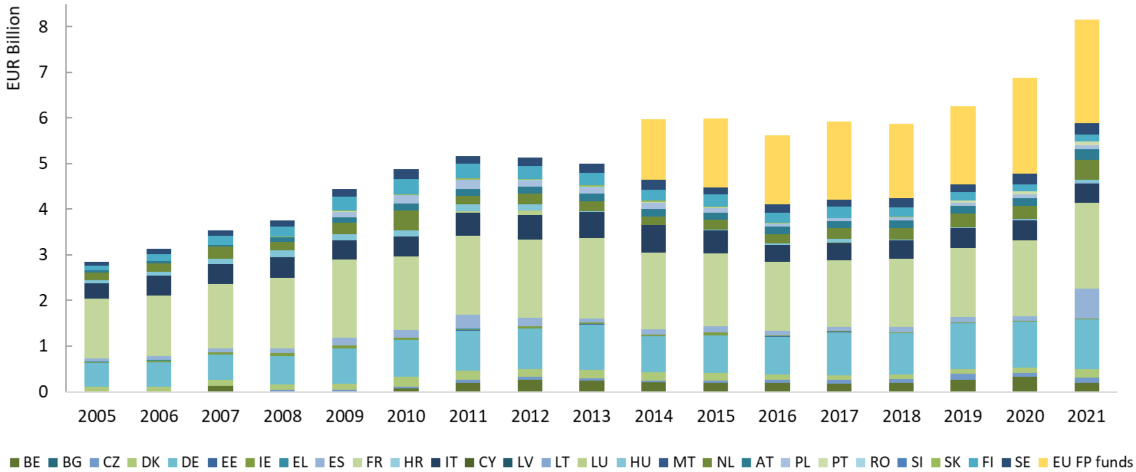
[30] BERD by NACE Rev. 2 activity and source of funds [RD_E_BERDFUNDR2]

Figure 3: Public R&I investments by EU MS as a share of GDP since the start of Horizon 2020.



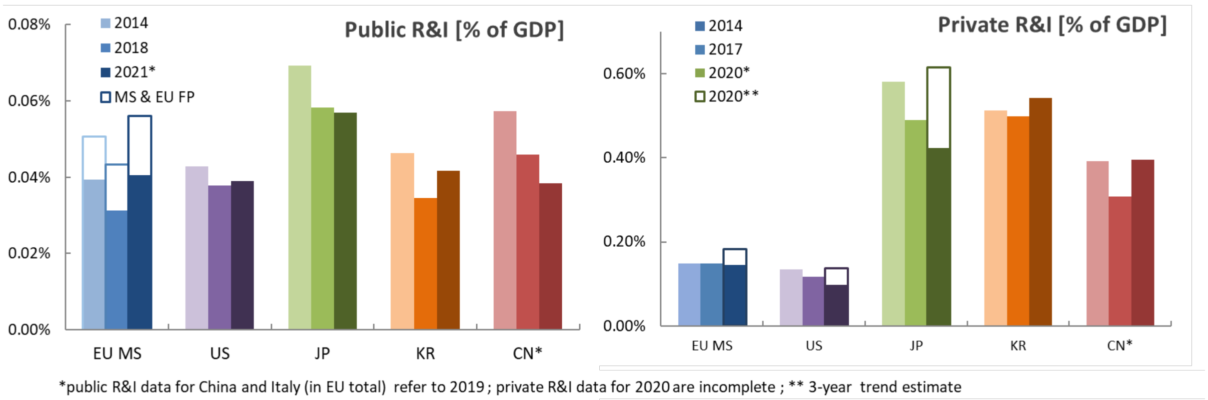
Source: JRC based on IEA[31] and own work[32].

Figure 4: Public R&I investments by EU MS and contribution of Framework Programme funds (since 2014).



Source: JRC based on IEA[31] and own work[32]

Figure 5: Public and private R&I investments in major economies as a share of GDP



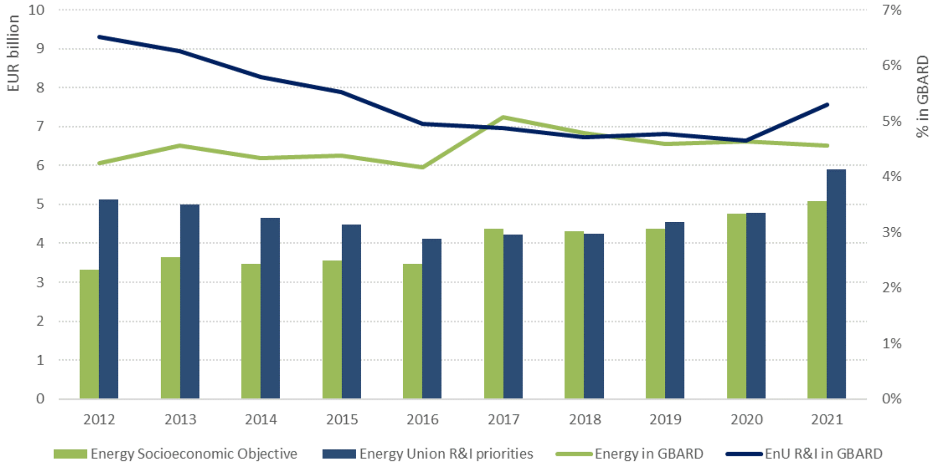
Source: JRC based on IEA[31], MI[33], own work[32].

[31] Adapted from the 2023 spring edition of the IEA energy technology RD&D budgets database.

[32] JRC SETIS Research and Innovation Data

[33] Mission Innovation Country Highlights, 6th MI Ministerial 2021

Figure 6: Public R&I investments in the Energy Union R&I Priorities and Government Budget Allocations for R&D (GBARD) in the Socio-economic objective of Energy in absolute values and as a share in total GBARD.



Source: JRC based on IEA[31], own work [32] and Eurostat[29].

Box 1 – R&I Methodology note[34]

Public R&I: Differences with previous datasets are due to a change in methodology. The R&I data presented here reflect MS funding reported in national currency and converted to Euro using the OECD annual national currency average exchange rate per US Dollar (and then Euro). Thus, values refer to current prices and the exchange rate of the reporting year to obtain a snapshot of the investments at a certain point in time. This will avoid difference from year to year in future time series, which can be exacerbated by inflation.

In addition, from 2021 there has been a significant methodological change in the data reported by Spain[35]. The coverage has been expanded, including data from state and regional governments in a GBARD basis. However, the changes have not been retroactively extended to previous years resulting in a significant break in the time series between 2020 and 2021, i.e. the 2021 figure is more than 7 times what was reported in 2020, increasing the EU Member State total by over EUR 0.5 Million – around a fifth of reported investment.

Private R&I: Private R&I investment is estimated using patents as a proxy, resulting in a longer time-lag for data availability; 2020 data are provisional. Figures are revised every year, with new estimates taking into account the most recent information from the EU R&I Scoreboard and patent dataset. Beyond any changes in the underlying patent information, the Private R&I figures also reflect an update and harmonisation of the underlying company dataset and multinational corporation structure used for the estimation. This is a periodical revision carried out to maintain coherence with the EU R&I Industrial Scoreboard. In certain occasions, this refinement of the private R&I estimation methodology has induced notable changes from previous years for major industry hosts in the dataset.

Periodical revisions of the underlying datasets can induce changes in both public and private R&I estimates; as such they should be viewed as provisional and indicative of a trend rather than reflecting absolute values.

Data availability, adjustments and estimates: Public R&I data for Italy are available with a longer lag due to the national collection process. As they represent a significant share of the EU Member State total, an expenditure equal to the one of the previous year is used as an estimate in EU figures. Similarly, information of previous years is used as an estimate for China, as reporting on public R&I investment in the context of Mission Innovation has not been forthcoming in recent years. A projection for the estimate of private R&I is employed for the most recent year, where we note that the completeness of underlying data may affect the totals for some of the major economies; this is not in practice where projections align with the current estimates.

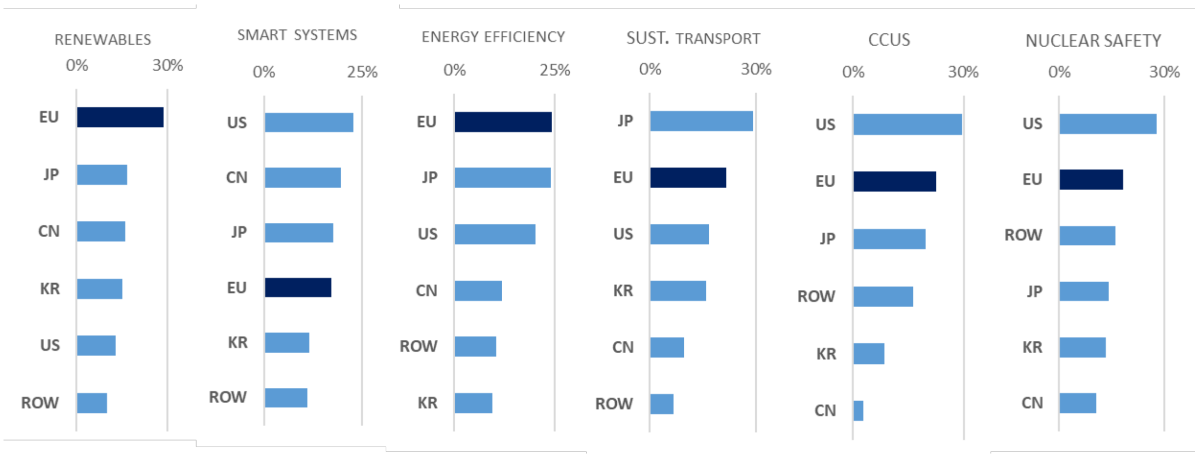
34 For more information on methodology see:
Fiorini A; Georgakaki A; Pasimeni F; Tzimas E. Monitoring R&I in Low-Carbon EnergyTechnologies. JRC104652
Pasimeni, F., Fiorini, A., Georgakaki, A., 2019. Assessing private R&D spending in Europe for climate change mitigation technologies via patent data. World Patent Information 59, 101927.
and other relevant literature listed on JRC SETIS Research and Innovation Data

35 IEA, 2023. Energy Technology RD&D Budgets, May 2023 Edition, Database documentation

2.2.2 Patenting Activity

Since 2014, EU patenting output in the Energy Union R&I priorities has been increasing by an average 5% per year. While there are notable differences in patenting trends both between Member States and for specific technologies, globally the EU maintains the strong position in internationally protected inventions that was highlighted in previous reports. It remains second to Japan in international patent filings (22% vs 24%, respectively in the period 2014-2020), while leading in renewables (29%) and energy efficiency (24%), having however lost some ground in smart systems (17% and ranking fourth among major economies (Figure 7)).

Figure 7 Share in global high-value patent filings relevant to the Energy Union R&I priorities 2014-2020.



Source: JRC based on EPO Patstat[36].

2.2.3 Coordinating R&I efforts in the EU and global context

Launched in 2007, the Strategic Energy Technology Plan (SET Plan) constituted a first step to establish an energy technology policy for Europe. The overall objective of the SET Plan is to provide a common vision, goals and coordination in accelerating the development and deployment of efficient and cost-competitive low-carbon technologies, and to enhance the EU's geo-political resilience and security of energy supply. Under its umbrella, the SET Plan is gathering experts from governments, industry, and research institutes in the EU and Associated Countries to develop research and innovation roadmaps for key energy technologies.

In 2015, the SET Plan was updated by introducing 10 Actions supported by a new structure with European Technology and Innovation Platforms (ETIPs) developing Strategic Research and Innovation Agenda's, and 14 corresponding Implementation Working Groups (IWG) to accelerate the energy system transformation. The SET Plan played a central role in implementing the Research, Innovation & Competitiveness dimension of the Energy Union, and in guiding national energy research strategies, as reflected in the National Energy and Climate Plans. Thus, the role of the SET Plan is crucial in coordinating national R&I agendas on low-carbon energy.

One of the key recent contributions of the SET Plan actors towards European cross-sectoral cooperation is the establishment of the European Clean Energy Transition Partnership (CETP) . Emanating from the SET Plan implementation plans, many of the working groups (e.g. Solar PV, Wind energy, Geothermal energy, Positive energy districts, Energy systems, Sustainable and efficient energy use in industry, Energy efficiency in buildings and others) have been successfully involved in the strategic design of the topics within the CETP, including co-authoring input papers and contributing to the development of the Strategic Research and Innovation Agenda (SRIA). The collaboration under the CETP is expected to boost and accelerate energy transition in all its dimensions. In addition, it will enable joint R&I programmes from regional to national and global level, co-supported by industry, public organisations, research and citizens' organisations to make Europe a frontrunner in energy innovation.

In a rapidly changing policy context, the SET Plan must align the EU, national and industrial research & innovation objectives with the European Green Deal, Fit for 55, REPowerEU, and the new European Research Area (ERA) Agenda. This new policy context underlines the need for increasing the resilience, autonomy and

[36] idem

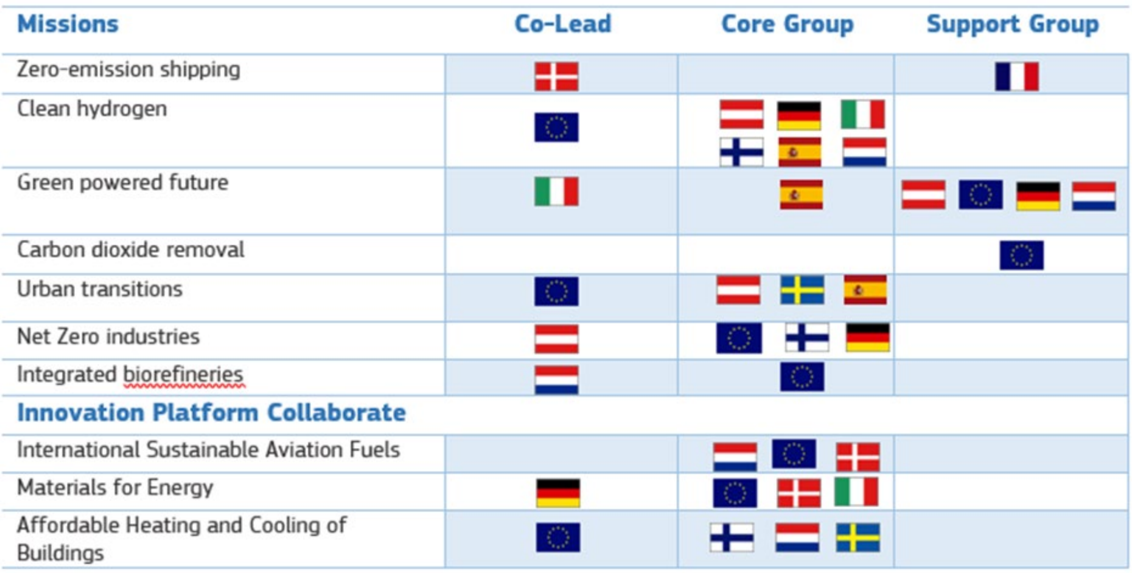
competitiveness of the European energy system and its supply chains, using circular and human-centred solutions. To this end, in 2023, the Commission is preparing a new Communication on the revision of the SET Plan to reinvigorate and further increase the efforts in supporting research into the development and deployment of clean energy and enabling technologies. The renewed SET Plan will aim to tackle the following pressing needs:

- increase the performance and cost efficiency of clean energy technologies as well as the efficiency and resilience of clean energy value chains, including at industrial manufacturing level;
- accelerate the development and the deployment of clean energy technologies;
- define an overall strategy to exploit synergies between R&I strategies and the innovation landscape at national, European and international level, and limited synergies between the various instruments for financial support for R&I at national and EU level;
- pay more attention to cross-cutting issues, such as environmental needs (sustainability, circularity, best use of resources) and social needs (health, safety, security, availability and affordability of energy, public engagement);
- consider challenges to the energy transition which have emerged since the creation of the SET Plan, such as the availability of critical materials, skills gap, digitalisation, technology dependence and resilience, amongst others;
- address the increasing role of enabling technologies or fuels by widening the scope of some of the working groups and creating a new one on hydrogen;
- reinforce the Research, Innovation and Competitiveness chapters in the National Energy and Climate Plans;
- create synergies between the European Research Area, the National Energy and Climate Plans, and the SET Plan reporting.

The Communication on 'EU external energy engagement in a changing world' aims to reinforce EU's engagement with partners, strengthen its climate and energy diplomacy, and support the green transition by addressing crucial topics and technologies that help to decarbonise energy systems globally.

To advance international cooperation on clean energy innovation, the EC continues its engagement in Mission Innovation (MI) and the Clean Energy Ministerial (CEM) on behalf of the EU. MI is the key forum for the EC to globally stimulate action and investment in research, development and demonstration to make clean energy affordable, attractive and accessible to all. The EC currently plays a key leadership role in MI, by co-leading two missions – Clean Hydrogen and Urban Transitions, and through its commitment in and contribution to the governance of MI, MI Secretariat and its Technical Advisory Group.

Table 2: EU participation in Mission Innovation 2.0



Missions	Co-Lead	Core Group	Support Group
Zero-emission shipping			
Clean hydrogen			
Green powered future			
Carbon dioxide removal			
Urban transitions			
Net Zero industries			
Integrated biorefineries			
Innovation Platform Collaborate			
International Sustainable Aviation Fuels			
Materials for Energy			
Affordable Heating and Cooling of Buildings			

Source: JRC based on MI, 2023

CEM is also one of the key international institutions (that include the G20 energy ministerial, the IEA ministerial, and other relevant fora), through which the EC promotes policies and programmes that advance the clean energy transition. The EC co-leads three CEM initiatives: Hydrogen, Super-Efficient Appliances and Devices, and Empowering People.

2.2.4 Venture Capital investment

The analysis presented in this section focuses on clean energy technologies. It differs from the section 2.2.7 of the previous edition of this report[37] by excluding activities previously included in PitchBook's climate tech vertical such as related to food systems, land use, micro-mobility, shared mobility, and autonomous vehicles. It also captures a wider selection of technologies and companies (~ 4 250) achieved by supplementing industry verticals from PitchBook with technology deep dives realised by the JRC [38].

As highlighted in the 2022 edition of the Competitiveness Progress Report, innovative clean energy solutions have a key role to play in achieving carbon neutrality by 2050. As Venture Capital (VC) funding is at the forefront of innovation, VC investment[39] in clean energy technologies is key to foster EU's competitiveness and to strengthen the EU's technology sovereignty.

In 2022, rising inflation, higher interest rates, bank failures[40] and the Russia's invasion of Ukraine leading to a new and unstable geopolitical context, negatively affected global VC funding. Total VC investment in EU firms decreased by -18% in 2022 compared to 2021. A similar trend has been observed in the US (-20%), China (-36%) and also worldwide during the first half of 2023. Amidst the global funding slowdown, EU-based start-ups and scale-ups have attracted an increasing share of global VC investment in 2022 (accounting for 11% of the total), confirming the sustained growth of VC in Europe observed since 2015[41]. The funding of EU start-ups stayed resilient, and the EU is closing the early-stage funding gap with the US. The funding slowdown in the EU is due to the drop of later-stage investment in scale-ups and a reduction of capital flows from US investors resulting from the global contraction of venture capital[42].

Despite the VC industry downturn, clean energy technologies performed better than other VC segments[43], such as Biotechnology and Digital, where both early-stage and later-stage investment fell in 2022. In 2022, the clean energy domain has attracted an increasing amount of VC investment (+4.4% compared to 2021, EUR 39.5 billion), accounting for 6.2% of total VC investment. While this confirms the positive trend observed since 2015, it also shows a slowdown compared to the increase registered between 2019 and 2020 (+37%), and the record growth of 2021 (+109%). Global early-stage investment in clean energy start-ups continued to grow and reached EUR 7.4 billion in 2022 (+59% compared to 2021), confirming private investors' confidence in clean energy technologies. Compared to 2021, global later-stage investment in clean energy scale-ups registered a slight decrease at EUR 32.1 billion in 2022 (-3.3% compared to 2021), but was still more than double than in 2020 (Figure 8).

In the EU, VC investment in the clean energy domain reached EUR 7.4 billion in 2022, a 42% increase compared to 2021. The EU accounted for 19% of global VC investments in clean energy technology firms and ranked third behind the US (38%) and China (28%). While US based clean energy start-ups and scale-ups lead the investment race, China and the EU have accounted for growing shares of the total since 2015 and, in 2022, VC investment in the clean energy domain also proved to be more resilient in the EU than in the rest of the world.

Early-stage investments in EU clean energy start-ups more than doubled in 2022 (x2.2 compared to 2021) and grew much faster than in the US (no growth) but less than in China. Deals in industry (green steel production and renewable carbon products for the manufacturing industry) and clean energy generation (small modular nuclear reactors and installation services for solar PV) drove the growth of EU early-stage investments in 2022. Later-stage investments in EU clean energy scale-ups also grew in 2022 (x 1.3 compared to 2021), in contrast to significant drops in the US and China (resp. -10 % and -29 % compared to 2021). Electric vehicles are

[37] Clean Energy Technology Observatory: Overall Strategic Analysis of Clean Energy Technology in the European Union – 2022 Status Report, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/12921, JRC131001.

[38] European Commission, 2022, JRC, commissioned by DG GROW - European climate-neutral industry competitiveness scoreboard (CIndECS) (Draft, 2022)

[39] VC investments consist of early-stage and later-stage deals. Early-stage deals include accelerator/incubator, angel, seed, Series A and Series B deals. Later-stage deals include all later series and private equity growth. Undisclosed series, deals occurring more than 5 years after the company's founding date and very large early-stage deals are re-classified as later-stage deals.

[40] In March 2023, the US government stepped in to protect the customer deposits of the Silicon Valley Bank (SVB). The SVB was the 16th largest US bank and specialized in financing and banking for venture capital-backed start-up companies.

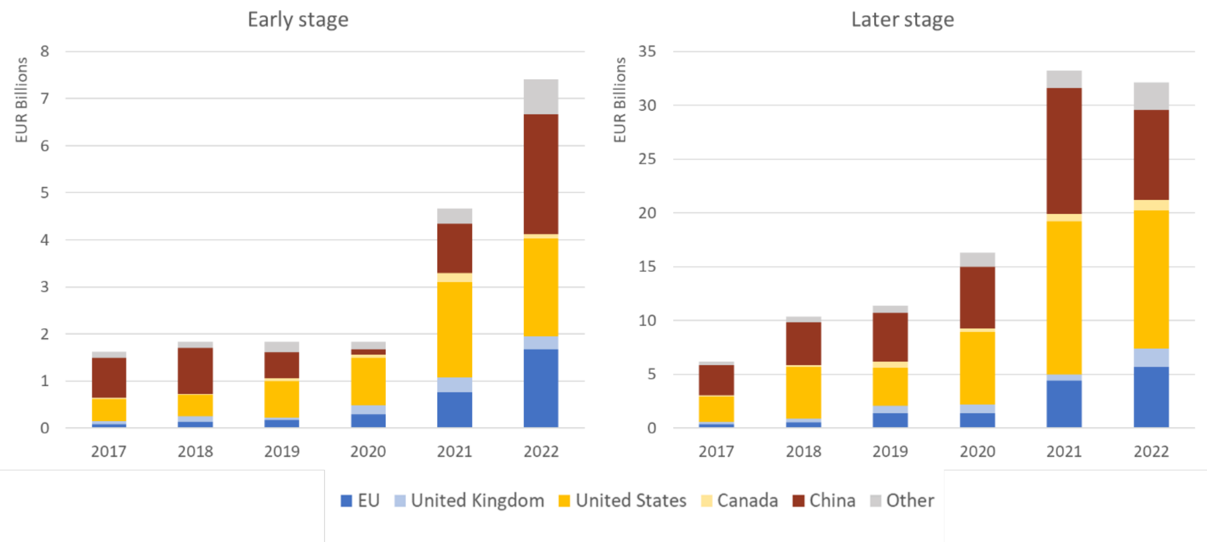
[41] PitchBook, 2023, 2023 European Private Capital Outlook: H1 Follow-Up

[42] Atomico, 2023, State of the European tech - first look, 2023,

[43] IEA, 2023, World Energy Investment 2023, IEA, Paris,

responsible for the largest increase in volume in 2022 and compensate for the drop of investments in battery manufacturing and recycling[44]. Several technologies contributed to the growth of EU later-stage investments in 2022, including solar PV, followed by green hydrogen and e-fuels for heavy transport and energy management systems for buildings.

Figure 8 - Venture capital investments in clean energy tech companies, by location, for early and later-stage deals.



Source: JRC elaboration based on PitchBook data.

As shown on Figure 9, VC investment in EU clean energy is largely concentrated in a few technologies (mainly battery manufacturing and recycling and electric vehicles). As shown on Figure 10, the EU is competitive in mobilising VC investment in energy storage and in particular in battery manufacturing and recycling. On the other hand, VC investment in EU electric vehicle (EV) and hydrogen EVs firms remain comparatively low despite an outstanding growth over the past years (x 16 in 2020-22 compared to 2017-19). The latter was driven by several later-stage and growth deals above EUR 100 million in high performance EV tech, electric trucks, charging stations and hydrogen EVs. While it became the 2nd largest area of investment in the EU, the funding level of EU electric vehicle firms over 2020-22 remains more than 4 times lower than those realised both in China and the US.

Historically, the EU has developed a strong presence in hydrogen and fuel cells[45] and EU firms captured almost 65 % of early and 43 % of later-stage investments realised worldwide between 2015 and 2019. However, fast growing investments (which tripled in 2021 and again doubled in 2022) and the pressure of multiple deals in manufacturers of fuel cells in China (in 2021 and 22) and in manufacturers of hydrogen production, transport and storage equipment in the US and China (in 2022) have changed the position of EU firms. Despite a sustained growth (in particular of later-stage investments), VC investment in EU Hydrogen and fuel cell firms now lag behind those in China and the US and the EU only accounts for 10 % and 26 % of global early and later-stage investments realised between 2020 and 2022, respectively.

VC investment in renewable energy firms and in particular in early ventures, is also deemed as an EU strong point. Renewable energy accounts for 17 % of the total investment in EU clean energy tech realised between 2020 and 22 but weigh less in the EU clean energy tech total compared to the previous 5 years. VC investment in EU renewable energy firms increased over the past 3 years (in particular later-stage investments) and the EU strengthened its competitive position compared to 2017-19, capturing almost 19 % of global 2020-22 investments.

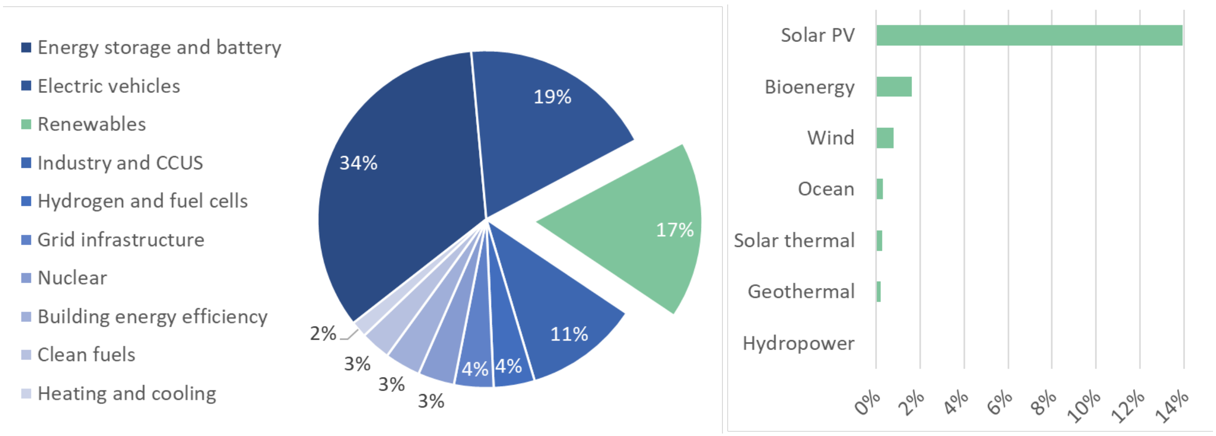
This performance is mostly driven by deals in solar PV, which account for most of VC investment in EU renewable energy firms realised over the past 3 years (Figure 9), and by a series of larger early and later-stage realised in solar installation services and project developers since 2020. In 2021 and 2022, VC investment in solar PV

[44] The Swedish company Northvolt accounts for 35% of all VC investment realised in EU clean energy tech firms between 2017 and 2022. As the company raised less venture capital in 2022 (EUR 1.12 billion compared to EUR 2.26 billion in 2021), VC investment in the energy storage and battery technology area dropped by –31% in the EU in 2022.

[45] Hydrogen and fuel cell does not include hydrogen EVs firms, which are accounted for in the electric vehicle technology area.

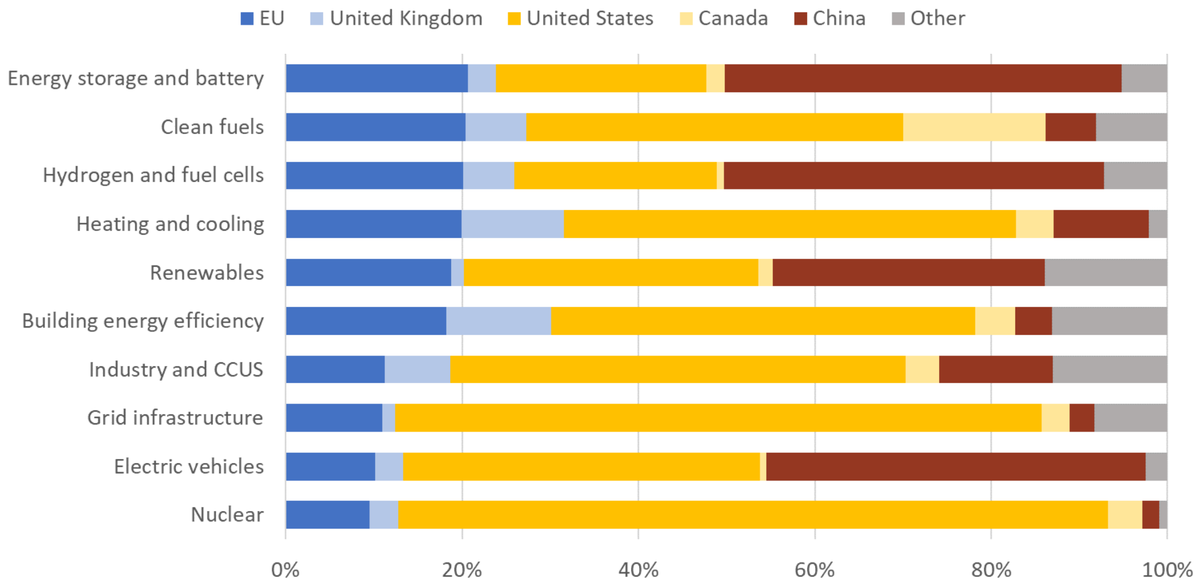
firms in China have however outpaced those realised in the EU and benefit to companies manufacturing solar PV cells, modules and panel frames.

Figure 9 - VC investment in EU clean energy tech companies, 2020-22, share by technology area (left)[46] and focus on renewable energy sources (right)



Source: JRC elaboration based on PitchBook data.

Figure 10 - Early and later-stage VC investment in clean energy tech companies by region, technology area, 2020-22[47]



Source: JRC elaboration based on PitchBook data.

46 Electric vehicles include technologies relative to powertrains, charging infrastructure and vehicles (incl. hydrogen EVs) but not autonomous vehicle technology and other mobility related solutions. Industry includes recycling, alternative routes to materials (such as building materials, critical mineral, cement, steel, chemicals) and to conventional production processes for the building and manufacturing industry. Building energy efficiency also includes energy management systems, building envelopes and insulation materials.

47 Electric vehicles include technologies relative to powertrains, charging infrastructure and vehicles (incl. hydrogen EVs) but not autonomous vehicle technology and other mobility related solutions. Industry includes recycling, alternative routes to materials (such as building materials, critical mineral, cement, steel, chemicals) and to conventional production processes for the building and manufacturing industry. Building energy efficiency also includes energy management systems, building envelopes and insulation materials.

Beyond solar, bioenergy, and to a lower extent wind, also contributed to the growth of VC investment in EU renewable energy firms over the past years. While investments in EU bioenergy firms have steadily grown since 2019 supported by a few larger deals, the growth of investments in EU wind firms is mostly supported by singular deals in 2022 (automated maintenance services and floating wind turbines). EU's attractiveness in those technology areas is however overshadowed by recent large private equity growth deals realised in China (ENVISION ENERGY, Wind, 2021) or the US (CALIFORNIA BIOENERGY, Bioenergy, 2022).

The EU also hosts a strong base of VC companies in in ocean energy. Nonetheless, the deal sizes and level of VC investment remain low, and this technology area remain dependent on public subsidies. Other more mature renewable energy technologies such as geothermal, solar thermal or hydropower do not attract significant levels of VC investment. Over the past years, there has been an increase of global VC investment in geothermal but a constant decrease in hydropower since 2020 and a sharp drop-off solar thermal in 2022. For those technologies, the main share of global VC investment is captured by a limited number of firms based in the US (or China).

In other technology areas such as clean fuels, heating and cooling and building energy efficiency, the EU has significantly strengthened its position compared to 2017-19 and accounts for ~20 % of the global VC investment realised between 2020 and 2022. Global VC investment in those technology areas has been increasing steadily over the past years, driven by deals in US firms (and Canada for clean fuels). Despite VC investment levels being low, the EU displays a late but clear acceleration in 2022 (x 3.7 for clean fuels, x 2.6 for heating and cooling and x 2.2 for building energy efficiency, compared to 2021).

EU's presence remains comparatively low in technology areas such as industry and CCUS and grid infrastructure. US based firms have steadily captured increasing amount of VC investment over the past years, with larger deals active in manufacturing and chemical, lithium extraction, building technologies and carbon capture. Despite their recent growth, VC investment in industry and CCUS in the EU remains less than a fourth of those in the US over 2020-22.

VC investment in EU nuclear firms is limited to early rounds in recently founded ventures developing small modular reactors or laser-based nuclear fusion. The low level of investment in existing EU firms contrasts with the multiple large deals realised in US based firms both active in the development of nuclear fusion and small modular reactors technologies.

With the Net Zero Industry Act proposal (NZIA), the EU has sent clear signals regarding the importance of a set of strategic clean energy technologies[48].

Strategic net-zero technologies, defined as in the Net-Zero Act Proposal, accounted for 70% of the total VC investment realised in EU clean energy tech firms between 2015 and 2021 (compared to 34% in the US and 40% in China). VC investment in strategic net-zero technologies achieved a +66% compound annual growth rate (CAGR) in the EU between 2015 and 2021, performing better than VC investment in strategic net-zero technologies in the rest of the world (+48% CAGR) or in electric vehicles worldwide (+54% CAGR).

In 2022 VC investment in strategic net-zero technologies in the EU continued to grow, but at a lower rate (+2.3% compared to 2021) as later-stage investment in scale-ups decreased (-2.3% compared to 2021). This contrasts with the overall resilience of VC investment in the clean energy domain in the EU and indicates that strategic net-zero technologies were more negatively affected by the global VC funding slowdown. This growth is also much lower than the one seen in the US (+41% compared to 2021) where early-stage investments in Hydrogen and fuel cells, and later-stage investments sustainable biogas/biomethane, and heat pumps and geothermal rose sharply in 2022. In China however, VC investment in strategic net-zero technologies peaked in 2021, following very large deals realised in battery and wind turbine manufacturers and decreased by -36% in 2022 (compared to 2021).

VC investment in battery manufacturers – the technology area that attracted the most VC funding in the EU - dropped[44] in 2022 in the EU due to the lower investments in the Swedish company Northvolt and to the decrease of later-stage foreign investments. Deals related to Hydrogen and Solar drove the growth of VC investment in EU strategic net-zero technologies. VC investment in other strategic net-technologies remains much lower in

[48] Strategic net-zero technologies include solar photovoltaic and solar thermal, onshore and offshore renewable, energy storage and battery, heat pumps and geothermal energy, electrolysers and fuel cells, sustainable biogas/bio-methane, carbon Capture and Storage and grid technologies

the EU than in the US and the EU has not demonstrated yet its capacity to attract larger growth deals beyond battery technologies, as seen in Bioenergy (in the US) or Wind (in China).

Over the years, the EU's innovation policy has expanded, and the institutional landscape has evolved with it, with the aim to address Europe's equity gap, and the fragmentation of its VC market and innovation ecosystems.

This includes complementary initiatives to foster equity investment and boost the funding of innovative start-ups and scale-up companies. The creation of European Innovation Council (EIC) fund - EU's own venture arm - aims to fund breakthrough innovation under the Horizon Europe's pillar III on "Innovative Europe". In partnership with the European Investment Bank and the European Investment Fund, the InvestEU fund provides – via a single financial instrument - a guarantee to funds and financial intermediaries that provide equity financing. The New European Innovation Agenda includes additional actions aimed to accelerate the growth of deep-tech start-ups in the EU.

As their continued resilience suggests, EU clean energy start-ups and scale-ups benefit from those initiatives. They also benefit from the EU Innovation Fund to address the challenge that constitutes the demonstration of innovative low-carbon technologies.

Growing policy effort to reduce technology dependencies has however driven major economies in an investment race for innovation and industrial leadership in strategic net-zero technologies.

In 2021 and 2022, VC investment in hydrogen and fuel cell firms in the US have outpaced those realised in the EU - despite their sustained growth. In Bioenergy, Heat pump and geothermal and Hydrogen and fuel cells, the growth of VC investments in EU firms is also largely due to foreign later-stage investment. This has grown much faster than local EU investment and represents more than half of the funding of EU firms in each of those technology areas in 2022 (against 15% overall in 2021).

The funding and growth of clean energy technologies companies it is key to securing EU's competitiveness, resilience, and technology sovereignty. It is therefore essential to ensure that capital keeps flowing towards EU innovative start-ups and at the required scale to accelerate the deployment of strategic net-zero technologies.

Unlocking and mobilising private investments at scale however requires consistently providing sufficient and sustained public funding towards clean energy technologies and clear demand signals (e.g., by earmarking public funding). Announced in 2022, the European Strategic Technologies for Europe Platform (STEP)[49] will provide public funding in the form of equity support to deep tech and clean tech companies throughout their lifecycle. This can contribute to de-risking innovation investments, bridging the gap between project developers, and corporate and institutional investors and ultimately to boosting and channelling further private investment.

[49] European Commission, Strategy and policy, EU budget, Strategic Technologies for Europe Platform

2.3 Human Capital and Skills

Box 2. – Human Capital and Skill Methodology Note

Statistical classifications do not delineate clean energy sector nor clean energy technologies as such. Therefore, publicly available statistics are not well suited to obtain socio-economic data for clean energy sector or clean energy technologies. This presents difficulty to consolidate robust employment data and leads to the use of different data sources that apply different methodologies and classifications. For this report, the following data is used for the different scopes and purposes:

'**Renewable energy sector**' is based on the data from EurObserv'ER, which publishes annually data, including employment, turnover and gross value added, for a set of renewable energy technologies. EurObserv'ER uses 'follow-the-money' approach, implying following the investment expenditures per technology, which then generate employment effect based on the estimation model. The advantage of this methodology is granularity, i.e. ability to track development per technology and per Member State based on a uniform approach. One of the main drawbacks is that this approach does not take into account the time span of the employment effect as generated jobs are assigned to the year when the project is commissioned. This results in swings between years, which does not necessarily reflect the reality. As projects e.g. in hydropower, can be very lengthy, employment effect in reality occurs over several years. Therefore, the model may over- or underestimate in a given year depending on the growth trend of the sector. In addition, modelling is based on a set of assumptions, for example, in regards to job intensity. Especially in the fast growing technologies, this may evolve faster than the model is updated. In terms of scope, EurObserv'ER includes data for the main renewable energy technologies, such as wind, solar PV, biofuels, heat pumps, hydropower, etc. It does not include data related to energy storage (e.g. batteries) nor energy end-use sectors, such as electric mobility. IRENA is used a source for global comparison of renewable energy jobs. IRENA sources its data from national authorities and in the case of the EU, it mostly uses EurObserv'ER figures. The advantage is that IRENA includes data by technology for major global economies beyond the EU and its Member States. Nevertheless, the scope and granularity are narrower than in the case of EurObserv'ER.

'**Clean energy sector'** is based on Eurostat Environmental Goods and Services Sector [EGSS] data, which are collected by Eurostat from national accounting offices of Member States. Clean energy sector here refers to data based on the following categories 'CREMA13A', 'CREMA13B' and 'CEPA1'. 'CREMA13A' includes production of energy from renewable resources including also manufacturing of technologies needed to produce renewable energy. CREMA 13B - Heat/energy saving and management includes heat pumps, smart meters, energetic refurbishment activities, insulation materials, and parts of smart grids. CEPA1 – Protection of ambient air and climate – includes electric and hybrid cars, buses and other cleaner and more efficient vehicles and charging infrastructure that is essential for the operation of electric vehicles. This includes also components, such as batteries, fuel cells and electric power trains essential for electric vehicles. Thus this is based on a broader definition of clean energy beyond only renewables. The advantage of this approach is that it is based on data from official statistical offices and it is possible to disaggregate by NACE economic activities. The drawback is that reporting is not yet fully consistent between the Member States. Publication of data lags two years behind and it is not possible to disaggregate the data by technology.

2.3.1 Employment in clean energy

EU employment in the renewable energy sector totalled 1.5 million jobs in 2021, growing 12% on 2020 values[50], which is notable after the stagnation during the 2015-2020 period. The growth was particularly driven by heat pumps, solid biofuels and solar PV, and has led to changes in the distribution of jobs among renewable sectors. Since 2020, the heat pump sector has become the biggest employer, overtaking solid biofuels[51] and accounting for 26% of all jobs in renewables. In 2021, solar PV jobs grew 35% on 2020 values and became the third biggest employer ahead of wind energy.

The biggest growth of jobs from 2020 to 2021, was seen in solar energy sector (PV and solar thermal) PV (41%)[1]. Heat pumps (18%), solid biofuels (25%) and hydropower (36%) also experienced increases, whilst the

[50] EurObserv'ER, 2023. The state of the renewable energies in Europe – Edition 2022 21st annual overview barometer EurObserv'ER Report.

[51] Methodological revisions have especially affected biofuel data, which has been updated based on project data from the Horizon 2020 project ADVANCEFUEL.

wind sector saw a decrease of 25% due to the faltering installation rate, especially of offshore wind. The solar PV sector grew in 2021 despite disruptions in component supply and increases in module prices. While Germany remains the leader in the number of solar PV jobs ahead of Poland and Spain, the biggest increases in employment have occurred in France, Portugal and Austria. Meanwhile for wind, the past two years have been difficult, even leading to closures of turbine and component manufacturing plants[1]. While the overall trend was negative, Denmark and Sweden, which are among the biggest markets, saw an increase in wind employment.

Eurostat[52] data, which looks at the broader clean energy sector, confirms an overall growth in employment, which reached 2 million jobs in 2020 (the latest available year). Employment in renewables and in the energy and heat management sector grew by 6% from 2019 to 2020, outpacing the overall economy, which contracted by 2% in the same timeframe due to the pandemic[53]. Approximately a third of clean energy jobs are in the manufacturing segment of the sector, which has increased by 12% since 2015. In comparison overall manufacturing jobs have only increased by 4% in the same timeframe. This confirms that the clean energy sector can create quality medium-skilled jobs, as foreseen by the International Labour Organisation (ILO)[54]. In addition, these manufacturing jobs, such as many heat pump manufacturing plants, are often located in less urbanised areas with fewer job opportunities[55]. Creation of employment opportunities, especially decent jobs[56] in areas where jobs are disappearing is central to ensuring the just green transition[57].

EU Member States present a different split of jobs along the clean energy value chain[58]. According to the latest available data, in 2020, in Denmark, Estonia, Croatia, Austria, Portugal and Slovakia over half of renewable energy jobs were in the manufacturing sector. In Germany, which hosts the biggest number of jobs, manufacturing constitutes 44% of renewable jobs. Germany also accounts for up to 76% of manufacturing jobs in the energy and heat management sector, which includes heat pumps. In Denmark, export sales constitute an important source of wind manufacturing jobs[59]. In recent years, the manufacturing segment has particularly fuelled the growth of clean energy jobs in Czechia, Spain and Poland.

Globally, renewable energy employment reached 12.7 million[60] in 2021, with the biggest share of jobs in China (42%) followed by the EU (10%) and Brazil (10%)[61]. The solar PV industry (34%), with over 4 million workers, remains the biggest and fastest growing renewable energy employer globally, followed by bioenergy (27%), hydropower (19%) and wind energy (11%).

The recovery from the pandemic has been accompanied by supply chain disruptions and employment shortages experienced both in the overall economy and the clean energy sectors, see Figure 11. The manufacturing industry in the EU felt increasing labour and material shortages throughout 2021, which stabilised in 2022. Nevertheless, whereas the much more severe material shortages experienced by the manufacturing businesses seem to be easing towards 2023 Q3, labour shortages remain at the same level, with nearly 25% of businesses in manufacture of electrical equipment[62] still experiencing shortages of labour. Compared to the material and supply chain shortages, which can be linked to single or isolated events and/or producers, labour market changes tend to be slower. Moreover, labour shortages in manufacturing seem to have been more persistent across the EU in the past 10 years[63].

52 Employment in the environmental goods and services sector [env_ac_egss1]

53 Eurostat [lfsi_emp_a].

54 According to IRENA and ILO. 2022. Renewable Energy and Jobs – Annual Review 2022. International Renewable Energy Agency, International Labour Organization, Abu Dhabi, Geneva.

55 European Heat Pump Association. 2022. European Heat Pump Market and Statistics Report 2022.

56 Following the ILO definition adopted in the EU policy approach. See Employment and decent work

57 Asikainen, T., Bitat, A., Bol, E., Czako, V., Marmier, A., Muench, S., Murauskaite-Bull, I., Scapolo, F. and Stoermer, E., The future of jobs is green, EUR 30867 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-42571-7, doi:10.2760/218792, JRC126047 and IRENA and ILO. 2022. Renewable Energy and Jobs – Annual Review 2022. International Renewable Energy Agency, International Labour Organization, Abu Dhabi, Geneva

58 This is subject to Member State reporting along NACE activities in the Environmental Goods and Services sector accounts [env_ac_egss1].

59 IRENA and ILO. 2021. Renewable Energy and Jobs – Annual Review 2021. International Renewable Energy Agency, International Labour Organization, Abu Dhabi, Geneva.

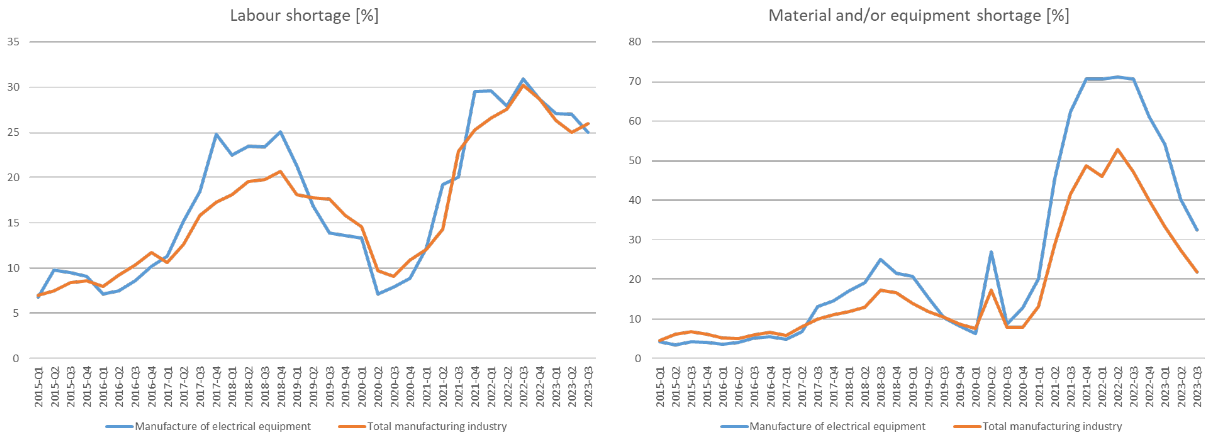
60 Includes direct and indirect employment.

61 According to IRENA and ILO. 2022. Renewable Energy and Jobs – Annual Review 2022. International Renewable Energy Agency, International Labour Organization, Abu Dhabi, Geneva.

62 'NACE 27: Manufacture of electrical equipment' used as a proxy for renewable energy manufacturing industry as many renewable energy technologies fall under this category. It is also used as a proxy for renewables industrial ecosystem in the EU Industrial Strategy [COM(2020)108 final and its recent update COM(2021)350 final].

63 European Commission. 2023. Employment and Social Developments in Europe: Addressing labour shortages and skills gaps in the EU – Annual Review 2023.

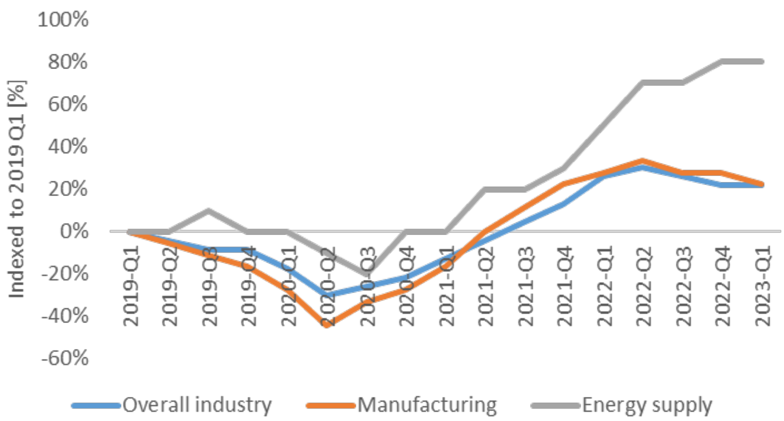
Figure 11: Labour and material shortages experienced by EU businesses in manufacture of electrical equipment and total manufacturing industry [%]



Source: JRC based on Business Survey data from DG ECFIN

This is also confirmed by a complimentary indicator, the job vacancy rate, which has increased gradually since 2020 Q2, when there was a notable drop due to the pandemic. Moreover, whereas in the overall industry, the job vacancy rate has increased by 75%, in the manufacturing and energy supply sectors they have more than doubled in 2020 Q2-2023 Q1, see Figure 12. Furthermore, whereas in the overall industry and manufacturing the situation seems to be stabilising and the vacancies decreasing, in the energy supply sector the job vacancy rate keeps growing. In a few countries, the job vacancy rate in the energy supply sector has increased to significantly above the overall industry average, such as e.g. Sweden where it is 7.4%, the Netherlands where it is 5.7% and Denmark, where it is 4.8%, see Figure 13. Starting from a lower level, the respective vacancy rates in Slovenia, Romania, Austria, Hungary, Luxembourg and Estonia have more than doubled in this period. Nevertheless, it is important to note that job vacancy rate does not distinguish whether high rate in a sector is driven by high turnover or by shortage driven by the growth of demand in the sector. Regardless, as the energy supply sector includes activities related to clean energy deployment and installation, this clearly points to the need to pay attention at the labour market issues in order for them not to become a bottleneck towards reaching the more ambitious deployment targets.

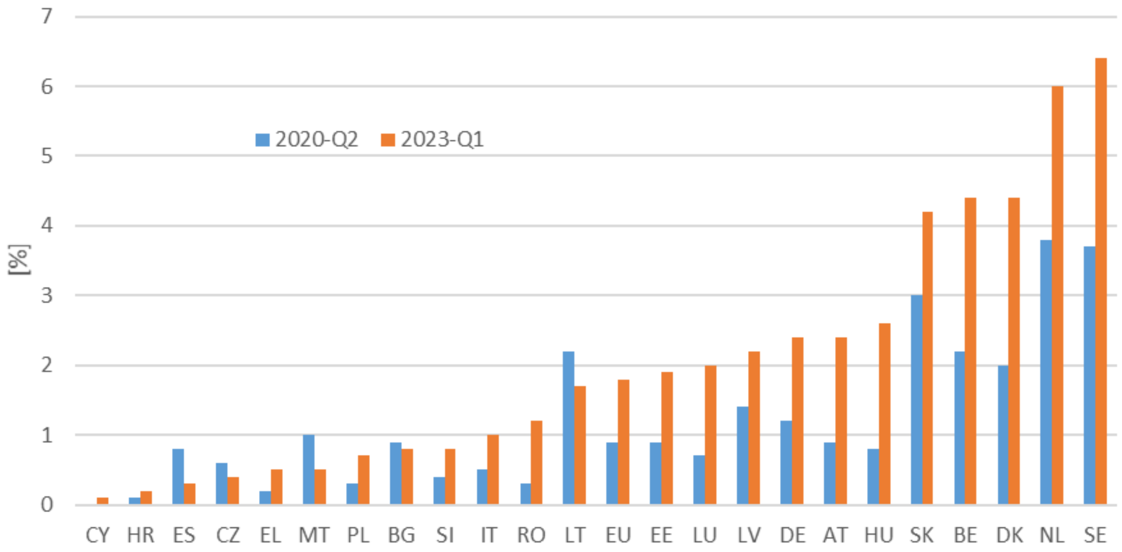
Figure 12: Change in the job vacancy rate[64] 2019 Q1-2023 Q1 in overall industry, manufacturing and energy supply sector [% indexed to 2019 Q1]



Source: JRC based on Eurostat [jvs_q_nace2]

64 Job vacancy rate is the share of job vacancies from the sum of total paid posts and job vacancies.

Figure 13: Job vacancy rate in the energy supply sector [%] in the EU and EU Member States in 2020 Q2 and in 2023 Q1



Source: JRC based on Eurostat [jvs_q_nace2]

2.3.2 Skills gaps

Labour shortages discussed in the previous, are mainly due to the overall economic recovery from the pandemic combined with the clean energy sector inertia in building the skills capacities required by the green and digital transition[65]. The lack of adequately skilled workforce has been highlighted by the Clean Energy Industrial Forum (CEIF), which commits to stepping up efforts and investments in the development of skills, strengthening reskilling and upskilling programmes[66]. The urgency of reskilling in the EU is already being felt in certain sectors, particularly given the accelerated deployment required by the REPowerEU Plan – the rollout of heat pumps, for example, requires a rapid recruitment and retraining of installation engineers. The European Heat Pump Association has calculated that a minimum of 500,000 skilled full time equivalent employees will be needed by 2030 in Europe.[67] The battery sector estimates it will need another 800,000 people to be trained or reskilled by just 2025[68].

According to the latest European skills and jobs survey conducted in 2021 by Cedefop[69], the majority of people working in the energy supply sector need some up/reskilling, with about 17% experiencing gaps in their skills to a great extent. Energy and manufacturing are among the sectors with the highest upskilling needs in terms of technical and job-specific skills, with over half of workers in need of upskilling, highlighting the importance of developing skills in partnership with the industry. In addition, 35% of energy workers experience gaps in numeracy skills and 46% gaps in social skills, see Figure 14.

In a tight labour market the previous CETO Overall Strategic Analysis report already mentioned that firms look into automation and digitalisation to gain a competitive advantage, especially in mature technologies, such as solar PV, wind and heat pumps[70]. Especially for Europe, where labour costs are higher, automation and innovative manufacturing is critical in order to remain competitive. For example in heat pumps, new factories coming online use innovative sensor controls and programming, 3D printing and modular designs, which can

65 The inertia is due to various job misalignments, such as spatial, sectoral, occupational and temporal coupled with the fast-paced change towards green and digital while it takes time to build the skills capacity. This is based on, e.g. Czako. 2022. JRC129676; Asikainen, T., Bitat, A., Bol, E., Czako, V., Marmier, A., Muench, S., Murauskaite-Bull, I., Scapolo, F. and Stoermer, E., The future of jobs is green, EUR 30867 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-42571-7, doi:10.2760/218792, JRC126047; and Cedefop (2022). An ally in the green transition. Cedefop briefing note, March 2022.

66 Clean Energy Industrial Forum. Joint Declaration on Skills in the Clean Energy Sector, published 16 June 2022.

67 European Heat Pump Association, Wanted: half a million heat pump workers, News piece 26 Jan 2023

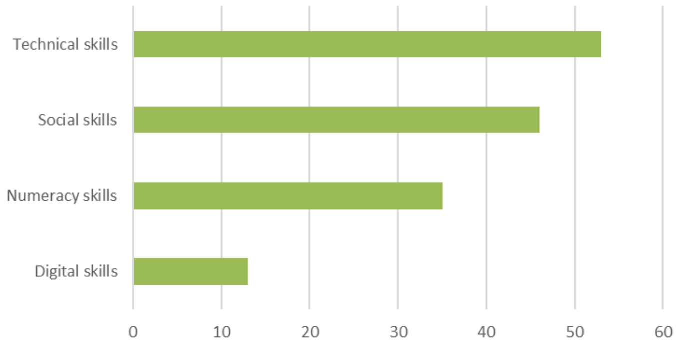
68 European Battery Alliance factsheet, 23 February 2022.

69 The CEDEFOP European skills and jobs survey (ESJS) is a periodic survey collecting information on the job-skills requirements, digitalization and skill mismatches and workplace learning of representative samples of European adult workers. A second wave – ESJS2 – carried out in 2021 in all EU Member States, Iceland and Norway, builds on the approach of the first 2014 survey.

70 IRENA and ILO. 2021. Renewable Energy and Jobs – Annual Review 2021. International Renewable Energy Agency, International Labour Organization, Abu Dhabi, Geneva.

make assembly lines more efficient and reduce manufacturing times and labour inputs[71]. Already 17% of workers in the manufacturing and 12% of workers in the energy supply sector operate robots in their daily activities, and around 40% of tasks have been digitalised or automated[72]. Still, 13% of workers have an acute need to develop their digital skills further[73]. Notably digital upskilling needs are most needed in high-skilled occupations, such as professionals and managers[74].

Figure 14: Skill gaps in the energy supply sector [% of work force]



Source: JRC based on CEDEFOP data

The digital transformation will change how jobs will be performed in future, including those in the energy sector. For example, artificial intelligence can facilitate more efficiency in the routine tasks creating more space to focus on varied tasks[75]. In the energy supply sector up to 13% of tasks are repetitive, while in manufacturing and transport up to a third can be automated[76]. Digitalisation will create new positions to meet the surging demand for roles at the forefront of the data and AI economy, as well as new roles in engineering, cloud computing and product development, which will rely more on non-routine interactive tasks.[77] Digitalisation and automation can also facilitate improvement of gender balance, which is of particular concern to the energy sector where women are under-represented (only 32% in renewables) [78].

Digitalisation does not only affect the low-skilled jobs that can be automated and replaced by robots. Fast technological change could also create skills obsolescence among the high-skilled workers such as ICT, managerial and engineering-related occupations. For example, 22% of plant operators, 20% of electrical trades' workers and 20% of science and engineering technicians, are at risk of skills obsolescence without a continuous on-the-job learning. These are among the highest risk groups right after ICT technicians (32%) and ICT professionals (32%). Therefore, up/reskilling needs a dual approach with a focus at both low-skilled and high-skilled occupations. [79]

While investment uncertainty increased significantly in 2022 due to the rising energy costs, availability of skilled labour is the most cited (85%) impediment to investment by European firms[80], larger firms especially concerned about the availability of labour with the right skills. The lack of appropriate skills is also linked to public

[71] IEA. 2022. The future of Heat pumps.
[72] JRC based on the CEDEFOP European skills and jobs survey data.
[73] idem
[74] JRC based on the CEDEFOP European skills and jobs survey data; and Centeno, C.; Karpinski, Z.; Urzi Brancati, C., Supporting policies addressing the digital skills gap – Identifying priority groups in the context of employment, EUR31045EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-51319-3, doi.10.2760/07196, JRC128561.
[75] Asikainen, T., Bitat, A., Bol, E., Czako, V., Marmier, A., Muench, S., Murauskaite-Bull, I., Scapolo, F., Stoermer, E. The future of jobs is green, EUR 30867 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-42571-7, doi:10.2760/218792, JRC126047.
[76] Based on CEDEFOP European skills and jobs survey ESJS2 2021.
[77] Asikainen, T., Bitat, A., Bol, E., Czako, V., Marmier, A., Muench, S., Murauskaite-Bull, I., Scapolo, F., Stoermer, E. The future of jobs is green, EUR 30867 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-42571-7, doi:10.2760/218792, JRC126047.
[78] Asikainen, T., Bitat, A., Bol, E., Czako, V., Marmier, A., Muench, S., Murauskaite-Bull, I., Scapolo, F., Stoermer, E. The future of jobs is green, EUR 30867 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-42571-7, doi:10.2760/218792, JRC126047.
[79] Centeno, C.; Karpinski, Z.; Urzi Brancati, C., Supporting policies addressing the digital skills gap – Identifying priority groups in the context of employment, EUR31045EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-51319-3, doi.10.2760/07196, JRC128561.
[80] EIB. Investment Report 2022/2023: Resilience and renewal in Europe.

investment gaps, particularly in Central and Eastern Europe, and to the successful implementation of the Recovery and Resilience Facility. Nearly 70% of municipalities report that inadequate environmental and climate assessment expertise is a major obstacle slowing down climate investment projects[81]. Also, 60% of municipalities report a lack of engineering or digital skills to deliver their investment programme[82].

The demand for workers possessing green skills[83] has been increasing at a faster rate than the availability of skilled individuals in this field. Over the past five years, job postings requiring green skills have experienced an annual growth rate of 8%, while the supply of qualified green talent has grown by approximately 6% annually during the same period[84]. This demand is reflected in the job vacancy rates, which have been on the rise since 2020, especially in the energy supply sector, as described in section 2.3.1. The disparity highlights the need for proactive measures to address the current skill gap and ensure a harmonious match between demand and supply.

The shift towards a climate-neutral economy is generating a surge in demand for individuals to fill various green-specific roles, including positions such as sustainability manager, wind turbine technicians, solar consultants, ecologists, and environmental health and safety specialists.[85] A few of these occupations are also relatively recent, which presents challenges in terms of recruitment and filling vacancies until a substantial labour market for these roles is established.

Therefore, the EU's Green Deal Industrial Plan, particularly its skills pillar, underscores the importance of nurturing a skilled workforce equipped to drive the transition towards a sustainable economy. Moreover, the Net-Zero Industry Act will enhance skills for net-zero technologies by setting up dedicated training programmes through Net-Zero Academies which will help to roll out up-skilling and re-skilling programmes in strategic industries for the green transition, such as raw materials, hydrogen and solar technologies.

2.3.3 Gender balance

The EU has set out a gender equality strategy for the years 2020–2025[86] that aims to make concrete progress on gender equality in the EU. Some of its key objectives are challenging gender stereotypes; closing gender gaps in the labour market; achieving equal participation across different sectors of the economy; addressing the gender pay and pension gaps; and achieving gender balance in decision-making.

Currently, in the energy sector there still are gender-related inequalities that have to be better addressed to ensure a successful energy transition. The number of women working with renewable energy sources (RES) is higher than for the traditional energy sector,[87] although it varies across subsectors. According to the 2022 IRENA report, which tracked the participation of women in the solar PV industry, women make up almost 40% of the labour force in full-time positions within this sector. This is almost double the proportion of women employed in the wind industry (21%) and the oil and gas sector (22%).[88] Moreover, women are overrepresented in low-paid non-technical positions. For example, women employed in solar PV work in administrative roles represent 58% of the workforce, while in women employed in STEM positions is only 32%.[89]

As the previous CETO Overall Strategic Analysis report already mentioned, women also participate less in decision-making in energy companies (based on IEA's analysis approximately 14% of senior management are women[90]). This gender gap also extends to innovation, as evidenced by the fact that women apply for patents at a significantly lower rate. In 2021, for instance, only about 20-21% of patents listed one or more women as inventors.[91] When we focus on patent classes closely associated with the energy sector, such as combustion apparatus, engines, pumps, and power, the representation of women drops to less than 11%.[92]

These disparities not only affect women's professional opportunities but also have wider societal implications. Women, as a result of such imbalances, often find themselves more exposed to energy and transport poverty.[93]

81 idem
82 idem
83 A definition for green skills used by the Cedefop is "the knowledge, abilities, values and attitudes needed to live in, develop and support a sustainable and resource-efficient society".
84 Global Green Skills Report, LinkedIn, 2022.
85 idem
86 European Commission, Gender equality strategy
87 IRENA 2019, Renewable Energy A Gender Perspective
88 RENA 2022, Solar PV: A Gender Perspective
89 idem
90 International Energy Agency, 2021
91 European Patent Office 2022, Patent Index 2021,Insight into our applicants
92 International Energy Agency, 2020, Gender diversity in energy: what we know and what we don't know
93 Mejía, DL & Murauskaite-Bull, I 2022, Transport Poverty: A systematic literature review in Europe, JRC Publications Repository

[94] This is further exacerbated by factors such as limited disposable income and their overrepresentation in lone-parent households, along with other challenges. Female-led households are disproportionately affected by classic energy poverty indicators. Across Europe, 8.1% of female-led households are unable to keep their home warm (7.5% for male-led) while 8.3% of female-led households appear to have arrears in utility bills (7.2% for male-led).[95]

The gender imbalances within the energy sector have far-reaching consequences for all energy consumers. It is imperative that concerted efforts are made to address these disparities and empower women in various facets of the energy landscape. Women should not only have equal opportunities as energy consumers but also as energy producers, innovators, and policymakers.[96] Bridging these gender gaps will not only promote fairness and inclusivity but also unlock a wealth of untapped potential that can drive innovation, sustainability, and progress in the energy sector, benefitting society as a whole.

2.4 Gross Value Added and labour productivity in clean energy

For the methodological note on data sources, please refer to Box 2 in Section 1.3. In 2021, renewable energy turnover in the EU grew by 13% on 2020 values and stood at EUR 185 billion[97]. Heat pumps, solid biofuels and solar energy experienced the biggest growth in 2020-21. In fact, heat pumps (28% of total) and solid biofuels (21% of total) overtook wind sector as the biggest contributors to the total renewable turnover. During the same period (2020-2021), gross value added in the EU renewable energy sector grew by 13% and stood at EUR 80 billion in 2021[98]. For comparison, gross value added of the EU economy increased by 7% in 2020-2021, thus renewable energy sector grew faster than the overall economy.

Gross value added for the broader clean energy sector stood at EUR 156 billion in 2020, up by 40% compared to 2015, outpacing the overall economy which grew 11% over the same period. Gross value added has increased at a much faster pace than employment in the clean energy sector, indicating growing labour productivity in terms of gross value added per employee. Renewable energy has the highest labour productivity at EUR 103 thousand per employee, having increased by 20% in 2015-2020. Labour productivity in the renewable energy sector is 60% higher than the average labour productivity in the overall economy and is growing at a much faster pace. While, in e-mobility labour productivity is lower than in the renewable energy sector, it is improving faster (26% in 2015-2020). The energy and heat management sector has the lowest labour productivity (EUR 62 thousand per employee) and has only increased 11% in the same timeframe, 2015-2020. Overall, as (labour) productivity has stagnated in the high-income economies since 1970s questioning the future of innovation-driven growth[99], the clean energy sector seems to be going against this trend. Together with digitalisation, the clean energy transformation could indicate a potential way out of the productivity gridlock.

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[94] Murauskaite-Bull, I., Koukoufikis G., Shortall R., Della Valle N., Feenstra M., Creusen A., Stojilovska A., Gender and Energy: The effects of the energy transition of women, JRC132744 Forthcoming

[95] Koukoufikis, G & Uihlein, A 2022, [Energy poverty, transport poverty and living conditions - An analysis of EU data and socioeconomic indicators](), JRC Publications Repository

[96] Murauskaite-Bull, I., Koukoufikis G., Shortall R., Della Valle N., Feenstra M., Creusen A., Stojilovska A., Gender and Energy: The effects of the energy transition of women, JRC132744 Forthcoming

[97] EurObserv'ER. 2023. The State of Renewable Energies in Europe. Edition 2022 – 21st EurObserv'ER Report.

[98] idem

[99] World Intellectual Property Organizaton (WIPO). 2022. Global Innovation Index 2022: What is the future of innovation-driven growth? Geneva: WIPO.

3 Strategic analysis

3.1 Industrial value chains and critical materials

2023 has seen a series of important initiatives on the strategic autonomy of the EU's value chains for clean energy technologies. These include:

- The proposed Net Zero Industry Act[100] and the accompanying staff working document[101] on Investment needs assessment and funding availabilities to strengthen the corresponding manufacturing capacity.
- Temporary Crisis Transition Framework (March 2023) to foster support measures in sectors which are key for the transition to a net-zero economy. *"Until 31 December 2025, Member States may grant aid to foster the transition to a net-zero economy. Aid may be granted to (i) accelerate the roll-out of renewable energy, storage and renewable heat relevant for REPowerEU and (ii) decarbonise industrial production processes. In addition, Member States may also grant aid to accelerate investments in key sectors for the transition towards a net-zero economy, enabling investment support for the manufacturing of strategic equipment, namely batteries, solar panels, wind turbines, heat-pumps, electrolysers and carbon capture usage and storage as well as for production of key components and for production and recycling of related critical raw materials."*
- The proposed Critical Craw Materials Act[102], with objectives
    - to strengthen the different stages of the European critical raw materials value chain;
    - to diversify the EU's imports of critical raw materials to reduce strategic dependencies;
    - to improve the EU capacity to monitor and mitigate current and future risks of disruptions to the supply of critical raw materials;
    - to ensure the free movement of critical raw materials on the single market while ensuring a high level of environmental protection, by improving their circularity and sustainability.
- The, Commission Recommendation of 3.10.2023 on ten critical technology areas for the EU's economic security for further risk assessment with Member States[103] included energy technologies[104], although this was not one of the four areas selected for immediate action.

Several of these initiatives have been supported by data from the CETO 2022 reports as well as dedicated JRC supply chain analysis for strategic technologies[105]. The findings of a subsequent contract study by EnTEC report on supply chain risks in the EU's clean energy technologies[106] included:

- the high strategic importance of PV, wind energy, and batteries whose growth is expected to be high to reach the 2030 targets, while the manufacturing of components and systems is significantly dependent on foreign imports.
- heat pumps, hydrogen technologies), and carbon capture and storage have become more strategic in light of the REPowerEU plan and the Fit for 55 goals, while remaining dependent on third countries for components.
- technologies of medium strategic importance e.g. ocean energy technologies (namely tidal stream and wave energy devices) are those not expected to contribute significantly to 2030 targets but can be

[100] COM(2023) 161 final, Proposal for a Regulation of the European Parliament and of The Council on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act)

[101] SWD(2023) 68 final, Commission Staff Working Document "Investment needs assessment and funding availabilities to strengthen EU's Net-Zero technology manufacturing capacity"

[102] COM(2023) 160 final Proposal for a Regulation Of The European Parliament And Of The Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020

[103] C(2023) 6689 final

[104] This covers "nuclear fusion technologies, reactors and power generation, radiological conversion/enrichment/recycling technologies, hydrogen and new fuels, net-zero technologies, including photovoltaics and smart grids and energy storage, batteries"

[105] Carrara, S. et al., Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/386650, JRC132889

[106] Energy Transition Expertise Centre (EnTEC), Report: Supply chain risks in the EU's clean energy technologies, 2023, doi 10.2833/413910

important in the longer term, for instance as part of the EU's Offshore Renewable Energy Strategy. Grid technologies are considered to fall in this category, since for some components EU manufacturing is weak.

- Technologies judged to be of lower strategic importance geothermal energy systems, solar thermal systems, sustainable biogas and biomethane technologies, and other storage technologies, due a lesser contribution to 2030 goals and an existing competitive manufacturing base.
- Non NZIA technologies were also analysed, but overall were found to be far less strategic. An exception is building insulation materials.
- It acknowledges that a longer time horizon could change the prioritization, and some technologies such as RFNBOs could be given more importance.

The 2023 CETO reports highlight that, aside from policy considerations, the current market for the EU clean energy technology sector is extremely challenging. Firstly, existing manufacturers are facing increased competition from imports, in particular from China, while having to contend with high OPEX costs for local factories due to high energy prices and inflationary pressures on other. Secondly, there is intense international competition for investors, driven by strong incentives in countries such as USA and India. Thirdly, large capacity investments in China beyond the needs of its large domestic market, puts pressure on global component prices, and makes local EU business conditions less attractive to investors in the short-to-medium term. A further risk to the EU is that, under these circumstances, the needed boost to research and innovation funding for clean energy technologies may not materialise (see section 2.2.1).

3.2 Sustainability

3.2.1 Current Status Assessment

Energy systems must be sustainable in terms of their environmental, social, and economic performance. The European Green Deal is the EU's long-term growth plan to make Europe climate neutral by 2050. Clean energy technologies are at the heart of this plan. Knowing the carbon footprint of a clean energy technology is therefore fundamental. This, and other specific policies, promote both more competitive and sustainable industries across Europe including, for example, through mandatory thresholds on carbon footprint such as article 7 of the 2023 Battery Regulation[107]. Policies such as this for batteries contribute to reducing both environmental and social impacts along the whole value-chain, promoting the adoption of more sustainable and circular technologies in various applications.

Such policies are supported in the environmental context at the value chain level by e.g. Product Environmental Footprint (PEF)[60] and associated "Product Environmental Footprint Category Rules (PEFCR) for different technologies. For example PEFCR for batteries[108] and PV panels[109] already exist. This, and associated product policies, complement more site/technology-specific analyses and requirements.

From the social side, Social Life Cycle Assessment is being applied to specific energy technologies, such as for example batteries[110] and hydrogen[111]. In the policy arena, some horizontal mandatory requirements exist for some raw material value chains at EU-level in the context of due diligence. Again, these are complemented by other schemes with mandatory and voluntary requirements for other materials and components contained in specific technologies. For example, due diligence provisions are suggested on social and environmental risk categories in the new Battery Regulation mentioned above. Related studies[112] suggest that responsible sourcing schemes can positively improve the social performance of the life cycle of batteries. Two recent Commission initiatives in this regard are:

- Proposal for a Directive on corporate sustainability due diligence (February 2022), which would aim to "foster sustainable and responsible corporate behaviour and to anchor human rights and environmental

[107] Regulation (EU) 2023/1542 concerning batteries and waste batteries

[108] https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Batteries.pdf

[109] https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_PV_electricity_v1.1.pdf

[110] see chapter 5 of JRC SASLAB Technical report (2018): https://publications.jrc.ec.europa.eu/repository/handle/JRC112543

[111] Eynard U., Martin Gamboa M, Valente A., Mancini L., Arrigoni Marocco A., Weidner Ronnefeld E., Mathieux F. (2022). S-LCA applied to hydrogen technologies in Europe: challenges for critical raw materials' responsible sourcing. Presented at International Conference of Social Life Cycle Assessment (S-LCA 2022) Sept 8th 2022, Aachen, Germany.

[112] https://www.sciencedirect.com/science/article/pii/S0301420721000325

considerations in companies' operations and corporate governance". The new rules, once adopted, would require that businesses address adverse impacts of their actions, including in their value chains inside and outside Europe.

- Proposal for a regulation on prohibiting products made with forced labour on the Union market (COM(2022) 453, September 2022)

Enhanced Circular Economy strategies aim to maximize the value of materials by extending the lifespan of products in which they are embedded (e.g. through reuse and second-use) and recirculating secondary materials (e.g. through recycling). Hence, current circularity performances of energy technologies and embedded components and materials need to be more systematically assessed. Doing so, improvement opportunities will be identified to improve resource efficiency and recycling, through e.g. better product design, improved collection and treatment practices. This can be done either through voluntary approaches, or through policy interventions (e.g. battery regulation proposal addressing second-use, design features, recycled content, collection targets and recycling performances). Improved circularity will, in principle, positively impact the sustainability of clean energy technologies.

Qualitative and quantitative analyses of sustainability performance for clean energy technologies in CETO highlight the heterogeneous and limited nature of available information and data (**Table 3**). For some key parameters, such as carbon and environmental footprints that account for the entire life cycle, the EU's Product Environmental Footprint requirements can be directly applied. Product Environmental Footprint Category Rules also exist already for some clean energy technologies, providing furthermore detailed analysis specifications to facilitate coherence and quality assurance. The European Platform on Life cycle Assessment offers references methods and data (through the International Life Cycle Data Network).

For other sustainability parameters, data, monitoring, and assessment methodologies may be lacking. As noted above, social Life Cycle Assessment could be helpful to assess social considerations but requires further development for clean energy technology analyses; both for current and forward looking perspectives.

Circularity is increasingly a key focus. Quantification of current and future-potential circularity opportunities is vital for most clean energy technologies. The economic, environmental and social implications of different current/future circularity potential and options can be assessed in existing life cycle assessment frameworks using detailed modelling of value chains. In this respect, the EC's Raw Materials Information System (RMIS) offers some relevant references data on recycling rates of raw materials[113] and materials stocks and flows datasets on specific technologies , for example batteries[114].

Concerning EU autonomy, the EC's methodology on critical raw materials (CRMs) considers high risks of supply disruption due to materials coming from a limited number of countries that are often associated with poor governance. Equally, CRMs are associated with sectors with a high added value. Due to the link with poor governance, critical raw materials may also be associated with poor environmental and social performance; while these are not routinely assessed. Hence, CRMs provide an important basis for analysing potential supply chain risk for clean energy technologies for extraction and processing of raw materials. These are also complemented by foresight analyses to consider also other semi-finished goods in the supply chains and that focus on future demand[115]. Other analyses, such as for batteries, provide more in-depth modelling of value chains, related demand, and also what is actually feasible/likely in relation to supply of both primary and secondary raw materials e.g. : RMIS – Raw Materials in the Battery Value Chain (europa.eu). Such model insights could be extended to foresight analyses of economic, social, and environmental considerations.

On the other hand, for the analyses of value chains in relation to current and future orientated autonomy (security-of-supply risk, criticality, resilience), no EC guidance exists.

[113] https://rmis.jrc.ec.europa.eu/?page=scoreboard2021#/ind/15

[114] https://rmis.jrc.ec.europa.eu/apps/bvc/#/v/apps

[115] Carrara, S. et al, Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/386650, JRC132889.

Table 3 Data availability for CETO sustainability indicators reported in individual technology status reports (see Annex 1). The colour coding scheme is as follows: green = quantitative data or standards available; yellow = qualitative info available; red = info not available; blank = no input.

	Adv, Biofuels	Batteries	Bio-energy	CCS	CSP&H	H2 Elec-trolysis	Geo-thermal	Heat Pumps	Hydro-power	Ocean	Solar PV	RFNBOs	Wind
Environmental													
LCA standards or best practice, LCI databases	2	2	2	2	1	1	2	2	2	1	2	2	2
GHG emissions	2	2	2	2	2	2	2	2	2	2	2	2	2
Energy balance	2	2	2	2	1		2	1	2	1	2	2	2
Ecosystem and biodiversity impact	1	1	2	2	0		1	2	1	1	1	1	1
Water use	2	2	2	2	2	2	2	1	2		2	2	2
Air quality	1		2	2	1		2	1	1		1	1	2
Land use	2	2	1	1	2		2		2	1	2	1	2
Soil health	1		1		0		1		1		1	1	2
Hazardous materials	1	2	1	2	1		1	2	1		2	1	0
Economic													
LCC standards or best practices		2			0	0	0	0	1				0
Cost of energy	2	2	2		2	1	2	2	2	1	2	1	2
Critical raw materials	1	2	1			2	1	1	2		2	2	2
Resource efficiency and recycling	1	2	1		1		0		1		1	1	1
Industry viability and expansion potential	1	1	1		2		1		2		2		2
Trade impacts	2	2	2		0		0		1		1		2
Market demand	2	2	2		2		2		2		2		2
Technology lock-in/Innovation lock out	2		2		2		1		1			1	2
Tech-specific permitting requirements	2		2		0		1	1	1			2	2
Sustainability certification schemes	2		2		0		0		2			2	0
Social													
S-LCA standard or best practice	0	2	0		0	1	0		2				
Health	1	1	1		1		1		2			1	1
Public acceptance	1	1	1		1		1		1		1	1	1
Education opportunities and needs	1	1	1		1		1		1			1	1
Employment and conditions	0	1	0		1		1		1		1		1
Contribution to GDP	2	2	2		1		2		2				2
Rural development impact	1	1	1		1		1		1			1	0
Industrial transition impact	1	2	1		1		1		1			1	1
Affordable energy access (SDG7)	1	2	2		2		2		2			1	2
Safety and (cyber)security	0		0		0		1	1	1				1
Energy security	1	1	1		1		1		1			1	0
Food security	1		1				1		1			1	0
Responsible material sourcing	1	2	1		0	1	1		1			1	1

Source: *JRC, 2023*

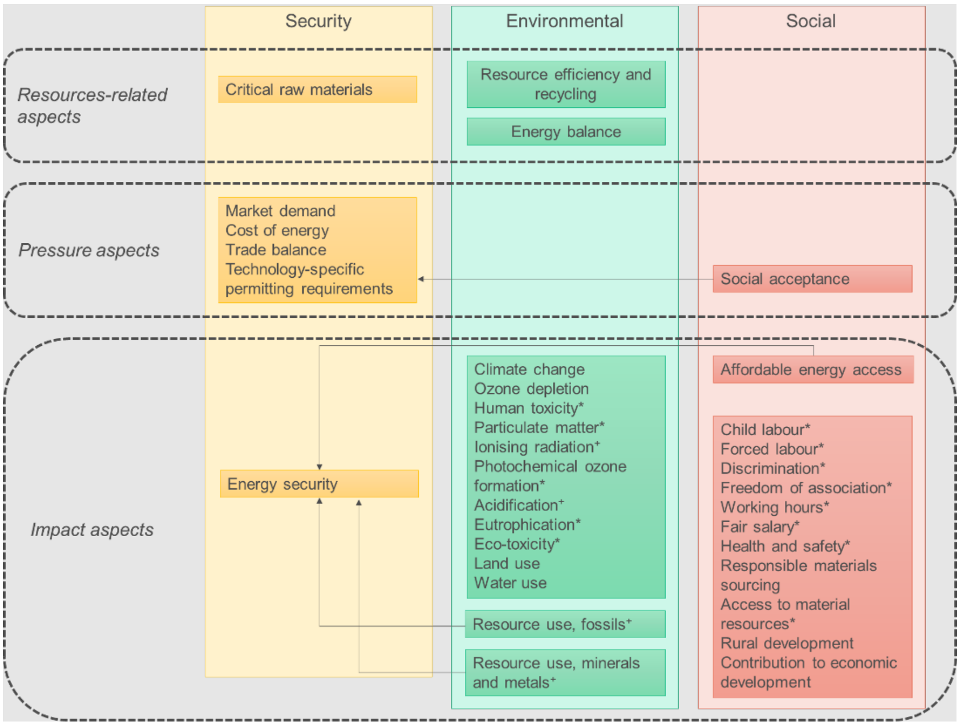
3.2.2 Framework for an integrated sustainability assessment

CETO has conducted initial qualitative analyses for selected sustainability criteria of clean energy technologies (Tasks A1 and A2). These qualitative analyses should be further expanded and maintained through more detailed studies but focusing on a limited subset of parameters. To address this, the JRC is proposing a new comprehensive sustainability framework[116] based on three dimensions: security, environmental sustainability, and social sustainability.

- Energy security encompasses economic aspects, such as stable energy supply, accessibility of resources, and trade considerations.
- Environmental sustainability is based on the Product Environmental Footprint methodology and aligned with the Safe and Sustainable by Design (SSD) framework (also developed by JRC[117]), especially for what concerns the structure, the definition of concepts, sustainability dimensions, life cycle based approach, hierarchical principle and the selection of aspects to assess.
- The social sustainability dimension considers impacts on workers, local communities, value chain actors and society, according to the Social Life Cycle Assessment methodology.

The hierarchical structure of the framework places energy security as the first step, recognizing its interconnections with environmental and social objectives. . Compared to the SSbD, however, this proposal does not include the safety assessment, which is used for the evaluation of hazard assessment linked to chemicals and materials, as well as the human health impacts and safety aspects in their processing and application phase. Instead, the aspect of security and access to energy is addressed. This new methodology will be applied in CETO in 2024, replacing the existing data gathering process.

Figure 15 Overall structure of the proposed sustainability framework for clean energy technologies, with security, environmental and social aspects organized based on a driver-pressure-state-impact-response (DPSIR) approach. Arrows indicate that specific social and environmental aspects can influence energy security



Source: Mancini et al, 2023[118]

[116] Mancini et al, Proposal for a sustainability framework for energy technologies, JRC Technical Report, 2023, JRC135255

[117] Caldeira, C. et al. Safe and sustainable by design chemicals and materials - Framework for the definition of criteria and evaluation procedure for chemicals and materials, 2022, https://doi.org/10.2760/487955

[118] Mancini et al, Proposal for a sustainability framework for energy technologies, JRC Technical Report, 2023

3.3 SWOT analyses

The section aims to provide overall SWOT analyses for global competitiveness, technology independence and sustainability and builds on the analysis made for each technology and reported in the individual reports listed in Annex 1.

Table 4 shows the analysis for global competitiveness, interpreted here according to the following criteria:

- Capability of EU organisations and companies to manufacture, supply, deploy and operate clean energy
- EU capability to create and maintain an environment that sustains more value creation for its enterprises and more prosperity for its people.

Table 5 shows the SWOT addressing technology Independence, where this is considered to be synonymous with the term technology sovereignty as defined by the 2021 study[119] of the European Parliamentary Research Service's Scientific Foresight Unit: "*…the ability for Europe to develop, provide, protect, and retain critical technologies required for the welfare of European citizens and prosperity of businesses, and the ability to act and decide independently in a globalised environment*."[120]

Finally **Table 6** considers the socio-environmental sustainability of the clean energy technology sector in the EU context.

[119] Key enabling technologies for Europe's technological sovereignty, STOA European Parliament, 2021, PE 697.184, I, doi: 10.2861/24482, QA-01-21-349-EN-N

[120] The STOA definition encompasses three key elements: a) Technological – the development of European research and development (R&D) competencies by maintaining a strong knowledge base, industry, and networks in the critical technologies; b) Economic – the achievement and preservation of a position of leadership in key enabling technologies (KETs), the ability to turn R&D into market products, and access to a diversity of resources along the value chain with the aim of reducing dependence on third countries; c) Regulatory – the development of adequate policies and standards that reflect European values, to influence global regulation, standards and practices

Table 4. CETO SWOT analysis of **global competitiveness** for the EU clean energy technology sector.

Strengths	Weaknesses
— Reputation as provider of reliable technology solutions: e.g. offshore wind, CSP, hydropower. — R&I: strong public funding, high-standing of the EU research community, impactful coordination (SET Plan): leader on high value patents — Production equipment: e.g. for PV, batteries, bioenergy — World-leading project development, capability to execute complex, high-performance, large scale engineering projects: e.g. power blocks, chemical systems — Digital systems and solutions already implemented in several sectors — Key player in international standards (industrial, environmental and social governance)	— High energy costs for manufacturiing — Slow manufacturing scale-up — External dependencies for some critical materials and components — Skilled workers shortages and gender-imbalance for STEM fields — Lower private R&I funding compared to main competitors. — Innovation “valley of death”, funding for first-of-a-kind plants — Investment, financing of new tech projects (risk-premium)
Opportunities	**Threats**
— Growing global market for clean energy technologies needed to achieve climate change mitigation goals — Higher fossil fuel prices and security of supply concerns driving green investments — Demand for sustainable solutions — Green Deal industrial strategy — EU carbon markets can help deploy large-scale green industries and support investments for R&I — Additional investment from RRP and Innovation Fund, — Steadily growing VC and competitive VC ecosystems (PV, heat pumps, grids) — Workforce with relevant skills — Integrated cross-sectorial solutions (e.g. energy + infrastructure, energy + agriculture)	— Falling behind in R&I — Infringement of IPR — Divergent MS policies and/or investment uncertainties — Subsidised international competition — Lower cost technology solutions from international competitors — Unfavourable geopolitical developments — Squeeze-out of some developing technologies

Source: JRC analysis

Table 5. CETO SWOT analysis of **technology independence** for the EU clean energy technology sector.

Strengths	Weaknesses
— Technical capability to produce all clean energy technologies — Innovative capability — Expertise in installation and operations — Technology expertise and R&D — IPCEI process to address key areas (e.g. batteries, hydrogen) — Pilot plants: e.g. CCSU, biofuels, ocean	— Lack of scale for manufacturing — Weak supplier ecosystem — Funding of FOAK plants — Import of many electronics components — Digital intelligence (for grids, smart cities etc) — Loss of IPR; ineffective IPR protection — Many EU mining activities closed (raw materials) — Critical raw materials : high dependency on third countries
Opportunities	**Threats**
— EU market growth can drive re-development of manufacturing base — Develop substitutes for critical materials and enhancing recycling — Products for circular economy and ESG-compliant — Diversification of importers to enhance resilience (triggered by Russian war)Export potential for high-end sustainable energy technology	— Loss of skills and expertise — Timescales to development new large-scale manufacturing facilities (solar glass) — Potential disruptions in the supply chain due to economic/geopolitical circumstances

Source: JRC analysis

Table 6. CETO SWOT analysis of socio-environmental sustainability for the clean energy technology sector

Strengths	Weaknesses
— EU policy framework (taxonomy, circular economy, social justice) — Solutions available for reduced environmental impact (on land, water, air, and for biodiversity) — Developed EU re-cycling technology and capacities (e.g. PV) — Synergies between different SDGs	— EU dependence on CRMs — Recycling industry pending material input — Many cases of down-cycling rather than re-cycling — ESG control of imported materials and goods
Opportunities	**Threats**
— Know on sustainability with EU companies as solution providers — Low and high-skill employment growth — Better products, lower life costs (less O&M) — Avoid programmed obsolesce — Globalise ESG standards	— Higher costs of recycled materials — Short term cost gains vs. long term sustainability

Source: JRC analysis

4 Conclusions

This report provides a strategic analysis of the EU clean energy technology sector, to complement the CETO individual technology and system integration reports. The main findings are summarised as follows:

The economic recovery has led to increased energy consumption and carbon intensity globally, offsetting the emission reductions seen in 2020. In the EU, both final energy consumption and intensity have increased, resulting in higher energy and electricity per capita. However, greenhouse gas intensity in the EU has continued to decrease. The share of renewables in final energy consumption remains at just over 20%, while import dependency has decreased.

In response to high energy prices and extreme weather events, comprehensive government measures are needed to protect public health. Price caps, windfall taxes, and handouts have helped reduce costs for consumers in the EU. Targeted policies and interventions, such as expanding energy assistance programs and promoting energy-efficient housing, can help mitigate energy poverty and its associated health risks.

Deployment of clean energy technologies is crucial to reduce fuel import dependence and increase EU competitiveness. The renewable energy sector in the EU has seen growth in turnover and gross value added, outperforming the overall economy. However, the production value of clean energy technologies has grown at a slower pace in 2022, and most technologies have a trade deficit. Carbon pricing is being implemented in more jurisdictions, but only a small percentage of global emissions are covered by a direct carbon price aligned with the Paris climate agreement.

EU public investment in energy research and innovation has increased, but it is still lower as a share of GDP compared to other major economies. Private R&I investments have also been increasing, with the EU ahead of the US in terms of private R&I investment per GDP. EU-based start-ups and scale-ups have attracted a larger share of global venture capital investment, particularly in the clean energy domain. EU patenting output in the energy sector has been increasing, and the EU maintains a strong position in internationally protected inventions.

Employment in the renewable energy sector has grown, driven by heat pumps, solid biofuels, and solar PV. The clean energy sector has the potential to create medium-skilled jobs, particularly in less urbanized areas. However, supply chain difficulties and labour shortages persist in the manufacturing industry. The job vacancy rate in the energy supply sector is high, indicating a need for skilled workers to achieve ambitious deployment targets. While EU strategic autonomy and the Green deal industrial plans have seen major policy proposals the CETO reports highlight that the current market for the manufacturing sector is generally extremely challenging.

The CETO analyses of sustainability performance for clean energy technologies have highlighted the heterogeneous and limited nature of available methods and data. For the environmental dimension, the EU's Product Environmental Footprint requirements can be directly applied for some products and the European Platform on Life cycle Assessment offers reference methods and data for applying LCA. On the other hand Social Life Cycle Assessment requires further development for clean energy technology analyses. For 2024 the JRC is proposing a new framework with security, environmental and social aspects organized based on a driver-pressure-state-impact-response (DPSIR) approach. Also by focusing on a limited set of parameters, this should be more straightforward to apply that the existing indicator scheme.

The studies and analyses performed for CETO in 2023 have again underlined the need to improve the quality and timeliness of public data for clean energy technology sector, in particular regarding investments and socio-environmental aspects. This can be bring benefits to policy makers, prospective investors and sector participants.

List of abbreviations and definitions

CEAP	Circular economy action plan
CETP	Clean Energy Transition Partnership
CPC	common patent classification
ESG	Environmental and social governance
ETS	Emission Trading System
FiT	feed-in tariff
FOAK	First–of-a-Kind
GW	Giga Watt
IA	Innovation Action
IEA	International Energy Agency
IRENA	International Renewables Energy Agency
IP	Implementation Plan
IPCEI	Important projects of common European interest
IPR	Intellectual property rights
LCA	Life cycle assessment
LCoE	levelised cost of electricity
MENA	Middle East and North Africa
MS	[EU] Member State
O&M	Operations and maintenance
PEFCR	Product environmental footprint category rule
PPA	power purchase agreement
PV	photovoltaic
RED	renewable energy directive (RED-II is the 2018 revision; RED-III is the 2023 revision)
RES	Renewable Energy Source
RIA	Research and Innovation Action
SET-Plan	[EU] Strategic Energy Technology Plan
STEM	Science, technology, engineering, mathematics
SWOT	Strengths, weaknesses, opportunities, threats (analysis)
TRL	Technology Readiness Level
VC	Venture Capital

List of boxes

List of figures

List of tables

Annexes

Annex 1 CETO report series 2023

Note: all the reports below are available for download on the CETO web pages at

https://setis.ec.europa.eu/publications/clean-energy-technology-observatory-ceto_en

Subject	Citation
Advanced Biofuels	Hurtig, O., Motola, V., Scarlat, N., Buffi, M., Georgakaki, A., Letout, S. and Mountraki, A., Clean Energy Technology Observatory: Advanced biofuels in the European Union - 2023 Status Report on Technology Development Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2023, JRC135082.
Batteries	Bielewski, M., Pfrang, A., Quintero Pulido, D., Bobba, S., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., Ince, E. and Shtjefni, D., Clean Energy Technology Observatory Battery Technology in the European Union - 2023 Status Report on Technology Development Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2023. JRC135406
Bioenergy	Motola, V., Scarlat, N., Hurtig, O., Buffi, M., Georgakaki, A., Letout, S., Mountraki, A., Salvucci, R. and Schmitz, A., Clean Energy Technology Observatory: Bioenergy in the European Union - 2023 Status Report on Technology Development Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2023, JRC135079.
CCS	Itul, A., Diaz Rincon, A., Eulaerts, O.D., Georgakaki, A., Grabowska, M., Kapetaki, Z., Ince, E., Letout, S., Kuokkanen, A., Mountraki, A., Shtjefni, D. and Jaxa-Rozen, M., Clean Energy Technology Observatory: Carbon capture storage and utilisation in the European Union - 2023 Status Report on Technology Development Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2023, JRC134999.
CSP & ST	Taylor, N., Georgakaki, A., Mountraki, A., Letout, S., Ince, E., Shtjefni, D., Kuokkanen, A., Tattini, J. and Diaz Rincon, A., Clean Energy Technology Observatory: Concentrated Solar Power and Solar Heating and Cooling in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2023, JRC135004.
Electrolysis for H2	Bolard, J., Dolci, F., Gryc, K., Eynard, U., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., Ince, E. and Shtjefni, D., Clean Energy Technology Observatory: Water Electrolysis and Hydrogen in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Petten, 2023, JRC135018.
Geothermal	Taylor, N., Ince, E., Mountraki, A., Georgakaki, A., Shtjefni, D., Tattini, J. and Diaz Rincon, A., Clean Energy Technology Observatory: Deep Geothermal Energy in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2023, JRC135206.
Heat pumps	Lyons, L., Clean Energy Technology Observatory: Heat pumps in the European Union - 2023 Status Report on Technology Development Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2023, JRC134991.

Subject	Citation
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