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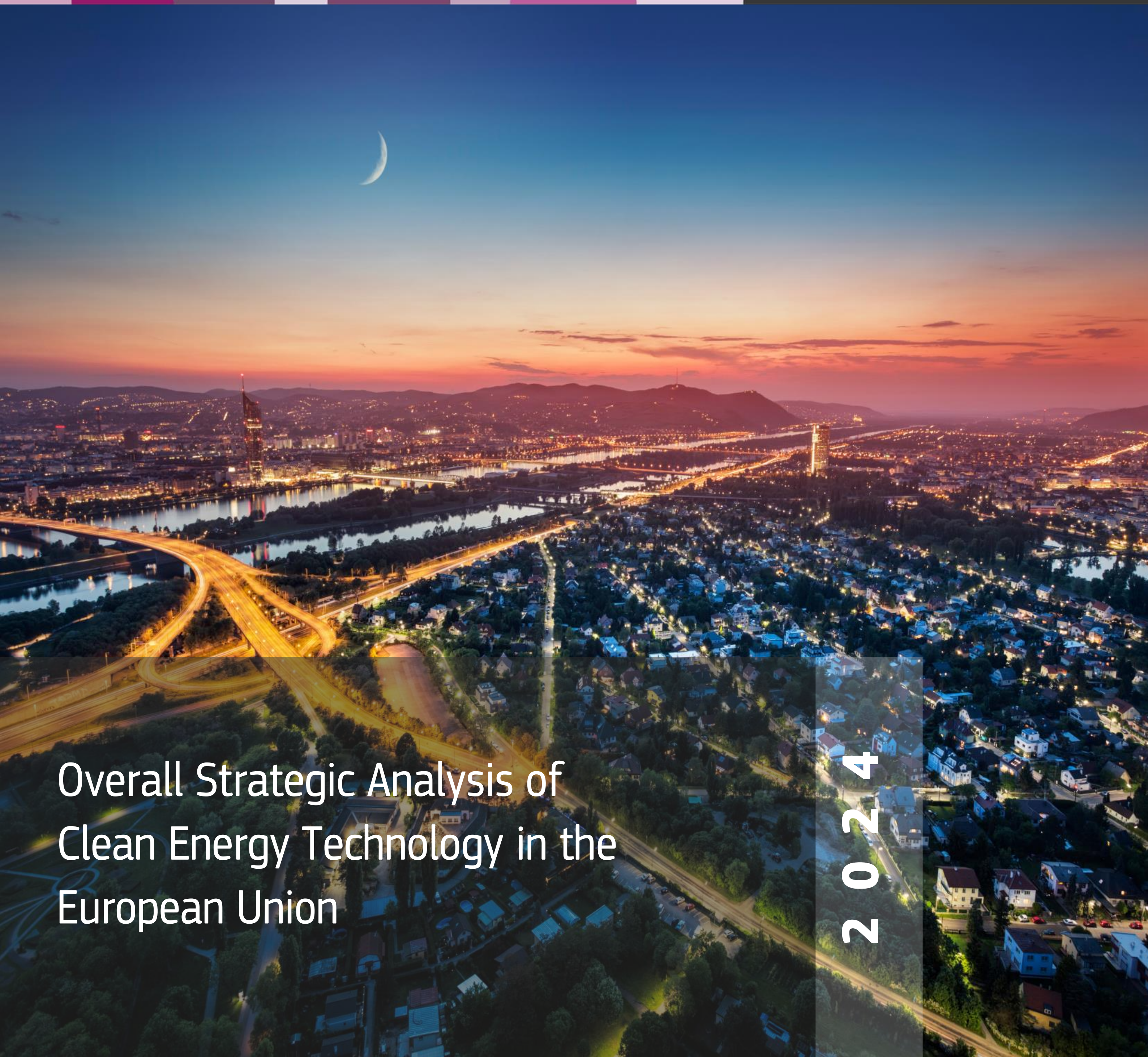

Overall Strategic Analysis of Clean Energy Technology in the European Union

2024

EUR 40083

Joint Research Centre

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Contents

Abstract

This report by the Clean Energy Technology Observatory (CETO) provides an updated strategic analysis of the EU clean energy technology sector. The EU's renewable share in gross final energy consumption rose to 24.5% in 2023, and to 44.7% of gross electricity consumption. The electrification rate however has remained almost unchanged at 26% over the decade to 2023, indicating slow progress on decarbonisation of transport and heating sectors. The EU renewable energy industry saw growth in turnover and gross value added in 2023, outperforming the overall economy. However, the production value of clean energy technologies declined in some areas, such as bioenergy, PV, and hydrogen electrolyser production. EU public investment in energy research and innovation has increased, but it remains lower as a share of GDP compared to other major economies. Employment in the renewable energy sector reached 1.7 million in 2022, growing at a faster rate than the economy as a whole. The clean energy sector however faces challenges in manufacturing. A new sustainability assessment framework has been applied for clean energy technologies, highlighting the need for a harmonized basis for comparing results. The report also underscores the general need to improve data quality and timeliness to better inform policy makers and investors.

Foreword

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

Policy context

This report is part of the 2024 annual series from the Clean Energy Technology Observatory. CETO monitors EU research and innovation activities on the clean energy technologies needed for the delivery of the European Green Deal and assesses the competitiveness of the EU clean energy sector and it's positioning in the global energy market. It contributes significantly to the Commission's annual progress reports on the competitiveness of clean energy technologies. 2024 has seen a series of important initiatives regarding value chains for clean energy technologies in the EU. The Net Zero Industry Act (NZIA) and Critical Raw Materials Act (CRMA) regulations were passed into law and implementation actions are in progress. The new Commission announced a Clean Industrial Deal for competitive industries in the first 100 days of its mandate. Wherever possible, CETO reports aim to highlight data relevant to these policies and initiatives.

Key findings

This report provides an updated strategic analysis of the EU clean energy technology sector, complementing the individual CETO technology and system integration reports. It is based on JRC analysis of a range of data from EU institutions, international organisations and private sources. In general data is up to and including 2023, but in some cases 2022 is the most recent available. The work also underlines the need to improve the quality and timeliness of data for clean energy technology sector, in particular regarding investments, the industrial value chain and socio-environmental aspects. This can bring benefits to policy makers, prospective investors and sector participants.

The findings include:

- The EU renewable share in gross final energy consumption rose to 24.5% in 2023. The share of renewables in gross electricity consumption increased by 3.4 pp to 41.2 % in the EU in 2022. However, the rate progress will need to accelerate to meet future targets.
- The EU's electrification rate of 26% has remained almost unchanged over the decade ending in 2023, suggesting that while decarbonisation of electricity is progressing, that of the transport and heating sectors is still at an early stage.
- The analysis of levelised costs of electricity (LCOE) per country and technology in 2023 confirmed that renewables (wind, solar and hydropower) continue to be the most cost competitive technologies, while CCGT became the most competitive thermal technology.
- The EU renewable energy industry saw continued growth in turnover and gross value added in 2023, outperforming the overall economy. The manufacturing production value of clean energy technologies reached approximately EUR 80 billion, but only batteries, heat pumps and fuel cells saw significant growth, while bioenergy, PV and hydrogen electrolyser production declined by 10% or more compared to 2022. The overall trade deficit persisted in 2023, driven by high imports of solar PV and batteries. The wind and district heating sectors had positive trade balances.

- Public investment in clean energy R&I is increasing, but not fast enough: The EU has been increasing its public investment in research and innovation (R&I) for clean energy technologies, with a 23% increase in 2022 compared to 2021. However, the share of clean energy R&I in overall energy research is stagnating, and the EU still lags behind other major economies in terms of private R&I investments.
- Private investment provides the majority of R&I funding for clean energy technologies, but the EU faces challenges in mobilizing sufficient private investment, particularly in areas such as solar PV and electrolyser technologies, where China is advancing rapidly. The EU needs to attract more strategic growth deals and improve access to finance for its clean energy start-ups and scale-ups.
- The EU has strengths in certain clean energy technologies, but needs to improve in others: The EU has a lead in scientific output on smart, green, and integrated transport, and is specialized in technologies such as wind energy, hydrogen, and green transportation. However, it lags behind the US and China in digital domains and needs to improve its specialisation in areas such as solar, nuclear, hydropower, batteries, and geothermal.
- Unlocking the potential of the EU's clean energy entrepreneurial ecosystem requires targeted public intervention: To mobilize private investors and equity financing, the EU needs to deepen its banking and capital markets, improve exit options for scale-ups, and allocate financial support to clean energy technologies. The EU's Strategic Technology for Europe Platform regulation, the European Tech Champions Initiative, and the proposed European Green Guarantee are steps in the right direction, but more needs to be done to address the EU's scale-up gap and unlock investments in clean energy technologies.
- Employment in the renewable energy sector reached 1.7 million in 2022, growing at a faster rate than the economy as a whole, driven by the heat pumps and solar PV sectors. The clean energy sector has the potential to continue to create medium-skilled jobs, but in many areas there are shortages for specific profiles. For manufacturing, the current market remains challenging. Labour productivity was EUR 119 thousand per employee in 2021, 44% higher than the average in manufacturing and growing faster than that of the economy as a whole.
- Up to now, efforts to develop a common methodology to disaggregate the key socio-economic parameters of clean technology value chains have not reached a sufficient level of reliability. Nonetheless the data gathered in the individual CETO reports provides useful insights regarding the challenges to scale-up manufacturing and of the need to exploit synergies between technologies, in particular in regard to hybridised deployment solutions. . The electricity grid and heating and cooling networks will play a key enabling role.
- CETO has applied a new sustainability assessment framework for clean energy technologies, with energy security, environmental and social sustainability as the main dimensions. A cross-technology comparison for the global warming potential (GHG emissions) aspect illustrates a range of approaches and analysis boundaries, ranging from fully regulated methods (the RED-III directive requirements for biofuels), prescribed component-specific methods (product environmental footprint category rules for batteries), to more self-defined LCA approaches. With the foreseen increased use of the carbon accounting in legislation, further efforts are needed to create a harmonised basis for comparing results for different clean energy technologies.

Related and future JRC work

The CETO project continues in 2025 and include also analysis to support the monitoring of the implementation of the Net Zero Industry Act. Within the JRC work programme 2025-2027, CETO will be part of Portfolio 11 on "Strategic technologies for economic security and innovative industrial ecosystems" and Portfolio 2 on "Energy solutions". The portfolio approach promotes synergies between JRC scientific activities.

Quick guide

The report addresses two main aspects:

— Consolidated data on the competitiveness of the EU clean energy sector, addressing energy and resources trends, employment and skills, research and innovation investments trends, patents, and scientific publications

— Strategic analysis, addressing critical industrial value chain relationships, sustainability assessment, and SWOT analyses focusing on global competitiveness of clean energy technologies, EU technology independence and sustainability.

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 analysis of the clean energy technology and system integration, to complement the individual technology and system integration reports (see Annex 1). 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, including 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

2024 has seen a series of important initiatives regarding value chains for clean energy technologies in the EU. The NZIA and CRMA regulations were passed into law and implementation actions are in progress. The new Commission announced a Clean Industrial Deal for competitive industries in the first 100 days of the mandate. Overall, the need for better data and analysis is apparent. Where possible, the report aims to highlight data relevant to these policies.

2 Overall competitiveness of the EU clean energy sector

2.1 Energy and resource trends

Energy and resource trends (e.g. energy consumption, GHG intensity, renewable energy share) are considered here as 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.

2.1.1 Energy consumption, GHG intensity and renewable energy share

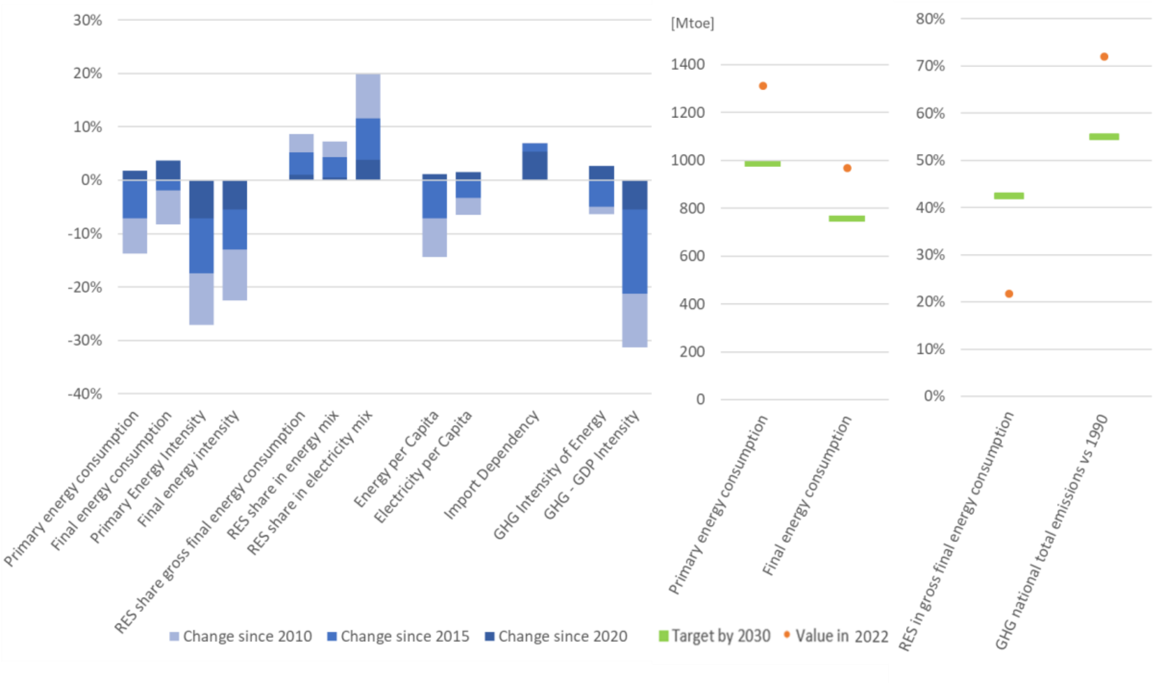
Figure 1 provides an update of the values of energy and resource indicators considered in previous reports. The previous edition of this report had reported increases in both final energy consumption and intensity, in the course of the recovery from Covid-19, resulting in higher energy and electricity use per capita. In 2022, all these indicators went back into decline. A slowdown of energy intensive industries, an unusually mild winter, price increases and energy saving measures following Russia's aggression against Ukraine, resulted in lower electricity and gas demand (down by 3% and 13%) [1, 2]. Even though energy consumption did not decrease to the extent seen in 2020 and the height of the crisis, energy intensity has continued improving and is at the lowest observed since 2005.

Import dependency, and the GHG intensity of energy are the other two indicators (besides energy consumption) where there has not been positive progress. Both increased in 2022 in comparison to the year before, import dependency rising to 64.4 % from 57.1 %, while the GHG intensity of energy increased by 3.3 %. The increased import dependency is accompanied by a very high import bill of EUR 604 billion in 2022, corresponding to 3.8 % of EU GDP[1].

Nonetheless, overall greenhouse gas (GHG) intensity in the EU continued to decrease. 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 [3]. The trend continued in 2023, with the EU achieving the most significant decrease among top emitting economies. GHG emissions were 33.9 % lower than 1990 levels, accounting for slightly over 6% of the world total, and showing decoupling from economic growth as the EU remains the lowest emitting major economy when normalising emissions per GDP [4].

[1] COM(2024) 136 final, Report on energy prices and costs in Europe, Brussels, 22.3.2024

Figure 1. Evolution of main indicators for energy consumption, GHG intensity and renewable energy contribution to the energy system, along with the 2022 value and 2030 targets.



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

Having exceeded the milestone towards climate neutrality by 2 % in 2020, but then stagnating in 2021 the EU renewable share in gross final energy consumption reached 24.5% in 2023. The share of renewables in gross electricity consumption increased by 3.5 pp to 44.7 % in the EU in 2023. However, progress will need to accelerate to meet future targets.

In particular, the EU's electrification rate[2] needs to start increasing. The value was almost unchanged at 26% over the decade 2013 to 2023. This suggests that efforts to decarbonise transport and heating are at an early stage. However, there are significant differences between the Member States (Figure 2). The rate of electrification in 2022 varied widely from 47% in Sweden to 6% in Luxembourg. Furthermore, in the 2013-2023 period, several countries made substantial progress. This suggests that there is considerable scope for Member States to use national policies to stimulate electrification towards the value of 33% by 2030, as foreseen in the analysis supporting the 2040 climate target planning[3].

While the trend in all renewable indicators remains positive, it needs to accelerate as the next milestone towards the increased ambition of achieving 42.5 % by 2030 is approaching.

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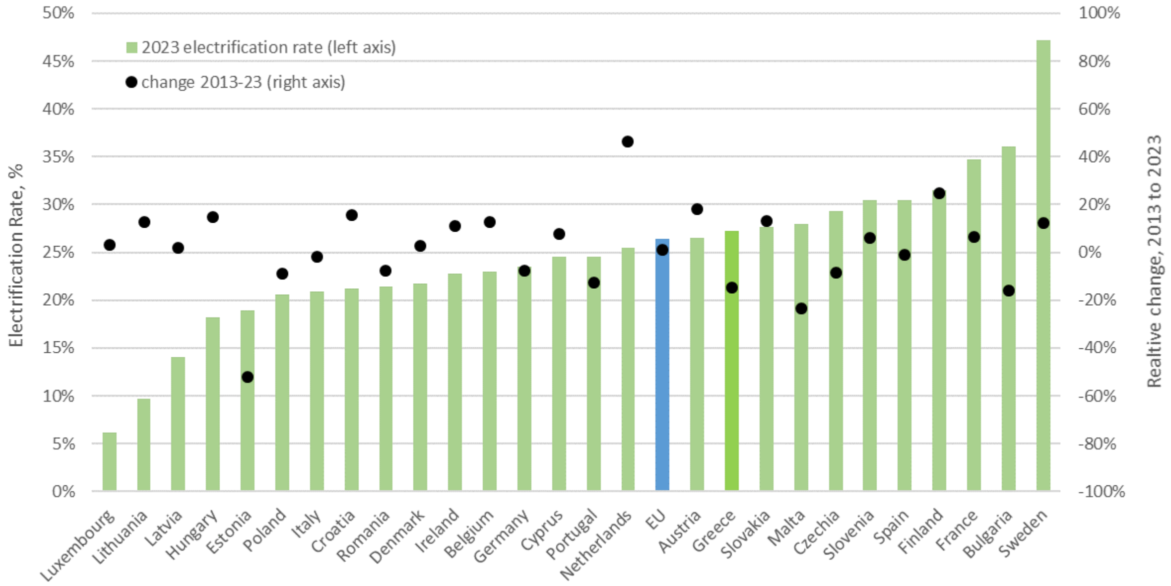
[2] Electrification rate is defined here as the ratio of gross electricity production to final energy consumption

[3] Derived from SWD(2024) 63 Impact Assessment Report, Part 1, accompanying COM(2024) 63 "Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society"

Figure 2. Electrification rate (ratio of gross electricity production to final energy consumption) in the EU for 2023 (columns, left axis) and the relative % change over the preceding decade (points, right axis).



Source: JRC elaboration of Eurostat data

2.1.2 Production and trade

In 2023, production value[4] was highest for Li-ion batteries (EUR 21 billion), followed by biodiesel (EUR 13 billion) and bioenergy (mainly pellets and woodchips; EUR 10 billion). At the low end, in terms of production value, were fuel cells (EUR 0.2 billion), CCUS (EUR 0.3 billion) and hydropower (EUR 0.6 billion). Compared to 2022, EU production for six out of 14 clean energy technologies monitored (see Box 1 for methodology) increased in terms of value, while it declined for an equal number of technologies and remained stable for two (Figure 3). Production value of Li-ion batteries and heat pumps increased the most (around 30 %), followed by fuel cells (18 %), ocean, ethanol and CCUS (nearly 10 %). In contrast, the sharpest decrease was observed for hydrogen[5] (44 %), though the estimate production volume remained the same; this can be viewed as a ‘correction’ to the steep increase observed in 2022 [6, 7] as a result of the price of gas used as feedstock for the majority of EU hydrogen production.

In 2023, the EU had a trade deficit in eight out of 12 technologies monitored (see Box 1 for methodology), the largest being in solar PV and Li-ion batteries (nearly EUR 19 billion each). In the case of batteries, the trade deficit increased by 21 % compared to 2022, while for solar PV it declined by 13%. Bioenergy (mainly wood pellets, wood chips, charcoal and starch residue) and

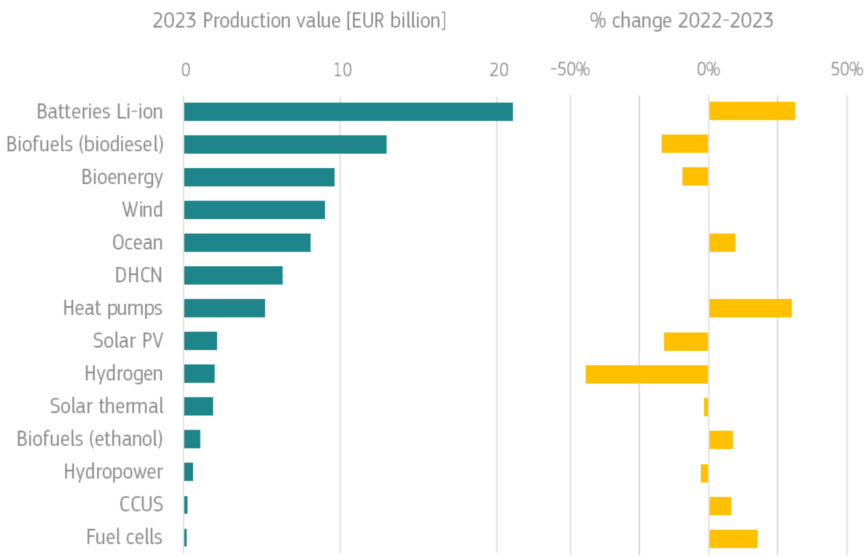
[4] Production value refers to the Eurostat PRODCOM statistics for industrial production (with the exception of military products and some energy products) carried out by enterprises classified in Sections B, C and E of NACE Rev. 2

[5] Referring to all hydrogen, irrespective of production route

biodiesel had a deficit of over EUR 1 billion, while heat pumps and ethanol had a deficit of around EUR 0.5 billion **(**Figure 4).

From the technologies in surplus in 2023, the most prominent was wind (EUR 1.7 billion), where imports fell by 65 % and exports increased by 50 % compared to the previous year. Heating and cooling networks had the second largest surplus (EUR 1.3 billion) followed by hydropower (EUR 0.2 billion), hydrogen[5] (EUR 7 million) and CCUS (EUR 4 million). Compared to 2022 and previous years, EU demand for hydrogen decreased further [6, 7]; trade surplus in hydrogen more than tripled as imports reduced by 70 % and exports increased by 40 %.

Figure 3. EU production value in 2023 [EUR billion] and % change compared to 2022.



Source: JRC based on PRODCOM data

Figure 4. EU trade balance in 2023, % change compared to 2022 and share of extra-EU exports in global exports for 2023 for the CETO technologies.

Source: JRC based on COMEXT and COMTRADE data

Box 1. Production and Trade methodology note

Data and Sources: International trade is monitored using six-digit codes of the Harmonised System (HS) classification[6]. The production of manufactured goods in the EU is monitored through Eurostat's eight-digit codes of PRODCOM list[7]. PRODCOM is based on the Combined Nomenclature (CN)[8] classification system, which in turn is derived from the HS system. This allows for a consistent and standardized approach to classifying goods and collecting data on the production and trade within the EU.

Data availability: CETO releases 17 technology reports[9], which may cover multiple sectors of a technology within a single document. For example, the 2023 report on concentrated solar power examines thermal solar separately. These reports may also focus on various technological subdivisions, such as the 2024 report on advanced biofuels that categorises "biofuel technology" into biodiesel and bioethanol. However, data may not always be available for all technologies. Emerging technologies (e.g., novel energy storage) may not yet have an HS or PRODCOM code. Similarly, multi-purpose equipment (e.g., heat pumps used in heating and cooling networks or lifting equipment in ocean energy) may lack a dedicated code, acting only as a proxy to understand the overall trends. Furthermore, HS codes cannot be linked to production processes or the applications of the traded good, and EU Member States may not agree to create a more detailed PRODCOM code due to confidentiality reasons. Therefore, data does not differentiate between green and conventional (e.g. hydrogen).

The table below provides an overview of the codes selected to monitor the CETO technologies.

Technology	HS	PRODCOM
Batteries Li-ion	850760	27202350 (as of 2019)
Bioenergy	cocoa shells: 180200; starch residue: 230310; bagasse: 230320; wood fuel: 440111, 440112; wood chips: 440121, 440122; wood pellets: 440132, 440131; charcoal: 440210, 440220, 440290; sawdust: 440139, 440141, 440149	starch residue: 10622000; bagasse: 10812000; wood chips: 16102503, 16102505; wood pellets: 16291500; charcoal: 20147200
Biofuels (biodiesel)	382600	20595800
Biofuels (ethanol)	220720	20147500
CCUS	MEA: 292211; DEA: 292212	MEA: 20144233; DEA: 20144235
DHCN	841950	28251130
Fuel cells	not available	27904200
Heat pumps	841861	28251380
Hydrogen	280410	20111150
Hydropower	turbines: 841011, 841012, 841013; parts: 841090	turbines: 28112200; parts: 28113200
Ocean	not included	insulated conductors: 27321400; lifting equipment: 28221470
Solar PV	PV cells (as of 2022): 854142, 854143	semiconductors: 26112240; parts: 26114070
Solar thermal	841912 (as of 2022)	27521400
Wind	850231	28112400

6 World Customs Organization (WCO), Nomenclature and classification of goods, HS Nomenclature 2022 Edition

7 Eurostat, European Business Statistics, PRODCOM – Statistics by product

8 European Commission, Taxation and Customs Union, The Combined Nomenclature tool for classifying goods

9 Clean Energy Technology Observatory (CETO) reports, available through SETIS – the SET Plan information system

During 2021-2023, (extra-)EU exports of wind rotors held the largest share in global exports of the technology (67 %), followed by solar thermal and hydropower with around 40 %. In contrast, the EU had the lowest share in global exports for solar PV (3 %) and ethanol (4 %). China was the major exporter to the EU for all technologies except for CCUS (Saudi Arabia and US), hydrogen (UK and Switzerland), ethanol (US and Brazil) and bioenergy (US and Ukraine).

The Net-Zero Industry Act is designed to stimulate investments and industrial production capacities for clean technologies. When it comes to supporting these industries, modelling analysis[10] indicates that a coordinated, simultaneous approach by EU countries would result in a higher benefit than individual action at the Member State level. In addition, joint action would contribute to strengthening the Single market and have more indirect positive impacts on the rest of the EU and other non-supported industries. The effect would be expected to be more significant in improving the EU strategic position in manufacturing industries critical for the green transition, if simultaneous action was taken across the EU.

2.1.3 Levelised cost of electricity

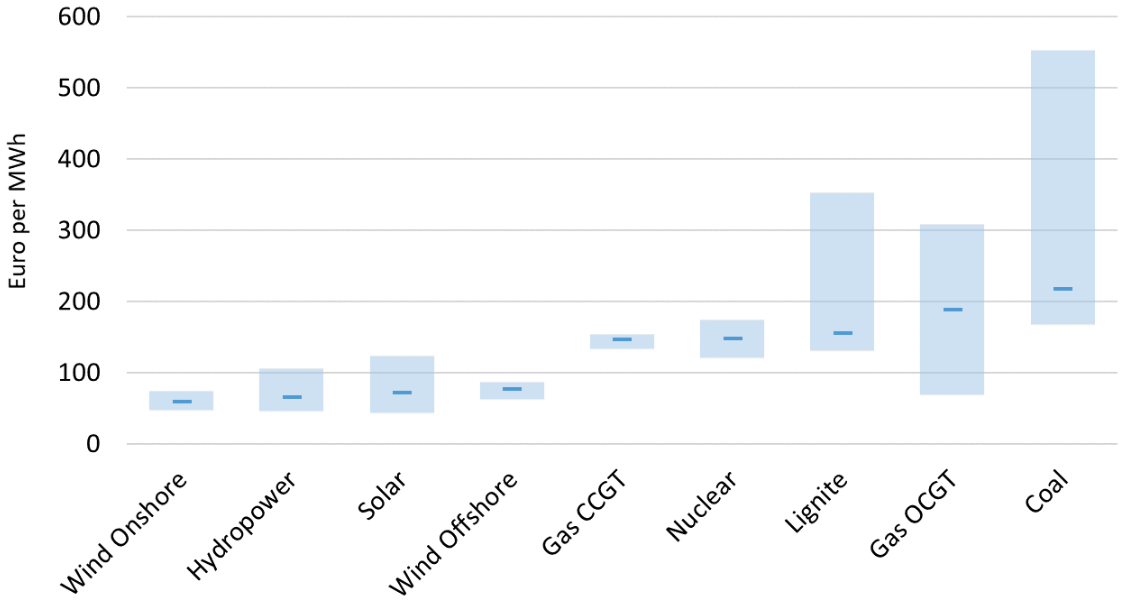
Figure 5 shows the levelised costs of electricity (LCOE) in the European Union, estimated based on the specific characteristics of electricity systems in each country for the year 2023. The results reflect increases in investment costs, as well as operation and maintenance costs, in 2023 due to inflation, higher material costs, and increased labour costs. In particular, the elevated inflation and high interest rates played a major role in impacting or delaying investment decisions in 2023, both for project developers and for manufacturers.

The LCOE value of a given technology is influenced by the ratio between the annual generation volume of the technology and its installed capacity. The less utilized a technology is, the larger its LCOE value will be. For this reason, conventional technologies, such as lignite, open cycle gas turbines (OCGT), and coal, that have had lower generation in some Member States, see larger upward spreads in their LCOE values. In contrast, the LCOE spread for combined cycle for natural gas (CCGT) remains very narrow as the usage rate of CCGT power plants is high in most Member States.

Compared to last year's results, the trend of renewable energy sources being more cost-competitive continues, albeit with some adjustments. Renewables continue to be the most cost competitive technologies, while CCGT became the most competitive thermal technology on cost. This trend is partly explained by the large drop in natural gas prices compared to the previous year. Additionally, while last year saw significant fuel switching between gas and coal due to fluctuating prices, this year the focus has shifted more towards the impacts of higher fixed costs across all technologies. The consistency in CCGT's narrow LCOE spread highlights its stable usage rate, contrasting with the broader LCOE spreads observed in other conventional technologies like lignite and coal. This underscores the ongoing evolution of cost dynamics in response to economic pressures and market conditions.

[10] EU Science Hub News Announcement: Boosting EU's clean tech industries: how would State aid impact the Single Market? 13 August 2024 referencing Rueda-Cantuche J.M., Pedauga, L.E., RuizGarcia, J.C. and Ciriaci, D. (2024), 'Green transition, single market and EU's open strategic autonomy: the impact of state aid', Single Market Economics Papers 10. European Commission, Directorate General for Internal Market, Industry, Entrepreneurship and SMEs, Brussels

Figure 5. Snapshot of technology-fleet specific levelised costs of electricity (LCOE) for the year 2023. The solid blue lines denote the median and the light blue bars display a ±25 % range across the EU, highlighting differences among Member States.



Source: JRC METIS model simulation[11]

Over the past decade, the LCOE for various generating technologies in Europe has evolved significantly due to several factors. Technological advancements have led to increased efficiency and larger capacity designs, particularly in solar PV and wind energy, driving down costs substantially. For renewables, economies of scale, especially with larger projects and mass production, have further reduced costs. Policy support, including subsidies, tax incentives, and carbon pricing, has encouraged the adoption of cleaner energy sources while increasing the costs associated with fossil fuels like coal and natural gas. All this has shifted the energy landscape, so that now renewables are cost-effective and reliance on traditional energy sources is reduced.

2.1.4 Energy poverty and well-being

The EU's ambitious energy transition aims to achieve a low-carbon, sustainable future. However, this transition cannot be truly successful without addressing the pervasive issue of energy poverty, which significantly affects social equity and economic competitiveness. The latest updates to the Energy Efficiency Directive (EED) and the Energy Performance of Buildings Directive (EPBD) reflect this commitment, emphasising the need to mitigate energy poverty. However, as the EU progresses towards our 2030 and 2050 targets, the recent rise in energy poverty indicators and the persistency of the problem, including summer energy poverty [8], suggests that the social dimension of the

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[11] According to: 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 2023. Capex and Opex based on the 2040 climate target PRIMES reference 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 2023 commodity prices, variable Opex and the dispatch in the METIS simulation.

transition demands more attention. Support programs for vulnerable populations, industries, or regions are necessary to underpin the energy transition and make sure that all benefit from the structural benefits expected to bolster European competitiveness.

Energy Poverty and the Energy Transition. Energy poverty remains a critical challenge that can undermine the pace and success of the energy transition. It has only recently been defined in EU legislation, in the recast EED of 2023, as 'a household's lack of access to essential energy services, where such services provide basic levels and decent standards of living and health'[12]. As energy prices fluctuate and retrofitting costs for energy efficiency rise, economically vulnerable citizens face disproportionate challenges. In 2023, more than 10.5 % of the EU population struggled with inadequate home heating, an increase of almost 4 percentage points since 2021; a trend that is especially concerning in countries like Greece, Romania, and Bulgaria, where up to 20 % of individuals face arrears on their utility bills and heating inadequacies in their dwellings (see Figure 6) [9]. Without targeted interventions, energy poverty can exacerbate social inequality and create resistance to the transition, thereby slowing down the adoption of clean technologies and practices that are essential for achieving the climate goals defined in the European Green Deal.

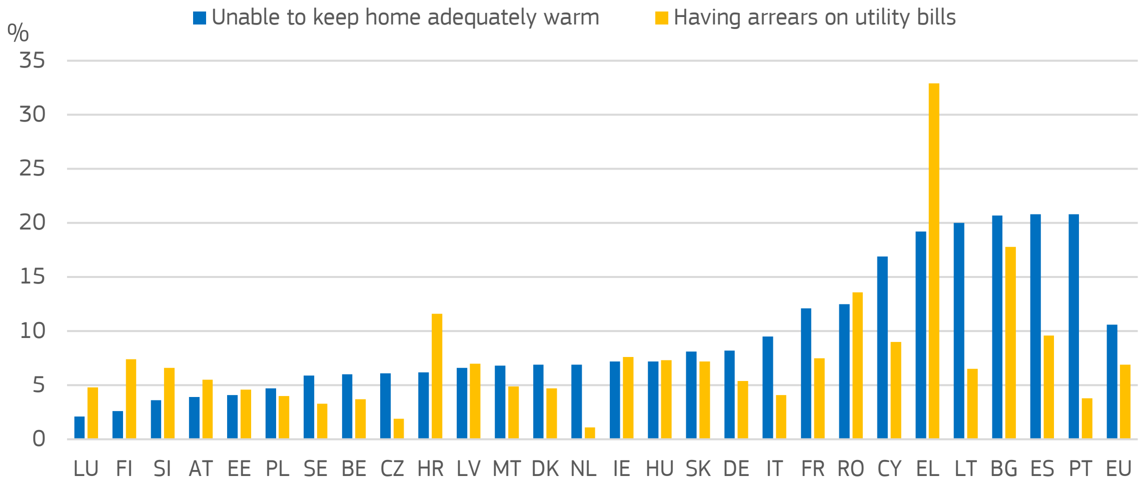
The Intersection of Energy Poverty and the Housing Crisis. The issue of energy poverty is deeply intertwined with a broadening housing crisis in the EU. The lack of affordable, quality housing exacerbates energy poverty, as many low-income households are likely to live in poorly insulated, inefficient homes that drive up energy costs. A recent JRC analysis has revealed that those exposed to a heavy burden of housing costs in proportion to their household income for a longer period had higher energy poverty persistency rates (Figure 7) [10]. This vicious cycle does not only perpetuate economic hardship, but it also places an additional strain on the housing market, as demand for affordable, energy-efficient housing far outstrips supply. It is crucial to address the housing crisis through robust policies, which promote the construction and renovation of energy-efficient homes in proximity to areas where job opportunities are found. This dual approach can simultaneously alleviate energy poverty and contribute to a more sustainable and equitable housing market, ultimately supporting the EU's goals for social equity and economic competitiveness.

Competitiveness and Social Support Programs: The link between competitive economies and social well-being is well established. Support programs designed to alleviate energy poverty can stimulate job creation in the green construction and retrofitting sector, promote innovation in energy-saving technologies, and increase consumer spending-power by reducing energy bills. In the absence of such programs, the energy transition risks leaving behind a segment of the population and industries that are integral to the economy's overall productivity and growth (e.g. farmers, SMEs).

Moreover, unaddressed energy poverty can lead to higher health costs, reduced workforce productivity, and increased social tensions—all of which can erode the competitive advantage that a comprehensive energy transition is poised to offer. By investing in social support programs, Member States can prevent these negative outcomes and ensure that the transition contributes to the overall resilience and competitiveness of the European economy.

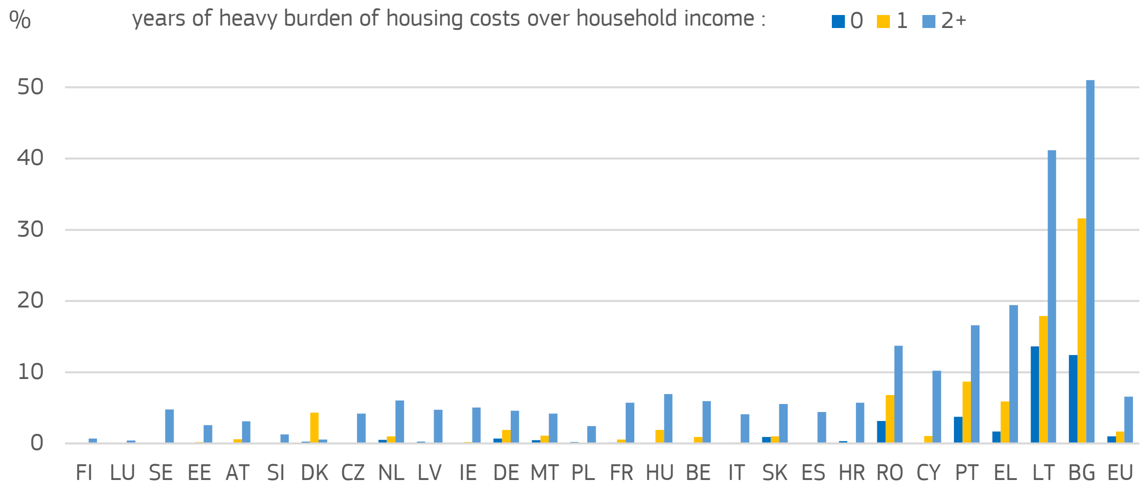
[12] Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast).

Figure 6. Proportion of individuals unable to keep their housing adequately warm and of those having arrears on utility bills, 2023 (%)



Source: JRC based on Eurostat Economic Strain (ilc_mdes01 and ilc_mdes07)
Note: Member States ordered ascendingly by the proportion of individuals being unable to keep home adequately warm.

Figure 7. Proportion of individuals persistently unable to keep their home adequately warm by years spent with a heavy burden of housing costs over household income, 2020



Source: JRC analysis of EU-SILC longitudinal microdata data sets (version 05/10/2023) [10]
Note: The EU total does not include DE. For DE, values for 2020 refer to 2019.

The EED and EPBD Legislative Updates: The recent legislative updates to the EED and EPBD reflect a growing recognition of the need to address energy poverty within the framework of the energy transition. The EU level adoption of an energy poverty definition opens the door to further policy developments, for example in the EPBD, adopted in 2024[13]. The EPBD builds on the definition

[13] Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast)

established in the EED and prioritises the renovation of those buildings with the highest potential to alleviate energy poverty. These directives now include provisions that urge Member States to prioritise energy efficiency improvements in households affected by energy poverty. By doing so, the EU acknowledges the interdependence between social equity and environmental sustainability.

The updated directives offer a promising direction, but a further effort is required to translate legislative intent into tangible progress against energy poverty. This underlines the need for holistic policy approaches that integrate social, economic, and environmental objectives to ensure that the energy transition is both socially equitable and competitive. Measures can range from financial support mechanisms for low-income households, access energy-efficient upgrades, to training programs to equip workers with the skills needed for emerging green jobs; from targeted investments in energy infrastructure that benefit both vulnerable regions and industrial sectors, to incentives for industries to adopt energy-efficient technologies that can reduce operational costs and improve competitiveness. By doing so, the EU can achieve its climate goals while ensuring that no one is left behind, ultimately fostering a more competitive and resilient economy.

2.2 Research and innovation trends

The political guidelines for the 2024-2029 Commission recognise research and innovation as a key driver for competitiveness that needs to be at the heart of the EU economy. As such they announce measures to increase research spending and provide a thriving environment for research in strategic technologies[14]. The Draghi report, drawing much of its evidence from the work of the JRC, also pointed to the need for renewed efforts on innovation to fend off pressure on EU's advantage on green technologies [11]. It also called for better coordination of public funds and access to additional private funding to successfully address future innovation challenges.

2.2.1 Public and private R&I spending

Even though both public and private R&D budgets for clean energy technologies are increasing globally, corresponding investments in fossil energy technologies are also on the rise, meaning that the share of clean energy R&D in overall energy research is stagnating, or even slightly decreasing in the last couple of years [12, 13].

Public investment in research and innovation in the Energy Union R&I priorities[15] has been steadily increasing, with the values reported by EU MS in 2022 being 23 % higher than 2021[16]. Half of the EU Member States that provide data[17] increased their public R&I investment in the Energy Union priorities in 2022 in comparison to 2021. Topped up by Horizon Europe funds the public investment declared so far has exceeded EUR 9 billion. According to these figures, the EU leads in public R&I

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[14] Europe's Choice, Political Guidelines For The Next European Commission 2024–2029, Ursula von der Leyen Candidate for the European Commission President, Strasbourg 18 July 2024

[15] COM(2015) 80 final. A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy

[16] A significant share of the increase in 2021 and 2022 was due to a change in reporting by Spain, and revisions by France. These two MS accounted for an additional EUR 1 billion of R&D investment in 2022. IEA, 2024. Energy Technology RD&D Budgets, May 2023 Edition, Database documentation. International Energy Agency (IEA), *Energy Technology RD&D Budgets - Database documentation*, 2024.

[17] Member States that reported an increase to the IEA: BE, DE, EE, ES, FR, LT, IE, PL, PT, FI; IT not reported

spending in clean energy technologies among major economies, both in absolute spending, as well as in terms of share per GDP (0.057 % followed by Japan 0.055 %).

A significant share of the increase observed in 2021-2022 was due to a change in reporting by Spain, and revisions by France (Figure 8). The former has expanded coverage to include data from both state and regional governments, while the latter has updated the methodology to better reflect demonstration projects. As such much of the increase for France comes from the implementation of Important Projects of Common European Interest (IPCEIs) on hydrogen. These two Member States accounted for an additional EUR 1 billion of R&D investment in 2022. While such revisions introduce breaks in the time series, there is a need to improve capacity and consistency in monitoring and reporting to provide an informed assessment at EU level as highlighted from the result of the National Energy and Climate Plans reporting exercise[18].

The latest increase means that EU Member States investments, from 2021 onwards, have surpassed the peak observed a decade ago (before the effects of the economic downturn), both in nominal terms and when accounting for inflation. Over the same period there has been a notable shift in the share of public R&I investment over the Energy Union R&I priorities. Nuclear safety used to be the most prominent thematic area, attracting nearly a third of public R&I investment; in recent years, sustainable transport has attracted a similar share, with a focus on battery and hydrogen technologies.

As part of climate action, the EIB Group invests own resources in research projects that mitigate global warming (climate change mitigation) by reducing, avoiding or absorbing greenhouse gas emissions. This includes investments on research, development and innovation averaging EUR 2 billion per year for the period 2021- 2023[19].

The closest other proxy to R&I spending in clean energy is the share of the energy socio-economic objective in government budget allocations for research[20]. The share of these over GDP is also highest for the EU among major economies. Figure 9 shows the public R&I spending on the energy socio-economic and the on the Energy Union R&I priorities as a share of the total government budget for R&D. While the socio-economic objective of energy has remained more or less stable over the last 5 years, the importance of R&I towards the Energy Union objectives, which encompasses more aspects of efficiency and decarbonisation across sectors, has been increasing. However, it needs to be noted that the energy topic may include research on topics not covered under the Energy Union priorities. More than half of the government budget allocations for R&D are classified under 'general advancement of knowledge' research, mainly in universities, that would include research relevant to the Energy Union R&I priorities; research under other socio-economic objectives, such as industrial production & technology, or environment, could also be relevant. It remains the case that official statistics are often a rather poor source of information for monitoring public investment and the compilation of data, and reporting by Member States could be improved.

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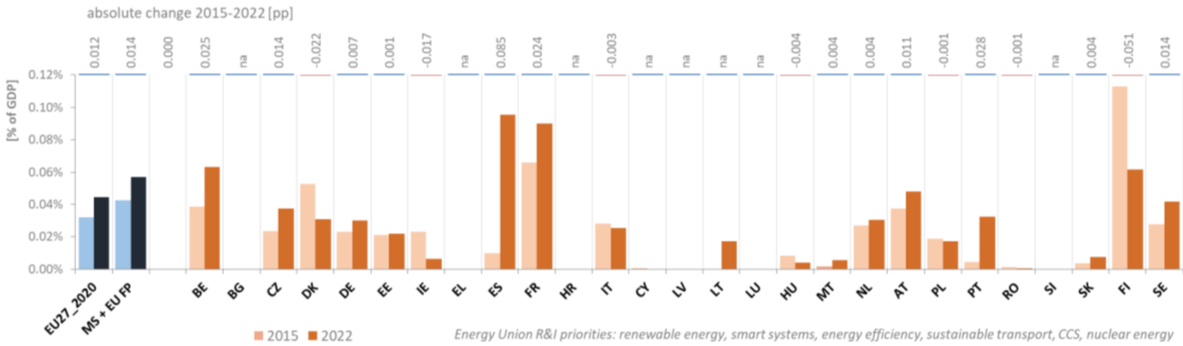
[18] The Commission's technical assessment of the NECP progress reports SWD(2023) 646 final was part of the 2023 State of the energy union report. The integrated national energy and climate progress reports are available on the CRICABC e-platform.

[19] EIB's RDI climate signatures by year (based on the EIB's taxonomy for climate and environmental sustainability activities). European Investment Bank Group Sustainability Report 2023

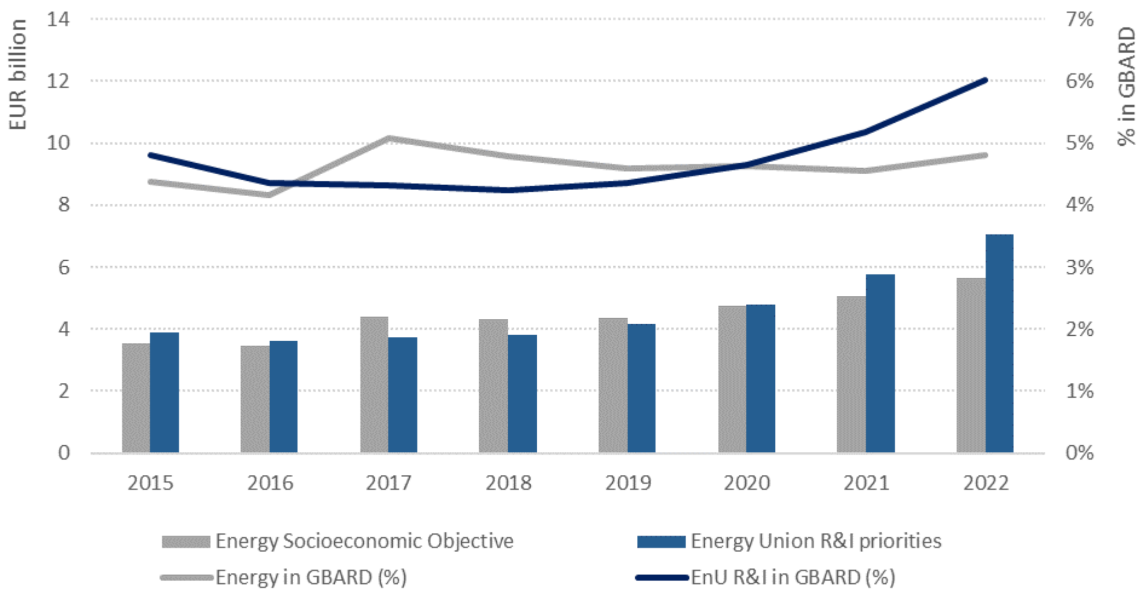
[20] See Eurostat Government budget allocations for R&D (GBARD) metadata for more information on the nomenclature for the analysis and comparison of scientific programmes and budgets.

Figure 8. Public R&I investments by EU Member States as a share of GDP, 2015 vs 2022 (left vs right bar) and change in percentage points between the two (top).



Source: JRC based on IEA[21] and own work[22].

Figure 9. 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[21], own work[22], and Eurostat[23]

Research indicates that OECD countries (and also the EU) put a stronger emphasis on deployment compared to direct R&D support of renewable technologies, even in the case of technologies that are not mature enough to go to market. Public R&D support is designed to primarily benefit domestic firms and industries. Nonetheless, the scale-up and expansion of these industries rely on deployment support policies, which due to the global nature of supply and value chains, will propagate beyond the domestic economy, benefiting not only the development of foreign industries,

21 Adapted from the 2024 spring edition of the IEA energy technology RD&D budgets database, IEA (2024), Paris.

22 JRC SETIS - SET Plan information system Research and Innovation Data

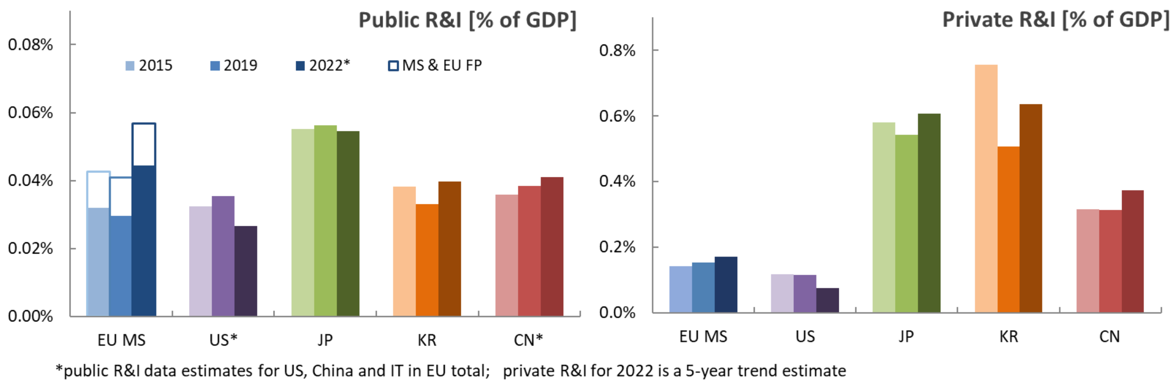
23 GBARD by socioeconomic objectives (NABS 2007) [gba_nabsfin07]

but subsequently and indirectly also supporting advances in innovation abroad. Indicatively the research in question cited (2018) that the ratio of public R&D vs deployment support for renewable energy in the EU was over 170; 15 times higher than the US and 4 times that of Japan [14]. Such evidence has led to recommendations for R&D support to be direct, and take into account the technology and the stage of development, not only of the technical aspects but also other potential bottlenecks such as e.g. skills shortages along domestic value chains. This would lead to more benefits for targeted parts of the value chains in question.

Private investment continues to provide the majority of R&I funding for clean energy technologies, both in the EU and across all major economies (Figure 10). Investment per GDP remains significantly higher in major Asian economies (0.37 %-0.64 % GDP) than in the EU (0.17 % GDP) and the US (0.08 % GDP). Nonetheless, the contribution of the private sector to R&I investment in the Energy Union R&I priorities is higher than to that observed overall (Figure 11). Considering all R&I fields, the EU has the lowest R&D intensity among major economies, mainly due to the lower level of expenditure within the business enterprise sector, which contributes around 58 % of R&I funds[24]. In contrast, businesses provide over three quarters of R&I spending in the Energy Union R&I priorities.

The R&I intensity of the energy sector is consistently low compared to other sectors [15]. However, the Energy Union R&I priorities require R&I effort from other sectors, such as automobiles and transport and industrials that invest multiple times more – as a share of their turnover – than the energy sector (automotive over 7% vs. energy under 1% for 2021).

Figure 10. Public and private R&I investments in major economies as a share of GDP



Source: JRC based on IEA[25], MI[26], own work[27].

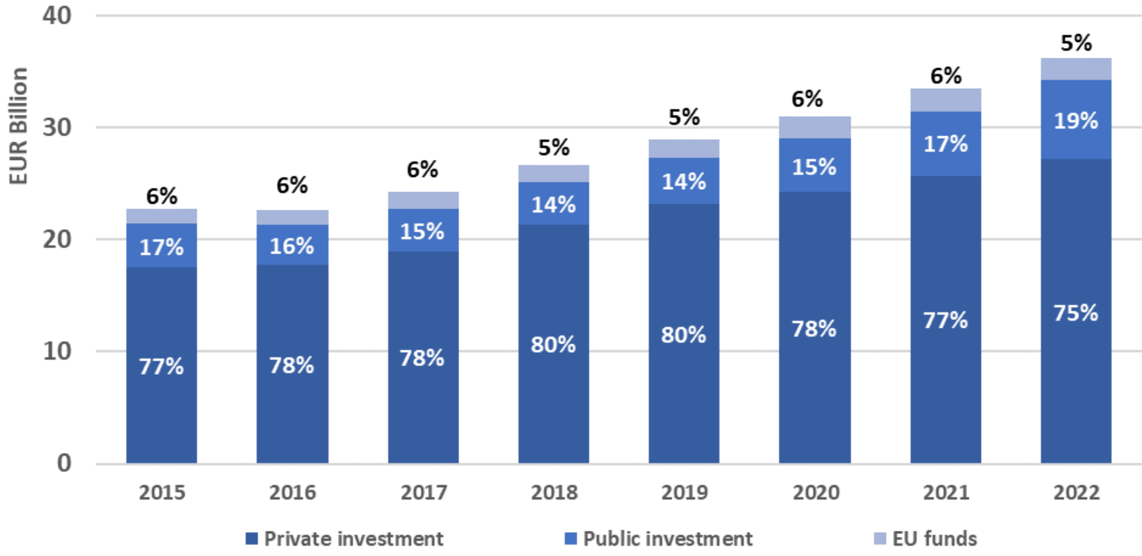
[24] Eurostat, Statistics explained, R&D expenditure, Data extracted in September 2024

[25] Adapted from the 2024 spring edition of the IEA energy technology RD&D budgets database, IEA (2024), Paris, and JRC own work, see Box 2 on methodology.

[26] Mission Innovation (2020) Country Highlights, 5th MI Ministerial 2020. Public R&I estimated for CN, and JRC own work, see Box 2 on methodology.

[27] JRC SETIS - SET Plan information system Research and Innovation Data.

Figure 11. Share of public and private R&I investment on the Energy Union R&I priorities in the EU.



Source: JRC based on IEA[28] and own work[29].

Box 2. R&I methodology note[30]

Public R&I

The primary source of public R&I data is the IEA [16], which covers 33 countries and the EU. While 20 EU Member States are members of the IEA and are expected to provide national funding figures through the IEA's annual monitoring exercise (AT, BE, CZ, DE, DK, EL, ES, FI, FR, HU, IE, IT, LT, LU, NL, PL, PT, SE, SK) not all of them do so consistently (EL and LU do not report, data for IT are available with a longer lag due to the national collection process).

Until 2023, the JRC was using IEA's dataset in deflated values, reported in national currency and then "inflated" converted first to USD using the OECD annual national currency average exchange rate per USD and subsequently to EUR. As of 2024, JRC uses IEA's dataset in nominal values in national currency, converting to EUR using the OECD annual national currency average exchange rates of the reporting year. As R&I values in nominal prices provide a snapshot of the investments at a certain point in time, this approach prevents discrepancies with future time series, which can be exacerbated by inflation. The difference between these two methods is in the range 0 to 10% for all values reported in previous editions. The following IEA technology codes are used for the CETO technologies:

— Batteries: 1311; 6311; 6319
— Biofuels: 34

28 Adapted from the 2024 spring edition of the IEA energy technology RD&D budgets database, IEA (2024), Paris.

29 JRC SETIS - SET Plan information system Research and Innovation Data

30 For more information on methodology see: - Fiorini, A. et al, Monitoring R&I in Low-Carbon Energy Technologies. JRC104652; - Pasimeni, F. et al, 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 on JRC SETIS Research and Innovation Data

— CCUS: 23
— Distributed heating and cooling networks: 141; 632; 6222
— Geothermal: 35
— Heat pumps: 144
— Hydrogen: 51
— Hydrogen fuel cells: 52
— Hydropower: 36
— Novel energy storage: 6312; 6313; 6314; 6319; 632; 639
— Ocean energy: 33
— Solar energy: 31
— Solar heating and cooling: 311
— Solar PV: 312
— Wind energy: 32

Member States country notes: In 2021 France and Spain made significant revisions to the data collection methodology, to expand coverage. For France this led to increases of 15-28 % over the 2002-2019 data. Spain has not applied the changes retroactively, 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. These changes accounted for an additional EUR 1 billion of R&D investment in 2022. Data for other Member States is collated from multiple sources including the National Energy and Climate Plan Reports[31].

Data on the US**:** The US reported to the IEA for the years 2012-2015. The IEA also estimated values for 2016-2020, but stopped distributing these estimates after the May 2022 update. JRC uses IEA's estimates and, as of 2021, compiles data based on the analysis from the Fletcher School's Climate Policy Lab [17], the database of Gallagher and Anadon[32] and the Congressional Justification of Budget[33] and Congressional Budget Request summary tables [18] of the Department of Energy. However, this data only provides the total budgetary resources and the amount of funding earmarked for the selected fiscal year[34]. As a result, the requested amounts and the final sums enacted by Congress may differ significantly. To track the enacted funding, it may be necessary to review data from two fiscal years prior.

Data on China: Robust information on Chinese R&D investment is not readily available. The OECD has supressed publication of statistics for the country, citing "anomalies" in data reported to the organisation[35], and other sources are difficult to reconcile. The country is reportedly the largest [19] or second largest [20] public R&D investor in the energy domain, albeit with most of its investment still directed to fossil fuel technology, with the share directed to low-carbon research in decline [16]. The most reliable and widely used source for the country's clean energy R&D spending is China's reporting to Mission Innovation (MI) [26,36]; in the context of which China pledged to double clean energy R&D spending between 2015 and 2020. However, China has not reported data to the MI country insights beyond 2019. The data shown here are indicative estimates, based on the existing data from MI, and taking into account the slowing down of the

[31] The Commission's technical assessment of the NECP progress reports SWD(2023) 646 final was part of the 2023 State of the energy union report. The integrated national energy and climate progress reports are available on the CRICABC e-platform.

[32] : Gallagher, K.S. and L.D. Anadon, "DOE Budget Authority for Energy Research, Development, and Demonstration Database," Fletcher School of Law and Diplomacy, Tufts University; Department of Land Economy, University of Cambridge; and Belfer Center for Science and International Affairs, Harvard Kennedy School.

[33] USA spending, Department of Energy (DOE) [Accessed 02-10-2024].

[34] The U.S. government's fiscal year begins on Oct. 1 and ends on Sept. 30.

[35] OECD (2023). Information note for users of OECD R&D statistics: Anomalies in R&D data reported by China requiring comprehensive explanation and potential correction; in Science Business News: A puzzle stumps statisticians: How much does China actually spend on R&D? [published 31 Jul 2023, Accessed 13 Aug 2024]

[36] Low-carbon or clean energy classifications may differ among counties for their participation in Mission Innovation

Chinese economy and reported drop in the share of low-carbon investment in energy R&D. The approach is consistent with the efforts of others, and the estimates provided for the clean energy part of Chinese energy R&D elsewhere [21, 22].

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 and the 2022 estimate for the total expenditure of major economies is based on a 5-year tend. 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 change 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.

2.2.2 Patenting Trends

Filings for the protection of climate change mitigation inventions peaked in 2011 at 12.6 % of all patenting activity [14]. While the scope covered by “climate change mitigation” is quite broad to pinpoint all the drivers, there is enough evidence as to the effect of carbon pricing. To that point, and since the introduction to of the scheme, companies regulated under the EU ETS filled 30% more patents in low-carbon technologies, particularly in renewable energy, energy storage, energy efficiency and carbon sequestration [23].

The share of climate mitigation technology filings has since declined to 9 % of the total in 2020, affecting all clean technologies except for hydrogen and fuel cells and energy storage. Nearly half of these are filings for Chinese inventions only protected domestically. In terms of inventions filling for international protection (otherwise known as high value), 10 % addressed climate change mitigation technologies. South Korea and the EU had the highest shares in their overall patent portfolio with 13 % and 12 %, respectively. In the EU, the US and China, there was a more diverse contribution to green inventions from applicants beyond the top industrial innovators, compared to Japan and South Korea[37].

In parallel to the slow-down of ‘green’ patenting activity, applications for trademarks for related goods and services has grown, increasing their share in all trademarks three-fold in US and Japan, and by four times in Europe, indicating a shift of emphasis to implementation and deployment rather than research and innovation [14].

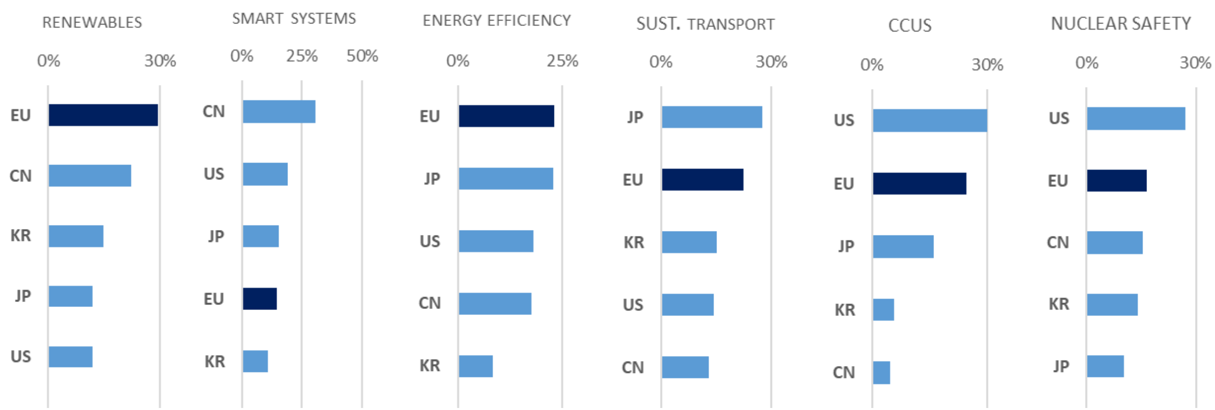
In terms of the global share of high-value patent filings in the Energy Union R&I priorities, the EU maintains a lead for renewables (29 %) and energy efficiency (23 %) and is second behind Japan in sustainable transport and behind the US in CCUS and nuclear safety. Nonetheless, it has not

[37] JRC SETIS for the 2023 EU Industrial R&D Investment Scoreboard, European Commission, JRC/DG R&I.

recovered any ground in smart systems (see Figure 12). Overall Japan has a slight lead over the EU, closely followed by China.

For the period 2010 – 2020, these findings indicate that the EU has consistently maintained specialisation above the global average in renewables, sustainable transport and CCUS; it also has an advantage in a number of technologies (see Figure 13). The SRIP [15] echoes the findings of CETO reports that the EU retains a comparative advantage in green technologies, but falls behind the US and China in digital domains – both overall and when the latter are related to clean technologies. A fifth of the patent filings in climate change mitigation technologies also have a digital aspect [25]. Digitalisation can introduce efficiency and environmental benefits in many processes; conversely, digital solutions may also increase electricity demand and need to be themselves optimised in terms of efficiency. Similar to what is shown in Figure 13, the SRIP finds that the EU shows a specialisation in wind energy, hydrogen and green transportation. It also noted that for some of the technologies currently lagging behind, such as solar, nuclear, hydropower, batteries and geothermal, the potential to specialise would come at a lower cost than other (digital) technologies, as the capabilities needed overlap with those already present in the Member States.

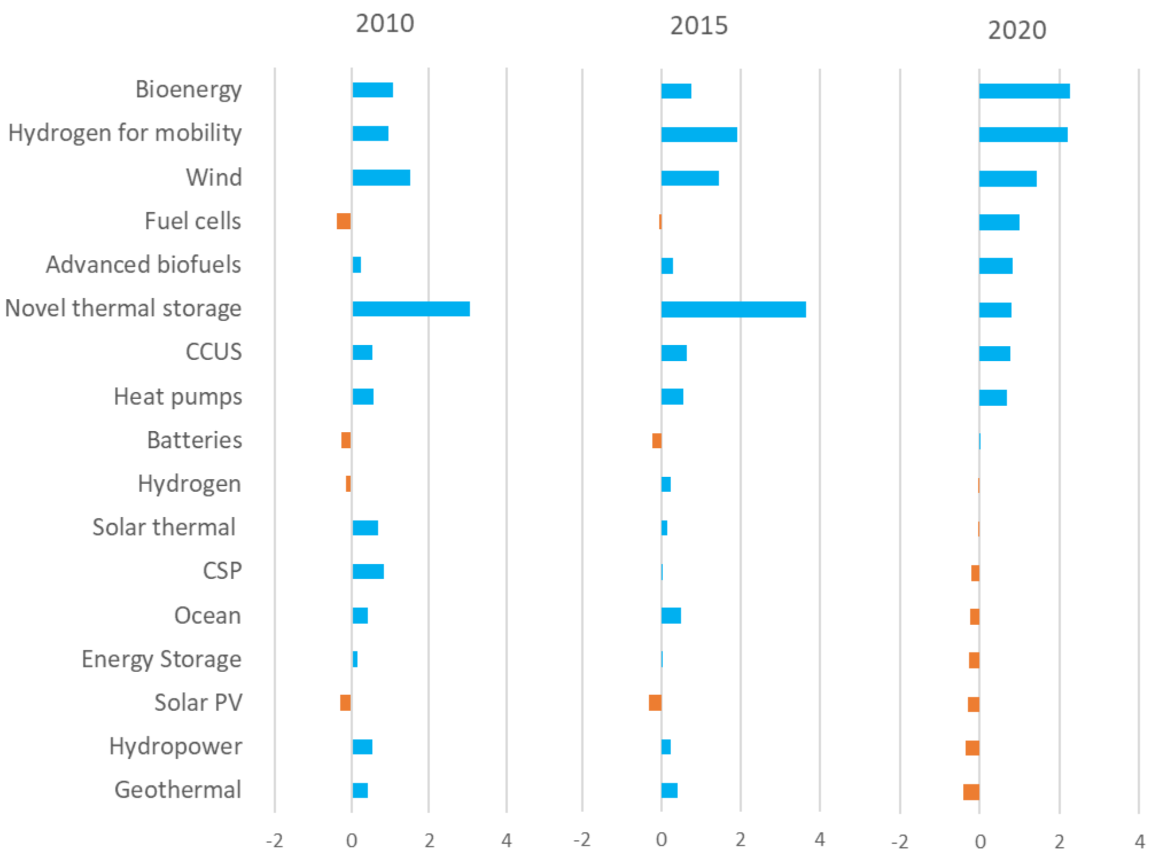
Figure 12. Share in global high-value patent filings relevant to the Energy Union R&I priorities 2018-2020.



Source: JRC based on EPO Patstat[38].

[38] For more information on methodology see: JRC SETIS Research and Innovation Data

Figure 13. Evolution of the EU specialisation index for selected technologies. The specialisation index shows the share of inventions for this technology within the climate change mitigation technologies portfolio for the EU over the same share globally.



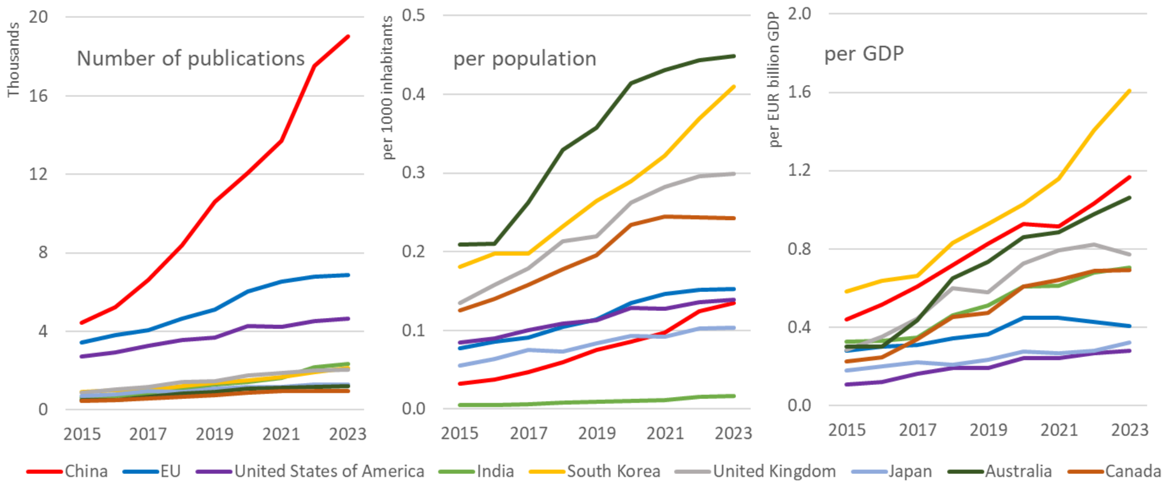
Source: JRC SETIS based on EPO Patstat

2.2.3 Scientific publications

China leads by far in the absolute number of scientific publications in the technologies included in CETO, followed by the EU and the US. The clear lead of these three is not maintained when looking at normalised figures that take population or GDP into account. South Korea performs very well in both normalised indicators. The EU has a lead over the US, China and Japan in terms of scientific output per population, but this is only maintained against the US and Japan in terms of GDP (Figure 14). The EU is third behind the US and China in the H-index ranking, which measures both the productivity and citation impact of publications, despite the fact that the EU share of highly cited publications is not among the highest among the best performing economies (Figure 15).

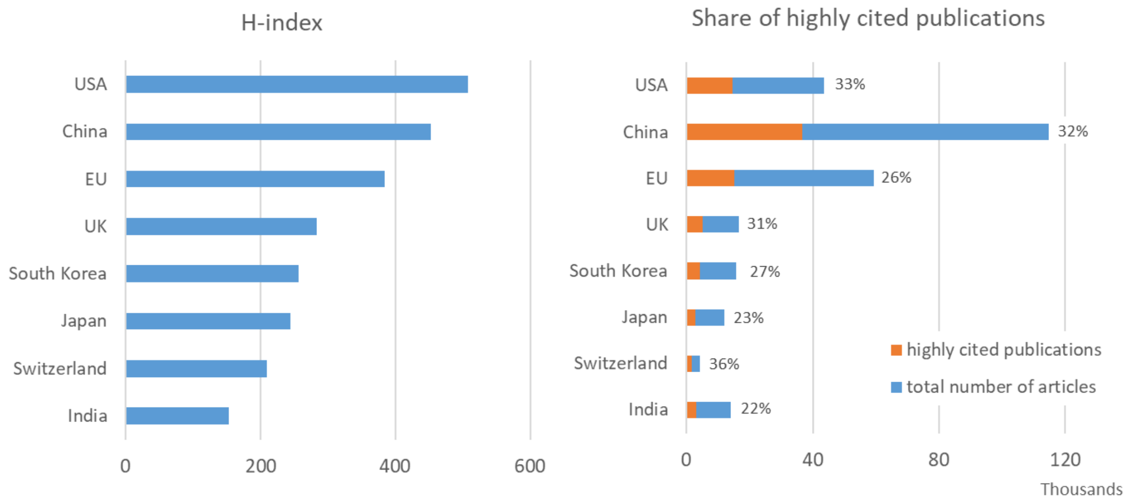
The Member States most prolific in scientific publications are Germany, Italy and Spain (23%, 13% and 12% of the EU total in 2023, respectively), followed by France (9%). This order is also maintained in terms of citation impact for the year 2023.

Figure 14. Top performing countries in scientific publications in the CETO technologies



Source: JRC based on TIM data

Figure 15. H-index and share of highly cited publications in CETO technologies for 2023



Source: JRC based on TIM data

Looking through the lens of Societal Grand Challenges, the 2024 report on the Science, research and innovation performance of the EU [15] found that, in the period 2000-2022, the EU has significantly increased its specialisation on scientific output on smart, green and integrated transport, but was less specialised in publications on secure, clean and efficient energy (energy). While the EU is still more specialised on both topics than the US, its specialisation against China has stagnated in both. Looking at the EU specialisation in scientific output with relation to the Sustainable Development Goals (SDGs), the report finds that the EU leads in SDG 7 (affordable and clean energy). It also finds a positive alignment between the SDG challenges and research priorities for the EU, noting however that this may be linked to historical research specialisation patterns and international research funding trends, rather than a response to the challenges as such.

2.2.4 Venture Capital investment

The funding of start-ups and scale-ups developing and manufacturing clean energy technologies (CET) is key to foster the EU's energy resilience and technological sovereignty, but also to ensure that the EU seizes emerging market opportunities and reaps the benefits of green industrialisation.

In 2023, the tightening of financing conditions negatively affected the global level of venture capital (VC) investment, which fell in the EU (-37 % compared to 2022), the US (-38 %) and China (-32 %). This trend – already seen in 2022 – reflects the fact that fund managers found VC investment less attractive than other investment classes due to high interest rates [13]. According to Clean tech for Europe[39], the contraction of VC investment in the US is *"driven by a cooling off of the US venture investment ecosystem, due to higher interest rates, more pronounced up/down cycles characteristic of the US, and weakened exit opportunities for investors"*. The contraction of VC investment in CET firms in China is in large part due its exposure to the transport domain. In 2023, respective VC investment dropped worldwide [26] and Chinese scale-ups developing and manufacturing electric vehicle and battery technologies did not attract as many large deals as in 2021 and 2022.

As shown in Figure 16, VC investment in CET decreased worldwide to EUR 32.6 billion in 2023 (-25 % compared to 2022). The clean energy domain however accounted for 9 %[40] of the worldwide VC investment total in 2023 - a larger share than any previous year - confirming investors' confidence in CET. Since 2021, the clean energy domain has kept performing better than other VC segments, such as digital or biotechnology, which saw their funding sharply drop in 2023 [13]. This is the case in the EU where the share of CET in the EU VC investment total doubled in 2023 compared to 2022, while it remained the same in the US and slightly decreased in China.

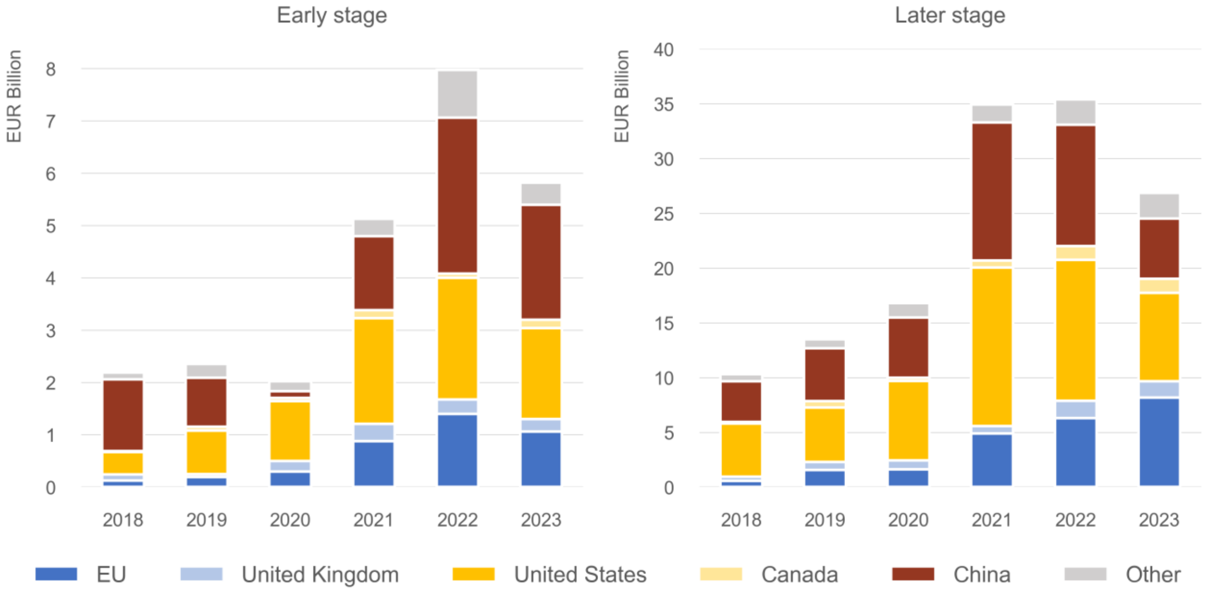
Despite the adverse macroeconomic environment, the EU demonstrated its capacity to attract strategic growth deals, and, among them, the 3 largest CET deals realised worldwide in 2023. Three companies - namely the battery manufacturers Northvolt (SE) and Verkor (FR), and the hydrogen-based steel manufacturer H2 Green Steel (SE) - pushed the boundaries of traditional financing with multi-million deals combining equity, commercial debt and subsidies to finance large-scale manufacturing facilities. Together, they captured 43 % of the VC investment total in CET in the EU.

Those deals drove the growth of VC investment in CET in the EU, which reached EUR 9.2 billion in 2023 (+20 % compared to 2022), boosting the EU's industrial leadership for the manufacturing of battery and green steel technologies. They also confirmed the essential role of public investors in closing large financing gaps and crowding-in other financiers, such as corporate and institutional investors. 2023 also marks the narrowest investment gap between the EU, where the share of CET in the VC investment total increased, and the US and China, where VC investment dropped, as they attracted fewer of the large late-stage deals that fuelled their growth in 2021 and 2022. Thus, the EU accounted for 28 % - a growing share - of global VC investment in CET in 2023 and ranked second between the US (30 %) and China (24 %).

[39] Clean tech for Europe (2024), EU Cleantech – Quarterly briefing Q1 2024, Clean tech for Europe.

[40] Share calculated on a comparable basis, not based on the totality of Venture Capital and Private Equity investment realised in 2023.

Figure 16. Early and later-stage venture capital investment in clean energy tech companies, by location.



Source: JRC elaboration based on PitchBook data (see Box 3 for methodology).

However, this leap forward only marginally improves the overall competitiveness of the EU's CET sector, as it is the result of a few single fundraising successes that shaped the CET sector investment trends over the past years. Northvolt's recent bankruptcy filing[41] serves as a reminder that such exceptional deals remain insufficient to ensure the successful scale-up of industrial companies facing high financing needs and intense global competition. As shown in Figure 17, the US and China remain competitive in mobilising VC investment in energy storage, where EU scale-ups are attracting very large deals, and have attracted most of VC investment across all technology areas. Such fundraising successes need to be replicated over time and across further technologies where start-ups and scale-ups contribute to the growth of manufacturing capacity, and VC investment in the EU is still being outpaced by those in China and in the US.

This is the case in solar PV and electrolyser technologies where China is forging ahead with manufacturing investment[42], resulting in potential overcapacities that can have repercussions for manufacturing investment in the EU. In 2023, Chinese solar PV manufacturers drove a rapid expansion of global production capacity by doubling their investment in new factories compared to 2022. China accounted for 91 % of the 2023 investment total, with the EU accounting for less than 1 %. Similarly, up to two-thirds of investment in new electrolyser factories took place in China. The EU, where planned manufacturing investments in new electrolyser factories are expected to ramp-up in 2024 and 2025, accounted for 25 % of the investment total in 2023.

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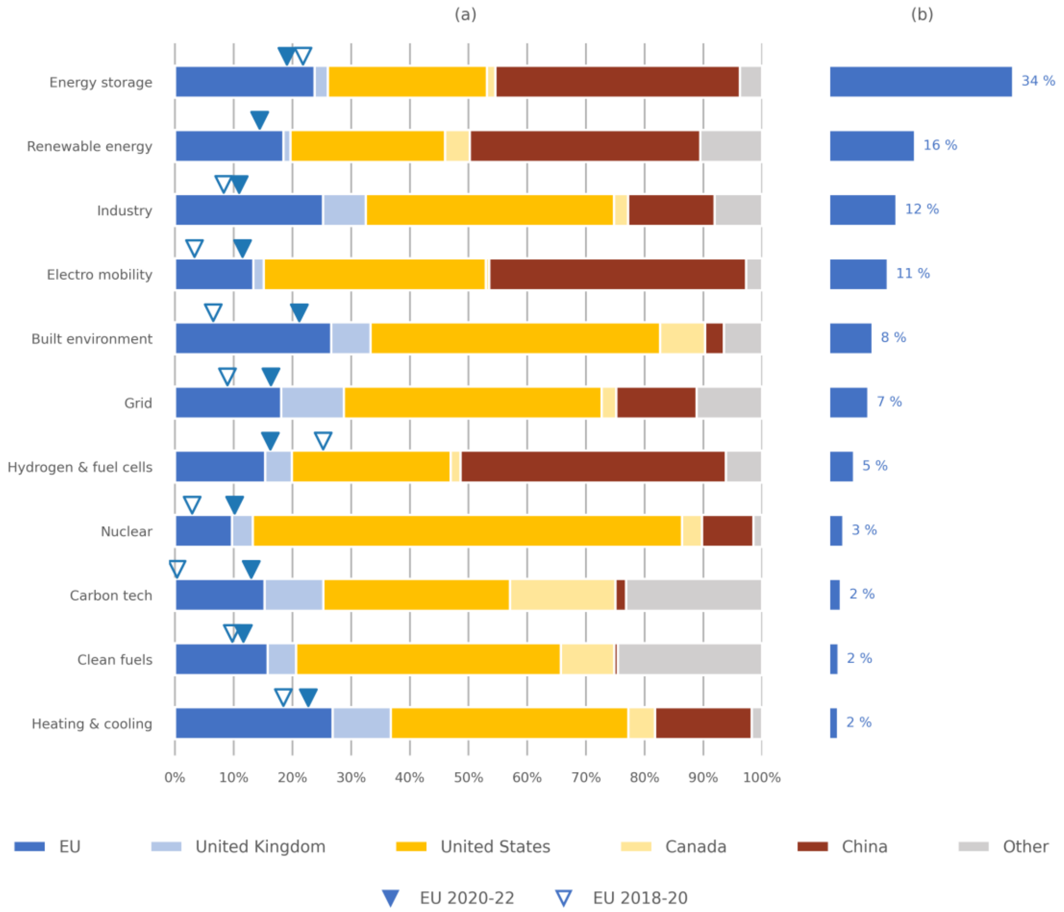
41 Northvolt takes major actions to support and enhance homegrown battery production platform. Northvolt Chapter 11: Court filings and information website. 21 November, 2024

42 Trends on manufacturing investment reported in this paragraph are based on Bloomberg New Energy Finance (BNEF), Energy Transition Investment Trends 2024, and International Energy Agency (IEA, 2024), Advancing Clean Technology Manufacturing. see Box 3 for methodology

Figure 17. VC investment (2021-23) in clean energy tech firms: (a) Share of global investment by region, for a given technology area, and comparison of the EU's share by period, and (b) Share of EU investment by technology area *(i.e. between 2020 and 2022, energy storage accounted for 34 % of VC investment captured by CET companies in the EU).*



Source: JRC elaboration based on PitchBook data (see Box 3 for methodology).

VC investment in solar PV technologies accounted for 40% of the renewable energy VC total worldwide between 2021 and 2023. Solar PV investments grew in the EU, capturing 20% of the total worldwide over 2021-23. However, this mostly benefited solar solution integrators and did not contribute to the development of a domestic solar module production. Nonetheless, in 2024, Enpal (DE) announced its willingness to build a pan-European coalition for the domestic production of solar modules[43]. Over the same period, Chinese firms raised 2.7 times more VC investment than their EU counterparts, most of which benefited scale-ups developing and manufacturing new types of solar cells and modules.

Between 2021 and 2023, the EU also accounted for 15 % of global VC investment in hydrogen technologies. The EU's position has weakened by decreasing VC investment in 2023, and by series of larger deals in Chinese fuel cell manufacturers in 2021 and 2022, and in US electrolyser manufacturers in 2023. In 2023, US start-ups developing electrolyser technologies raised 8 times

43 Enpal builds coalition for solar industry in Europe, Enpal press release, Berlin, 28 February 2024.

more VC funding than their EU competitors, with the aim to scale up their manufacturing capacities, reduce production costs and address overseas markets. Considering the historical position held by EU's hydrogen and fuel cells start-ups and their consistently decreasing share of global VC investment, this reflects poorer access to finance and exit opportunities [27].

North American start-ups traditionally prevail in all other CET and have attracted most of the related VC investment. This is the case for CCUS, concentrated solar power, geothermal, hydropower, nuclear, renewable fuels from non-biological origin and sustainable alternative fuels technologies, for which the EU consistently accounts for low shares of the total VC investment realised worldwide. Those technologies collectively account for less than 2 % of VC investment in CET in the EU between 2021 and 2023.

The EU has however developed a larger base of ventures than the US in bioenergy, EV charging, heat pumps, novel energy storage, ocean, solar thermal, and wind technologies. Together, they account for 11 % (EV charging firms making up half of that) of the 2021-23 VC investment in CET realised in the EU. In 2023, the EU accounted for the largest share of the total realised worldwide (on a par with the US) in each of those technologies. But despite increased investment levels since 2021, EU firms developing those technologies and components still lack the larger deals enabling them to gain a competitive advantage and support the rolling-out of these technologies at scale.

Following the global investment boom of 2021, several CET areas displayed increased and growing level of VC investment in the EU. Energy efficiency start-ups drove the growth of VC investment in the built environment in 2021 and 2022. Green steel deals were behind the growth of VC investment in industry in the EU. Following the hydrogen-based steel producer H2 Green Steel (SE), the American company Boston Metal (Molten Oxide Electrolysis technology) raised the second largest deal in this technology area. This highlights the feasibility and opportunity for CET start-ups to enter an incumbent-driven market, with the development of disruptive technologies that follow different routes to decarbonisation.

The evolution of VC investment in EU CET firms attests to the work undertaken by the EU to mobilise private investors and equity financing. However, access to finance remains a key barrier for most EU innovators developing and manufacturing CET [28].

Unlocking the full potential of the EU's CET entrepreneurial ecosystem requires removing investment barriers and targeting public intervention [29]. Deepening the EU banking and capital markets remains an essential pre-requisite to unlock additional sources of funding, foster cross-border investment and make scale-ups more attractive to investors by improving their exit options. Strategic investment can in turn create directionality and contribute to channel private investment towards clean energy technologies. Enabling strategic investment however requires a project-based approach and leveraging the financial instruments best suited to each clean energy market. It also calls for allocating (e.g. by earmarking public funding) financial support to CET investment at scale and in coordination with EU's industrial strategy.

Entered into force in 2024, the Strategic Technology for Europe Platform regulation will contribute to bolster and channel EU funding to support investment in EU start-ups, SMEs and small mid-caps developing and manufacturing critical CET[44] with (1) an increased endowment of the Innovation Fund to support the demonstration and scale-up of innovative technologies, (2) an expanded EU

[44] OJ L, 2024/795, 29.2.2024. For more information: Strategic Technologies for Europe Platform.

guarantee under InvestEU to further support funds that provide equity financing, and (3) a reinforced envelope for the European Innovation Council (EIC) to allow larger equity investment amounts and follow-up financing rounds in start-ups, but also in SMEs and small mid-caps. To further tackle the EU's scale-up gap, the EIB Group and five EU Member States launched in 2023 the European Tech Champions Initiative, a fund of funds that will invest in large-scale VC funds and channel growth capital to EU innovators[45]. The aim of this initiative is to boost funding for promising high-tech companies that must raise amounts of over EUR 50 million to compete on a global scale whilst staying in the EU.

The Draghi report identifies an underdeveloped VC market as one of the barriers to clean technologies in the EU and calls for stimulating private investments[46]. As the report suggests, scaling-up CET investment entails reinforcing and streamlining EU level budget and putting in place funding schemes to support private and higher-risk investments in innovative companies, for the scaling up of EU strategic companies or long-term transition projects. This could be achieved by increasing the use of public guarantees and other financial instruments to support the clean tech sector, the size of the EU guarantee under the InvestEU programme, and by developing the role of the EIB group.

A wider availability of EU risk sharing instruments[47] such as guarantees could support the industry's clean transition and address market failures by covering technology, adoption, and regulatory risks. The need to deploy public guarantees at scale is further highlighted in the Letta report [30], which calls to "establish a European Green Guarantee through which the Commission and the European Investment Bank can develop an EU-wide scheme of guarantees to support bank landing to green investment projects and companies."

Corporate off-takers that must transition to carbon neutrality also have a specific role to play. They can represent an alternative to traditional VC investors, be strategic partners or venture clients for start-ups, and contribute to de-risk investments in scale-ups by providing more patient capital and VC exit options. In the EU, the collaboration between large industry players and innovative CET start-ups is, however, not effective across all CETs, and, even when corporate off-takers invest in EU CET start-ups, their associated impact is often limited [27]. Moreover, global corporate VC investment in CET start-ups dropped by almost two-fifths in 2023, with automotive companies reducing their investment activity more than other sectors [13].

To ensure that finance flows at the required scale to address the EU's investment gap, clean energy technologies will need to be considered a strategic priority. In this regard, to unlock investments in clean and strategic technologies, President von der Leyen has announced a European Competitiveness Fund within the next multiannual financial framework[48].

[45] For more information see : European Tech Champions Initiative (ETCI)

[46] The future of European competitiveness: Report by Mario Draghi, 2024.

[47] COM(2024) 163 final, Clean transition dialogues - stocktaking communication

[48] Ursula von der Leyen (2024), Europe's choice. Political Guidelines for the next European Commission 2024–2029.

Box 3. Methodology note – Monitoring VC investment in clean energy technologies

The selection of clean energy technology start-ups and scale-ups leverages industry verticals from PitchBook in combination with technology deep dives realised by the JRC for the Clean Energy Technology Observatory and the European Climate Neutral Industry Competitiveness Scoreboard . It focuses on technologies, components and materials relevant for the clean energy transition, and excludes activities related to food systems, agriculture, land use, micro-mobility, shared mobility, autonomous vehicles, and carbon accounting and financial services usually considered under climate technologies.

Venture capital investment consists 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. Venture Capital investment tracks equity raised by start-ups and scale-ups, which can be used for different purposes including research and innovation, development of manufacturing capacity.

Manufacturing investment tracks assets receiving investment financed by debt or equity and owned by any type of manufacturing company.

The supporting dataset encompasses a global selection of 7,628 start-ups and scale-ups, out of which 5,274 have received VC or growth equity funding since 2010. Out of 4,267 early-stage deals completed since 2018, 12 very large early-stage deals (> 400 EUR Million) are re-classified as late-stage deals.

Energy storage, which includes battery and battery recycling technologies, and non-battery storage. Renewable energy includes sources and technologies for renewable energy generation. Electro mobility, which includes technologies relative to powertrains, and air, land and sea vehicles involving battery and hydrogen fuel cells. Industry, which includes low carbon mining, recycling, and alternative routes to materials and to conventional production processes for the manufacturing industry. Built environment, which includes alternatives to conventional construction processes, technologies to improve the energy efficiency of buildings and heat grid technologies. Grid, which includes technologies to improve the efficiency, stability and resilience of electric power grids and to incorporate renewable energy sources, focusing on analytics, management systems and EV charging technologies, but not storage technologies. Hydrogen, which includes renewable hydrogen production, fuel cells and other hydrogen technologies. Nuclear, which includes nuclear fission energy, small modular reactors, nuclear fusion and other nuclear technologies. Carbon tech, which includes carbon capture, utilisation and storage technologies. Clean fuels, which includes the low-carbon fuels other than hydrogen (such as sustainable alternative fuels and renewable fuels from non-biological), waste to-fuel technologies and hardware for the low-carbon use of conventional fuels. Heating & cooling, which includes heat pumps, thermal storage and other heating & cooling technologies.

Differences with previous edition of this report include the transfer of hydrogen production from Clean fuels to Hydrogen & Fuel cells; the addition of air and sea electric vehicles to Electro mobility; the transfer of EV Charging technologies from Electro mobility to Grid; the separation of Industry and Carbon tech into distinct categories.

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

The revision of the Strategic Energy Technology Plan (SET Plan), announced with the 2023 Communication[49], aligns the original SET Plan strategic objectives with the European Green Deal, REPowerEU and NZIA. In addition, the SET Plan continues to play a central role in implementing the research, innovation and competitiveness (RIC) dimension of the National Energy and Climate Plans (NECPs), under the Energy Union Governance Regulation.

In the framework of the NZIA Regulation[50], which entered into force on 29 June 2024, the Commission is setting up the Steering Group (SG) of the SET Plan as a high-level expert group. This formal link under NZIA is expected to provide a momentum for strengthening the bridge between European research, innovation and manufacturing of new innovative technologies. In addition, it is expected to further strengthen the efforts in coordinating a common R&I policy and planning for the key European energy technologies.

The NZIA provides, for the first time, a legal basis for the establishment and operation of the SET Plan SG, which shall be composed of Member States and the Commission. The members of the SET Plan SG shall meet at regular intervals to ensure the effective performance of its tasks and shall be assisted by an executive secretariat of the Commission that provides technical and logistic support. Thus, the SG will continue to ensure alignment between different energy research and innovation programmes at EU and national levels; will advise and recommend action on the RIC dimension of the NECPs; validate the implementation plans of the SET Plan working groups; and take decisions on the accession of new countries and entities that do not belong to the EU/EEA countries to the working groups.

The strengthening of the SET Plan under NZIA is expected to increase cooperation between governments, industry, and research institutes, between public and private investors in developing commercial and tradeable net-zero technologies. This is expected to boost the transition towards a climate neutral energy system in a fast and cost-competitive way.

An example 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[51] (CET Partnership) a multilateral and strategic partnership of national and regional research, development and innovation programmes in Member States and Associated Countries, aiming to boost and accelerate the energy transition and to support the implementation of the SET Plan. 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) have been successfully involved in the strategic design of the topics within the CET Partnership, including co-authoring input papers and contributing to the development of the Strategic Research and Innovation Agenda (SRIA). The collaboration under the CET Partnership is supporting the acceleration of the energy transition in all its dimensions. In addition, it enables joint R&I programmes from regional to national and global

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49 COM(2023) 634 final, on the revision of the Strategic Energy Technology (SET) Plan, Brussels, 20.10.2023

50 Regulation (EU) 2024/1735 of the European Parliament and of the Council of 13 June 2024 on establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem and amending Regulation (EU) 2018/1724

51 See The Clean Energy Transition Partnership

level, co-supported by industry, public organisations, research and citizens' organisations to make Europe a frontrunner in energy innovation.

The European Commission, on behalf of the EU, engages with major international initiatives, like Mission Innovation (MI) and the Clean Energy Ministerial (CEM), to develop together the green energy solutions of the future, solidifying its commitment to global sustainability. The Commission's active involvement in these initiatives strengthens the collective voice of the EU when engaging with international bodies such as the G7 and G20 and the United Nations Framework Convention on Climate Change (UNFCCC), particularly through its Conference of the Parties (COP). This interconnected approach reinforces the EU's external energy engagement strategy[52] and is a valuable platform for advancing global clean energy goals in line with the European Green Deal, the Green Deal Industrial Plan, and the targets set under the Paris Agreement. By aligning its efforts with global frameworks like COP, the Commission ensures that the EU's leadership in clean energy transitions contributes effectively to the broader international objective of achieving net-zero emissions by mid-century.

To accelerate the clean energy transition, substantial investments and actions are required across research, development, demonstration, deployment, and the establishment of supporting frameworks such as policies, standards, and licensing. This transition also demands the extensive scaling up of clean energy solutions across all sectors and society as a whole. CEM and MI play pivotal roles in this process. They facilitate long-term, mutually beneficial collaborations that enhance renewable energy and improve energy efficiency worldwide.

MI has seven Missions – these are public-private innovation alliances focusing on particular strategic areas to help reach tipping points in the cost and scale of clean energy solutions[53]. The Commission is strongly involved in MI, especially through its co-leading role in the Clean Hydrogen Mission and the Urban Transition Mission (see Table 1). The Clean Hydrogen Mission has been launched in June 2021 with the ambition to increase the cost-competitiveness of clean hydrogen by reducing its end-to-end costs to USD 2 per kilogram and by developing at least 100 hydrogen valleys worldwide by 2030. Concerning the Urban Transitions Mission, it aims to empower cities to adopt innovative solutions and achieve cost-effective, scalable urban transitions, with the goal of demonstrating and validating integrated, people-cantered pathways to decarbonisation in 250 cities by 2030.

52 Joint communication EU external energy engagement JOIN(2022)23

53 MI Missions are: Zero-Emission Shipping, Clean Hydrogen, Green Powered Future, Carbon Dioxide Removal, Urban Transitions, Net-Zero Industries and Integrated Biorefineries.

Table 1. EU participation in Mission Innovation 2.0

Missions	Co-Lead	Core Group	Support Group
Zero-emission shipping	Denmark		France, EU, Germany
Clean hydrogen	EU	Austria, Germany, Italy, Finland, Spain, Netherlands	
Green powered future	Italy	Spain	Austria, EU, Germany, Netherlands
Carbon dioxide removal			EU
Urban transitions	EU	Austria, Sweden, Spain	
Net Zero industries	Austria	EU, Finland, Germany	
Integrated biorefineries	Netherlands	EU	
Innovation Platform Collaborate			
International Sustainable Aviation Fuels		Netherlands, EU, Denmark	
Materials for Energy	Germany, EU	Denmark, Italy	
Affordable Heating and Cooling of Buildings		Finland, Netherlands, Sweden	
Innovation Community on Sunlight to X	EU	Denmark, Netherlands, Sweden, Germany, Italy, Spain	

Source: JRC based on Mission Innovation

2.3 Human Capital and Skills

Renewable energy employment[54] continued to grow in 2022 – up by 15 % on 2021 values compared to a 2 % increase for the overall economy[55] - with renewable energy jobs in the EU reaching 1.7 million. The heat pump sector remained the biggest employer among renewable energy technologies (up by 10 %), followed by solar PV which added nearly 130 000 new jobs (55 % growth). After a slump in 2021, employment in the wind sector also increased by nearly 30 % in 2022.

In the broader clean energy sector[56], including e-mobility, energy efficiency and management activities, employment exceeded 2 million in 2021[57]. Approximately a third of these jobs is in the manufacturing segment, which highlights the importance of the manufacturing of net zero technologies and their value chains in the EU.

Previous reports marked an increasing job vacancy rate. However, in 2023, the overall job vacancy rate as well as that of sectors relevant for the energy transition largely eased to nearly pre-pandemic levels (Figure 18). At the end of 2023, the overall vacancy rate in the EU economy was 2.5 %, while it was 1.9 % for the energy supply sector, where the job vacancy rate seems to be more persistent, in that it has not declined proportionally with the other sectors. Manufacturing had

54 Based on EurObserv'ER data. EurObserv'ER, 2024. The state of the renewable energies in Europe – Edition 2023 22nd annual overview barometer EurObserv'ER Report.

55 Based on Eurostat annual labour force survey (LFSA) for all NACE.

56 Eurostat, Environmental goods and services sector accounts [env_ac_egss1]. Clean energy sector contains CEPA1, CREMA13A and CREMA13B. Please see the Methodological note.

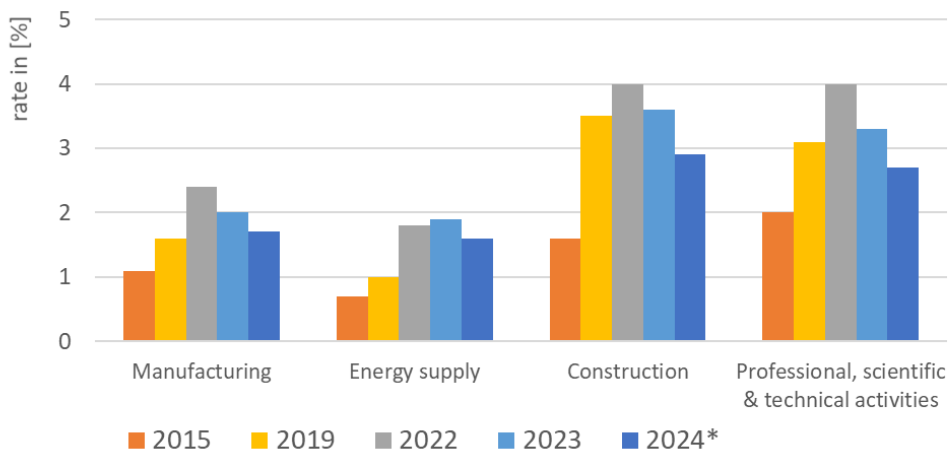
57 idem

a slightly higher rate at 2 %[58]. The decline in the job vacancy rate continued in 2024. The share of companies reporting labour shortages as the main factor limiting their production has also decreased; in the sector manufacturing electric equipment[59] it decreased from 25 % in the third quarter of 2023 to below 20 % in the first quarter of 2024[60] (Figure 19).

As the energy transition unfolds, structural mismatches [31] can lead to persistent shortages in some of the technical skills and occupations, such as installers and repairers of electrical equipment and machinery mechanics [32]. In addition, the electricity sector is among the most affected by the demographic shift (ageing population) [32] and persistent underrepresentation of women. Gender disparities in scientific publications, particularly in STEM fields, also persist [15]. Demand for trained and skilled technicians will remain high, since 75 % of the jobs created by the energy transition will be in these roles [33]. Employee participation in training, which could address some of these needs, while increasing, it is still below the desired levels (Figure 20).

In line with EU level projections, which expect modest net gains in terms of jobs by 2030 [34], Member States expect their energy & climate plans to generate a positive - albeit rather moderate - impact on employment, with the biggest job creation coming from the renovation and energy-efficient building sector. Member States also emphasise the urgent need to manage reallocation of labour across occupations, sectors and regions, including objectives and/or measures on skills as part of their research, innovation and competitiveness policy. This echoes the findings of studies on the economic and social impact of the European Green Deal that range between a slight gain in employment to very moderate losses overall, pointing out however that these changes could be significant at regional or sectoral level [35].

Figure 18. Job vacancy rate[61] for selected sectors in the last quarter (2024 values for the 3rd quarter).



Source: JRC based on Eurostat [jvs_q_nace2]

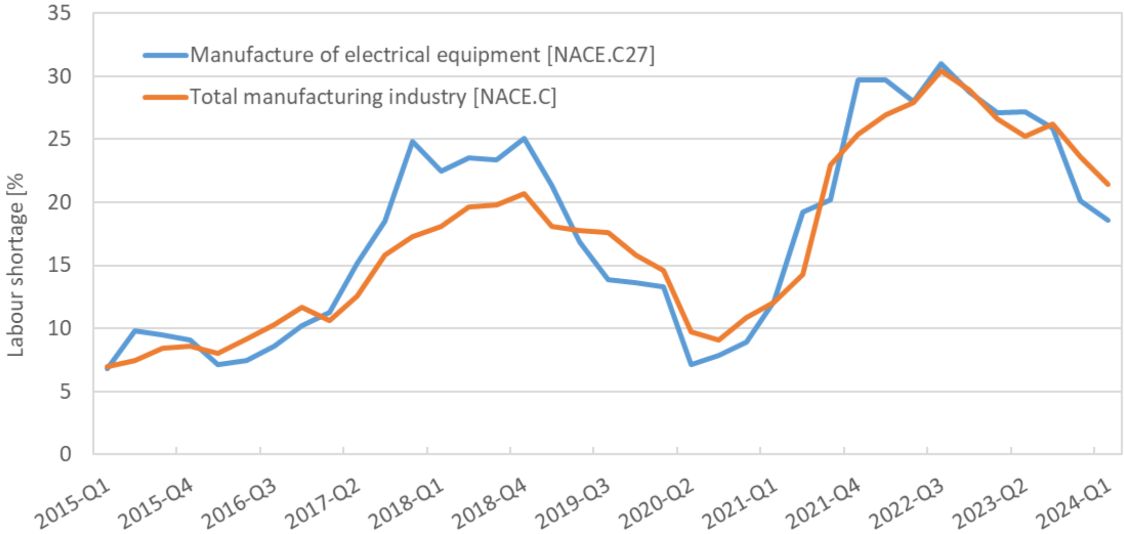
58 Eurostat, News, EURO INDICATORS, Fourth Quarter 2023, 15 March 2024

59 This is used as a proxy of clean energy technology manufacturing

60 DG ECFIN Business and consumer survey database, subsector data

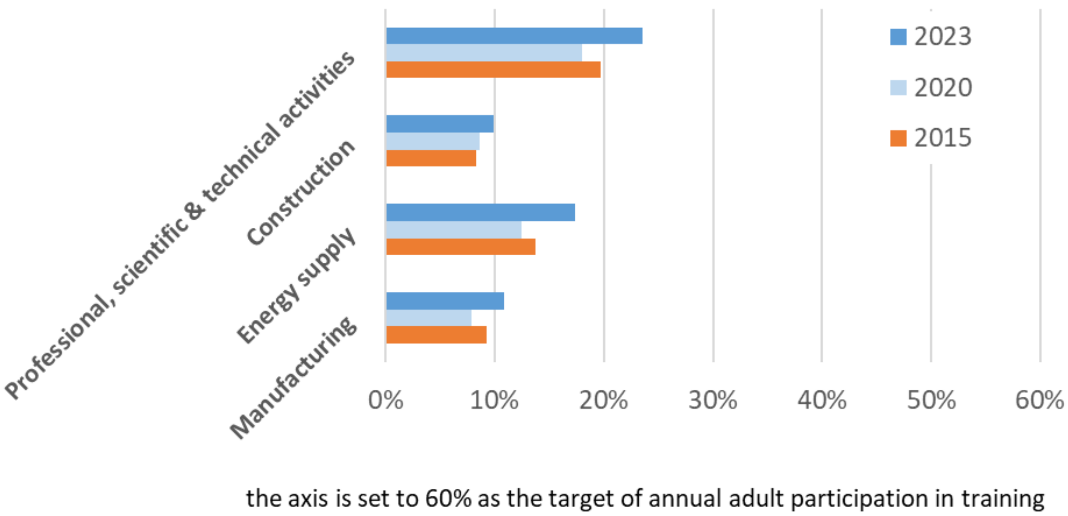
61 Job vacancy rate is the share of job vacancies from the sum of total paid posts and job vacancies.

Figure 19. Labour shortages experienced by EU businesses in manufacture of electrical equipment and total manufacturing industry [%]



Source: JRC based on Business Survey data from DG ECFIN

Figure 20. Employee participation rate [%] in education and training (18-64 years)



Source: JRC based on Eurostat [trng_lfs_08b

The transition from brown to green jobs in the EU, driven by the European Green Deal, is expected to bring about significant sectoral changes in the Member States' labour markets, with important implications for inequality and poverty. As employment in high-pollution sectors decreases and low-pollution sectors grow, there is a risk of increasing economic disparities and rising poverty levels, especially among workers in declining industries. However, Member States tax-benefit systems can potentially largely mitigate these negative effects, as they can be designed to cushion the economic impacts of job losses in high-pollution sectors by providing support to those most affected by the transition. This includes redistributing income and offering social protection that can offset the potential rise in inequality and poverty. Through these mechanisms, tax-benefit systems have a key role to ensure that the green job transition leads to a more balanced and equitable distribution of economic outcomes across the EU, preventing the most vulnerable parts of the population from experiencing the worst effects of this economic shift[62].

Box 4. Human Capital and Skills Methodology Note

Statistical classifications do not delineate the 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 leads to difficulties to consolidate robust employment data and results in 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**' figures are based on data from EurObserv'ER, published annually, including employment, turnover and gross value added, for a set of renewable energy technologies. EurObserv'ER uses a 'follow-the-money' approach, following the investment expenditures per technology, which then generate an 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, the employment effect in reality occurs over several years. Therefore, the model may over- or underestimate figures for a given year depending on the growth trend of the sector. In addition, the modelling uses a set of assumptions, for example, in regard to job intensity. Especially in fast growing technologies, this may evolve faster than the updates to the model. 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.

'NACE 27: Manufacture of electrical equipment' is 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 2021update [COM(2021) 350 final].

'**Clean energy sector**' figures are 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

[62] This evidence has been developed under AMEDI (Assessing and Monitoring Employment and Distributional Impacts of the Green Deal), a joint cooperation between DG EMPL and the JRC.

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.

2.4 Gross Value Added and Labour Productivity

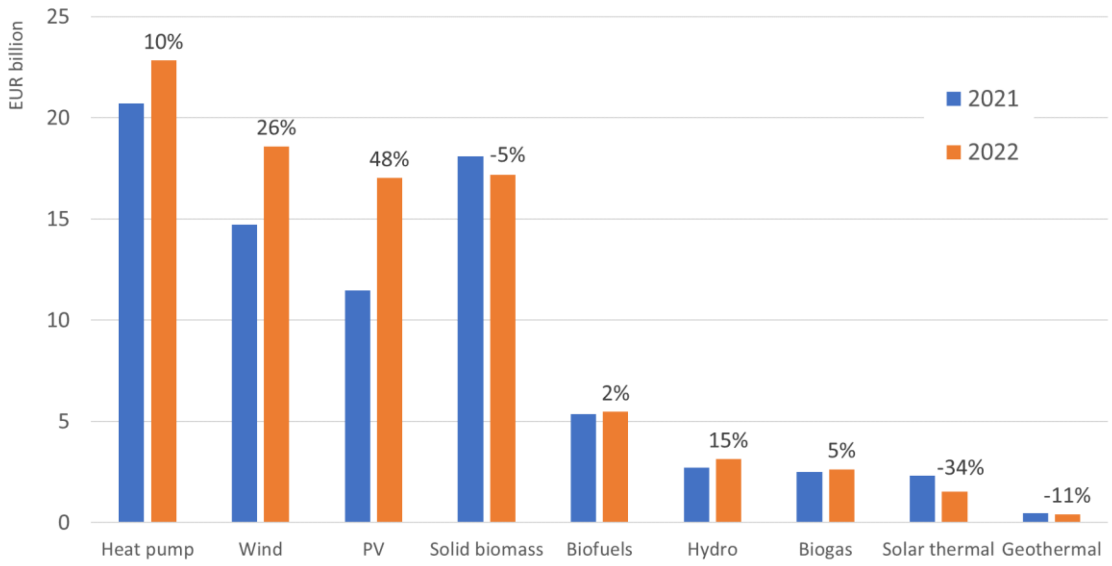
Estimates of gross value added (GVA) in the EU are subject to variations in methodology and data quality/availability. The following refers to the EurObserv'ER analysis for the EU, which calculates direct GVA using the sector's turnover figures and value added/input factors per sector from Eurostat input-output tables. More generally, direct GVA for a specific sector in a country is determined by subtracting the value of intermediate consumption from the value of output.

Similar to 2021, in 2022 renewable energy turnover and gross value added in the EU grew by 13% compared to the previous year reaching EUR 210 billion and EUR 90 billion, respectively [36]. The increase was not uniform across all technologies or Member States (see Figure 22). The heat pumps sector, which accounts for more than a quarter of both indicators saw a 10% increase. PV had the largest gains in both turnover and value added (up by 48% compared to 2021) followed by wind (up by 26% compared to 2021). Solid biofuels which were among the sectors that experienced large growth in 2020-21, saw a slight contraction (down by 5% compared to 2021).

For comparison, the gross value added of the EU economy increased by 10% from 2021 to 2022. As outlined in previous editions of this report, the renewable and broader clean energy sector have often performed better in terms of growth in gross value added than the economy as a whole (Figure 22). Gross value added for the broader clean energy sector stood at EUR 165 billion in 2021, up by 48% compared to 2015, outpacing the overall economy which grew 20% over the same period.

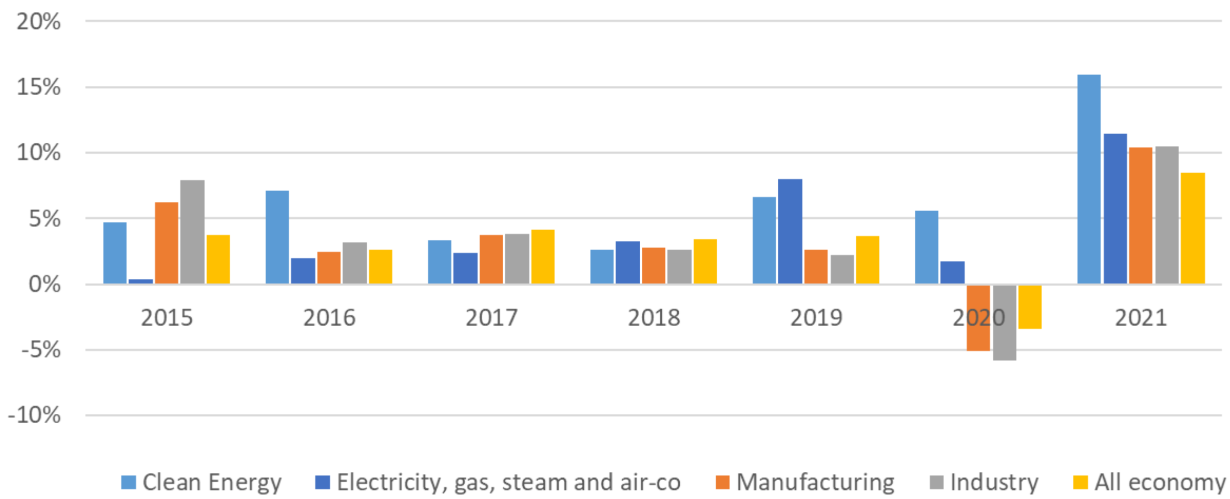
Gross value added has increased at a much faster pace than employment in the clean energy sector, indicating growing labour productivity in terms of gross value added per employee. In 2021 renewable energy has the highest labour productivity at EUR 119 thousand per employee, 44% higher than the average labour productivity in manufacturing and growing faster than the average labour productivity of both the manufacturing sector the overall economy. While, in e-mobility labour productivity is lower than in the renewable energy sector (EUR 77 thousand per employee), it is improving just as fast; both increased by 39% since 2015. The energy and heat management sector has the lowest labour productivity (EUR 65 thousand per employee) and has only increased 16% in the same timeframe. Overall, as (labour) productivity has stagnated in the high-income economies since the 1970s bringing in question the future of innovation-driven growth [37], the clean energy sector seems to be not have reached a plateau yet.

Figure 21. Change in Gross Value Added per renewable energy technology, 2021-2022.



Source: JRC based on EurObserv'ER[63]

Figure 22. Annual change in Gross Value Added for selected sectors and the EU economy, 2015 - 2021.



Source: JRC based on Eurostat[64]

63 Based on EurObserv'ER data. EurObserv'ER, 2024. The state of the renewable energies in Europe – Edition 2023 22nd annual overview barometer EurObserv'ER Report.

64 Eurostat, Environmental goods and services sector accounts [env_ac_egss2] ; Gross value added and income by A*10 industry breakdowns [nama_10_a10] ; National accounts aggregates by industry (up to NACE A*64) [nama_10_a64]

3 Strategic analysis

3.1 Industrial value chains and critical materials

Growth in clean energy technologies continues at a faster rate than that of the economy as whole, as reported in detail in the previous section. Present data encompasses the full value chain, while in principle disaggregation of the various elements is desirable to allow for the analysis of complementarities, and the identification of strategic nuclei, critical individual value chains and cross-cutting elements. Up to now, efforts to do this systematically across a broad range of clean energy technologies using publicly available data (e.g. Eurostat Structural Business Statistics) have not reached a sufficient level of reliability for all main activity segments(research and project development, manufacturing and installation and operation).

On the other hand, the individual CETO technology reports (Annex 1) provide data on the respective clean technology value chains, their breakdown (when available) and their resilience, in particular in regard to the use of critical raw materials. Table 2 provides a summary of this information. The following observations can be made:

- The level of EU manufacturing for a given technology is quite heterogeneous, ranging from high in the case of wind, heat pumps and bioenergy, to low in the case of photovoltaics and batteries.
- The scale-up phase to competitive mass production has proved to be a challenge for several technologies, and non-EU suppliers (particularly China) now dominate. Experience from countries developing new industrial capacity for clean energy technologies, such as USA and India for photovoltaics, indicate that a combination of both financial support and market protection may be necessary.
- Complementarities with existing energy technology manufacturing is advantageous. In areas such as hydrogen electrolysers, biofuels, carbon capture and geothermal, synergies with existing manufacturing processes (or oil & gas drilling in the case of geothermal) can allow established players to accelerate development.
- For some emerging technologies such as ocean or renewable fuels of non-biological origin, where the EU is considered a technology leader, specific efforts may be needed on deployment and to scale-up manufacturing in a coordinated way.
- Technology synergies need to be developed further and made commercially completive, particularly but not only for heating and cooling. In many cases, for both buildings and industrial applications, combinations of renewable energy sources can provide the most efficient solution. It is also essential that the technology options are supported by skilled developers and installers.
- For critical raw materials (CRMs), the data here complements the extensive analyses conducted in recent years, both at EU [38] and international [39] levels[65]. Since CRMs are used to varying degrees in many technologies, an EU materials-specific perspective is

[65] See also JRC Raw Materials Information System

needed to assess needs of clean energy technologies and grid infrastructure, also in relation to other uses.

Finally, it is noted that longer-term challenges to value chains have been addressed in an independent expert study [40] for DG Research and Innovation, to which CETO experts contributed. This study, delivered by RAND Europe, CE Delft and E3-Modelling, assessed the energy security challenges of 17 clean energy value chains now and looking to 2050, and identified 30 research and innovation actions to address them.

Table 2. CETO data summary on EU manufacturing and critical material dependencies

CETO Technology Report	**EU Manufacturing Industry Role**	**Critical materials**
Advanced Biofuels	The EU is the leader for operational, commercial plants for advanced biofuels. Many of the companies involved are also players in the traditional fossil energy business.	The dependence on CRMs is judged to be very low. Common materials include stainless steels and nickel–chromium alloys, depending on operating conditions (pressure, temperature) and working environment. Naturally occurring catalysts (dolomite, olivine, zeolite), alkali and alkaline earth metals are inexpensive and are readily available. Stable metal catalysts (Ni, Ru, Pd, Pt, Rh, Zn, Cu, Al, Co, Cr, Fe based catalysts etc.) show better performance but are costly.
Batteries	Na-ion battery production is scaling up quickly. Chinese companies are most active and the position of the EU is rather weak, with only two companies aiming to start production. Solid state batteries are just starting commercialisation in EV applications. EU players are actively participating in development, but global competition is high. For Li-ion batteries China has significantly strengthened its position. Announced new EU production would put it on track to meet 2030 policy goals, if realised. However, the lithium-iron–phosphate (LFP) chemistry, considered an enabling technology for high penetration renewable energy and also less CRM-intensive, is not in the focus of EU industry, and China has a dominant position.	Li-ion batteries have well-known dependencies on CRMs, notably (but not only) for lithium. Sensitivities depend on chemistry and range from medium for lithium iron phosphate (LFP) to high for lithium nickel cobalt aluminium oxide (Li-NCA) or lithium nickel manganese cobalt (Li-NMC). Solid state batteries are exposed to similar material risks as traditional Li-ion chemistries. Na-ion technology does not require CRMs and generally uses less costly materials.
Biomass	The EU is an industry leader for biomass energy, especially solid biomass and biogas.	Materials for various bioenergy technologies include stainless steels and nickel–chromium alloys, depending on operating conditions. Certain catalysts are needed in relatively small quantities to enhance yield in gasification, hydrothermal liquefaction, gas cleaning, gas shift reactions and cracking reactions. These include natural catalysts (dolomite, olivine, zeolite, etc.), alkali and alkaline earth metals and stable metal catalysts.
CCUS	Market research identified 186 key companies world-wide with activity in CCUS. Out of them, 45 (24%) are European or are active in the field through their European subsidiaries. The USA is leading the way as 42% of the key companies identified are American or are based in the USA.	The main commercially available adsorbents are activated carbons, zeolites, hollow fibres, and alumina. Limestone is also used in carbon capture by calcium looping and oxygen carrier materials used in chemical looping operation include monometallic oxides of nickel, copper, manganese and iron. CO2 transport and storage infrastructure rely heavily on steel.

CETO Technology Report	EU Manufacturing Industry Role	Critical materials
Concentrated Solar Power	Chinese suppliers, engineering companies and finance houses have emerged as major players in the market. Several European companies continue to play a role in international projects, both for plant engineering as well as for specialised solar field components, thermal storage and the power block.	The EU CSP industry is small and not known to use any imported materials with restricted availability. In terms CRMs, CSP plants use copper, potentially also aluminium in structural parts, and rare earths in generators.
Solar Thermal	Globally Chinese manufacturers are in the lead for solar thermal collectors, with several EU companies in the top 20. For solar heat for industrial processes, EU companies are well represented.	For solar thermal systems, the main materials in collectors include copper, aluminium and glass but the quantities are negligible compared to that for other uses.
Geothermal power and direct heat	The industrial position of Europe is seen as reasonably positive, although the EU is underrepresented in companies providing exploration and drilling services.	The main CRM sensitivities come from construction materials and the related alloying elements for steel, aluminium and copper. Geothermal is unique in offering the possibility of extracting materials from the geothermal brine e.g. gold, caesium, rubidium, manganese, zinc, lithium, and high-purity silica.
Heat Pumps	China is currently the leader globally, accounting for more than 35% of total manufacturing capacity, followed by the United States with approximately 25%. Europe's manufacturing capacity makes up 20% of the world capacity. Looking ahead to 2030, based on announced manufacturing capacity, Europe is projected to significantly increase its manufacturing capacity. In 2023, the value of EU heat pump production increased by 30%, to more than EUR 5 billion.	At the macro scale, heat pumps are manufactured from similar raw materials to the boilers they replace. Many components are not specific to heat pumps, and sourcing is closely linked to related sectors such as boiler, air conditioning, and refrigeration manufacturing. Nevertheless, heat pumps are vulnerable to volatility in metals prices and the supply of some components, such as semiconductors and permanent magnets. They contain some strategic raw materials and critical raw materials, from dysprosium with a high supply risk to copper with only a low supply risk.
Hydropower	The JRC database of EU companies active in the hydropower sector includes 524 entries (excluding services e.g. engineering consultancy, hydrological studies). Commercial companies account 85%. These provide significant manufacturing capacity and contribute by almost 50% to the global exports of hydropower equipment.	Hydropower hydraulic and mechanical equipment is typically made of materials, such as steel, concrete, and to a lesser extent copper, and expansion may not be limited by material availability. The equipment generally does not contain materials such as REMs, although variable-speed permanent magnet generators could be an alternative for very low-head hydropower.
Novel storage techs	No detailed manufacturing industry information available for the individual technologies, which include: supercapacitors, superconducting magnetic energy storage, mechanical & flywheel energy storage, liquid air energy storage, compressed air energy storage, gravity energy storage, thermal & sensible thermal energy storage, latent thermal energy storage and thermochemical energy storage.	See individual CETO report for data on individual technologies (see overview Annex 1).

CETO Technology Report	EU Manufacturing Industry Role	Critical materials
Ocean energy	Tidal energy: 41% of the major developers are based in the EU, leading with the Netherlands, France and Ireland. Non-EU players are predominantly based in the UK, Canada, USA and China. Wave energy: 52% of active wave energy companies are located in the EU. Denmark has the highest number of developers, followed by Italy and Sweden. Outside the EU, countries with a large number of wave energy developers are the UK, the USA, Australia, and Norway.	The low uptake of ocean energy so far means that material availability has not been an issue. The main materials present in all devices in different amounts are steel (mainly in the structure and moorings), cement (mainly for foundations and anchor points of the moorings), magnets (for linear generators), copper and iron (mainly for electrical connections and export cables).
RFNBOs	RFNBO production depends on several technologies include hydrogen production using renewables, carbon capture (or nitrogen separation) and fuel synthesis. Large-scale deployment remains still limited.	Regarding fuel synthesis, certain catalysts are needed in relatively small quantities to enhance the yield of desired product or promoting various reactions in fuel synthesis, gas shift reactions, cracking reactions, etc.
Photovoltaics	Almost all leading solar cell and module production companies are Chinese and they dominate PV module shipments. In 2023, China accounted for 87 % of global cell production and 82 % of module production. The respective shares for the EU were 0.3 % for cells and 0.9 % for modules. For inverters, the EU's share of the global market decreased from 23 % in 2019 to 6 % in 2023.	CRMs used in PV in the EU include silicon metal, gallium, and borates while copper, cadmium, selenium, silver, aluminium, indium and tellurium are considered materials with a lower supply risk. However, the highest risk is in the component segment, as EU imports over 90 % of the main components of solar modules, mainly crystalline silicon wafers and solar cells, and electronics for inverters.
Renewable hydrogen water electrolysis	According to Hydrogen Europe, as of September 2023, EU electrolyser manufacturing capacity amounted to about 3.9 GW/y (60% alkaline, 40% PEM and less than 1% solid oxide electrolysis). By 2030, the European manufacturing capacity could reach between 27.8 and 31 GWe/year. China has the largest manufacturing capacity globally with at least 20 GWe/year planned to enter in operation by the end of 2024.	Nickel, manganese, chromium and iron are common materials for all electrolysers. Aluminium, cobalt, copper, lanthanum, molybdenum, natural graphite and zirconium are also used, but to a lesser extent. Other key materials which are more specific for some electrolyser technology can also be identified, such as PGMs for PEM electrolysis and rare earths for SOE. For instance, the corrosive acidic regime employed by the PEM electrolyser, requires the use of precious metal catalysts like iridium for the anode and platinum for the cathode, both of which are imported.
Fuel cells	Japanese, US and South Korean companies dominate fuel cell system and component manufacturing. Nonetheless, in Europe several companies are producing fuel cell components and are setting up or expanding their manufacturing capacities for components, stacks and systems.	18 out of 24 materials needed for PEMFC and SOFC production are CRMs. 97% are imported. For several of these China leads in the production, e.g. cerium (100 %), yttrium (100 %), lanthanum (over 85 %), gadolinium (over 85 %), and natural graphite (65 %).
Wind	In 2023 Chinese OEMs dominated the global onshore market, holding 63% of the share, followed by European OEMs at 27% and American OEMs at 7%. In contrast, European OEMs lead the global offshore market, capturing 58% of the total due to the prominence of Vestas and Siemens. EU companies remain the largest suppliers of the domestic EU market.	Dependencies on supply of dysprosium, neodymium, praseodymium, terbium, niobium, borate, silicon, chromium, manganese, molybdenum, aluminium, iron ore, nickel, silica sand, copper, zinc, aggregates, lead, gadolinium, balsa wood

CETO Technology Report	EU Manufacturing Industry Role	Critical materials
	In terms of components, the EU holds 12% of the global manufacturing capacity for blades and 15% of that for nacelles	

Source: CETO reports 2024 (see references and links in Annex 1)

3.2 Sustainability

3.2.1 CETO sustainability assessment framework

The clean energy technologies at the heart of the EU's European Green Deal need to be sustainable in terms of their environmental, social, and economic performance. To provide a structured process for collecting data on the individual technologies, JRC has developed an assessment framework for clean energy technologies, building on sustainability principles, life cycle assessment, sustainable innovation, and energy-specific concepts [41]. The framework has three overall dimensions:

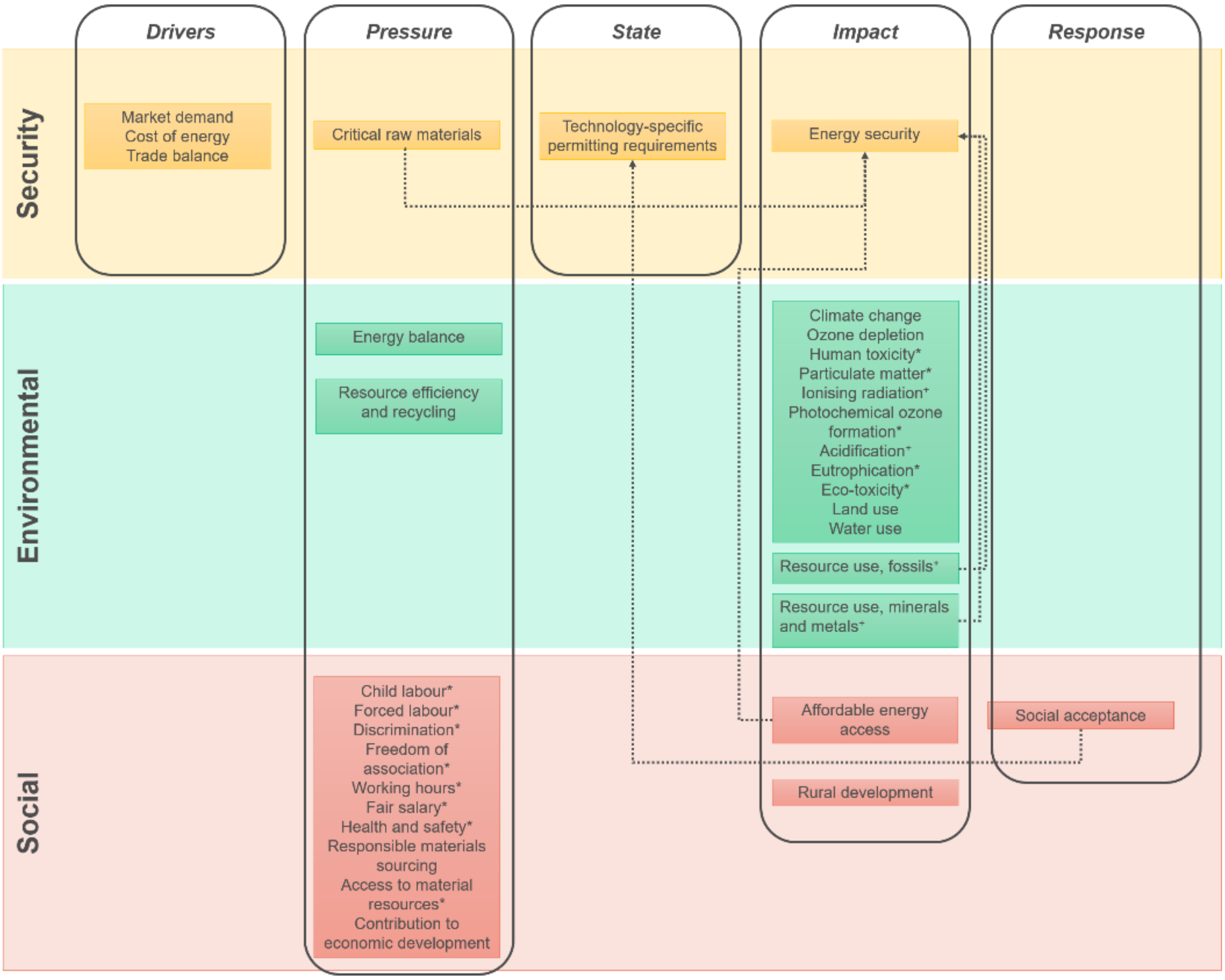
1. Energy security, encompassing economic aspects, such as stable energy supply, accessibility of resources, and trade considerations.
2. Environmental sustainability, based on the Product Environmental Footprint methodology (and the relevant EU legislation when available).
3. Social sustainability, considering impacts on workers, local communities, value chain actors and society, according to Social Life Cycle Assessment methodology.

The hierarchical structure places energy security as the first step, while recognizing its interconnections with environmental and social objectives. Figure 23 shows the overall framework structure based on the Driver – Pressure – State – Impact – Response (DPSIR) principles, identifying the sustainability "aspects" to be evaluated. This analysis is done for each technology in tabular form, where the following attributes are assessed for each aspect:

- Method: suggested impact assessment method
- Indicator: available indicators for the assessment of the aspect
- Tools/ Databases: available data sources and tools
- Assessment: reported data on the indicator and/or reference values
- Additional insights: other relevant information

In 2024 pilot assessments have been made for three technologies: batteries, photovoltaics and geothermal power and heat. The details are available in the respective reports (see Annex 1 for the links).

Figure 23. Overall structure of the sustainability framework with the individual aspects from the security, environmental and social dimensions organized based on the DPSIR approach. The arrows show how specific social and environmental aspects can also influence energy security.



Source: JRC elaboration

The social aspects continue to remain the biggest challenge for evaluation. On the one hand, recent policy developments underline the relevance of this dimension. The new Directive on corporate sustainability due diligence (Directive 2024/1760) includes rules to ensure that companies in scope identify and address adverse human rights and environmental impacts of their actions inside and outside Europe. . The new EU Forced Labour Regulation[66] on prohibiting products made with forced labour on the Union market will impact businesses starting from the end of 2027.

On the other hand, there are practical issues to identifying appropriate methods and indicators for the individual aspects specified in the framework. These are largely taken from social LCA methodology: child labour, forced labour, equal opportunities / discrimination, freedom of association and collective bargaining, working hours, fair salary, health and safety, responsible materials sourcing and access to material resources (incl. water, land, food) and contribution to economic development (including employment). A type I method is foreseen, that aims at assessing the social performance or

[66] Regulation (EU) 2024/3015 of the European Parliament and of the Council of 27 November 2024 on prohibiting products made with forced labour on the Union market and amending Directive (EU) 2019/1937

social risk of the system under investigation using a reference scale (type II focuses the analysis on organisations). Approaches are available for some specific components (such as batteries), but less guidance is available for technology systems containing a range of components (such as PV or geothermal systems), as only quite general indicators are available and reference scales require development. For the other three social aspects in the framework (affordable energy access, public acceptance and rural development) technology-specific indicators were not available, and a purely qualitative approach was used.

3.2.2 Cross-technology perspective: climate change (carbon footprint)

One of the reasons for developing a common sustainability assessment framework is to facilitate cross-technology assessments. Here carbon footprint is taken as an example case, as it represents a fundamental parameter for the EU's policy for climate neutrality by 2050 and has direct implications for the future expansion of policies such as the Carbon Border Adjustment Mechanism. Clean energy technologies are at the heart of this policy, and by definition comply with 100g CO2/kWh life-cycle emission threshold in the EU Taxonomy Regulation and its implementing acts. However, understanding the carbon footprint is fundamental to the development of policies aimed at making clean technology more competitive and sustainable in the future.

Several EU laws already include more rigorous mandatory thresholds on carbon footprint, such as the 2023 Battery Regulation[67]. Furthermore, the European Commission has proposed the Product Environmental Footprint (PEF) method[68] as a common way of measuring environmental performance, using Life Cycle Assessment (LCA) techniques to quantify the impacts of products. Product-specific Environmental Footprint Category Rules (PEFCR) have been developed for several products, including energy-related ones, to improve the reproducibility, comparability, and verifiability of results. PEFCRs however need to be regularly updated to reflect market developments, new data and methodological developments. A new Commission recommendation on environmental footprint methods is foreseen for 2025.

In the annual CETO technology reports, the intention is to take a snapshot of the state-of-the-art methods and reference values per technology. **Table 3** summarises these findings, where the indicator is typically carbon footprint or global warming potential (GWP100) expressed as gCO2eq/kWh. Analysing the data leads to the following observations:

- At technology system level, LCA is applied, although the methods and scope applied vary widely. It is not clear to what extent these are compliant with the current PEF guidelines. For some technologies, consensus reference methods and inventories have been established by stakeholder groups. For example, for photovoltaics, an IEA technology cooperation programme (PVPS), has published a benchmark LCA analysis. In the case of geothermal power, the EU GEOENVI project developed a simplified LCA method for addressing environmental impact. The European Platform on Life cycle Assessment also offers references methods and data (through the International Life Cycle Data Network).

[67] *Regulation (EU) 2023/1542 concerning batteries and waste batteries, Article 7*

[68] C(2021) 9332 final Commission Recommendation on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations

— Only batteries currently use a PEFCR methodology. A PEFCR for photovoltaic modules was developed, but its validity has since expired. Indeed, this product has seen rapid changes in technology and material usage, a factor which highlights the need to regularly update methods and inventories to take account of the innovation process.

— Renewable fuels (bio-based and those of non-biological origin) represent a distinct category as they must comply with EU law on environmental sustainability as set under the Renewables Directive (most recently RED-III, 2024) and its implementing acts. This covers biofuels, biomass, biogas and other bioenergy forms. Renewable fuels of non-biological must also comply with relevant RED-III requirements for alternative renewable transport fuels. Direct solar fuels would also fall in this category.

— Hydrogen produced using renewable energy is treated separately in EU legislation, with a taxonomy threshold of 3 $kgCO_2/kgH_2$. In LCA analysis, transport to point of use (if different form that of production) may also need to be taken into account.

— System and component approaches.

For future CETO reporting, it may be beneficial to complement legal requirements with data from LCA assessment, clarifying the boundaries used.

Table 3. Collation of data on the climate change aspect for the CETO technologies, summarised from the data provided in the respective reports (references in Annex 1).

Technology	Approach	Typical Assessment (see relevant CETO report)	Additional Information
Advanced Biofuels	RED-III (default values per product or product specific calculation by the defined methodology)	Default values range from 5.2 to 30.4 g CO_2eq/MJ	Depends heavily on the product and feedstock
Batteries	PEFCR	0.42 kg CO_2eq./kWh (e-mobility Li-ion batteries)	Excludes end-use phase Values under revision for the proposed battery regulation NB this value refers to the battery capacity, not the electricity discharged.
Biomass	RED-III default values per product or product specific calculation by the defined methodology	See default values	Depends heavily on the product and feedstock
CCUS	LCA	Not available	Carbon footprint relevant to a full system (e.g. BECCS) rather than the CCUS processes themselves
Solar Thermal	LCA	CSP: <= 40 gCO_2eqv/kWh	Need to clarify how CO_2 releases during site preparation are taken into account.
		Solar thermal heating Flat plate collector: 23.8 gCO_2eqv/kWh; vacuum tube collector 22.2 gCO_2eqv/kWh [xx]	Solar thermal heating/cooling systems must comply with Ecodesign Regulation requirements for space heaters and domestic hot water

Technology	Approach	Typical Assessment (see relevant CETO report)	Additional Information
Direct Solar Fuels	LCA NB subject to RED-III requirements for RFNBOs	Not available	No commercial products available yet
Geothermal power and direct heat	LCA (No regulated method or inventory) LCA tool available from EU project	Electricity: 190 gCO2e/kWhe CHP electricity: 5 to 898 gCO2e/kWhth, CHP heat: 3 to 723 gCO2e/kWhth	Average values from meta-analysis of LCAs reported in the literature
Heat Pumps	LCA HPs required to comply with Ecodesign Regulation requirements for space heaters and domestic hot water	average CO2 emission value of 0.11 kg CO2/kWh over the operation lifetime (JRC analysis of relevant sources)	The use phase (gas or electricity consumption) dominates its life-cycle emissions, followed by refrigerant.
Hydropower	LCA (No regulated method or inventory)	24 gCO_2-eq/kWh (IPCC)	Recent studies suggest much lower values for large plants > 5 MW (CETO hydropower report)
Novel storage techs	LCA	Not available	diverse technology group, requiring specific analysis for each option
Ocean energy	LCA	10-106 g CO2eq/kWh [42]	main impacts are from raw material extraction for structural components, manufacturing devices, energy consumption and mooring foundations
RFNBOs (other)-	RED-III requirements for alternative renewable transport fuels, including RFNBOs	Product dependent	Regulation (EU) 2023/851 for CO_2 emission performance standards for cars and vans potentially depicted a new scenario for RFNBO and advanced biofuels beyond 2035, making them a decarbonisation solution only for those sectors where electrification is challenging, such as aviation and maritime.
Photovoltaics	Systems: LCA (No regulated method or inventory)	42.5 gCO_2/kWh [43]	Ground mounted system with cSi modules Lower values possible for systems using CdTE and CIGS thin film
	Modules: LCA (No regulated method or inventory) NB A PEFCR issued in 2017 is no longer valid	13 and 30 gCO_{2eq}/kWh [43]	New methodology included in the proposed Ecodesign Regulation for PV modules
Renewable hydrogen water electrolysis	EU Taxonomy threshold of 3 $kgCO_2/kgH_2$	5±1 to 11±5 kg CO2e/kg H2 (GWP100), 12-33 kg CO2e/kg H2 over 20 years (GWP20) [45],	Includes the effect of H2 losses Results subject to a very high level of uncertainty 2024 Nature article cites median 2.9 kg CO2e /kg H2

Technology	Approach	Typical Assessment (see relevant CETO report)	Additional Information
			1,000 km transport via pipeline 4.4 kg CO_2e /kg H_2 liquid hydrogen shipping 4.7 kg CO_2e /kg H_2 [46]
Fuel Cells	LCA (No regulated method or inventory)	Not available	Manufacturing phase provides the main impact Use phase: depends on the fuel: natural gas or hydrogen
Wind	LCA (No regulated method or inventory)	*Onshore wind values:* *MIN: 4.4 gCO_2eq/kWh* *MAX: 12.2 gCO_2eq/kWh;* *AVERAGE: 7.4 gCO_2eq/kWh* Offshore wind values: *MIN: 8 gCO_2eq/kWh;* *MAX: 32 gCO_2eq/kWh; AVERAGE: 17 gCO_2eq/kWh*	JRC literature review based on manufacturers LCA, environmental product declarations and case studies from scientific literature

Source: JRC elaboration 2024

3.3 SWOT analysis

Table 4 shows the strength-weakness-opportunity-threat (SWOT) analysis for competitiveness, technology independence and sustainability, updated from earlier reports.

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

Strengths	Weaknesses
— R&I: strong public funding, high-standing of the EU research community, impactful coordination (SET Plan): leader on high value patents and scientific output — Strong production equipment industry for some technologies — World-leading project development capability — Key player in international standards for clean tech — Advanced sustainability framework (taxonomy, circular economy, social justice, forced labour regulation, biodiversity etc.) — EU re-cycling technology and capacities	— High energy costs for manufacturing — Slow manufacturing scale-up, lack of funding for first-of-a-kind plants — External dependencies for many components and critical raw materials — Skilled workers shortages and gender-imbalance for STEM fields — Lower private R&I funding compared to main competitors — Digital intelligence for grids, smart cities etc
Opportunities	**Threats**
— Large and growing EU and global markets — Security of supply concerns driving green investments — Demand for sustainable and circular economy solutions — More pro-active industrial policies under the Clean Industrial Deal strategy — Steadily growing VC and competitive VC ecosystems (PV, heat pumps, grids)	— Falling behind in R&I — Loss of IPR; ineffective IPR protection — Divergent Member State policies and/or investment uncertainties — Subsidised international competition; the "uneven playing field" — Lower cost technology solutions from international competitors — Unfavourable geopolitical developments and related supply risks — Squeeze-out of some developing technologies — Social imbalances for potential benefits of clean technologies — Gender disparities in industry, research and education

Source: JRC analysis 2024

4 Conclusions

This report provides an updated strategic analysis of the EU clean energy technology sector, complementing the individual CETO technology and system integration reports. The main findings are as follows:

- In 2022, final energy consumption and energy intensity decreased, after increases in 2021 linked to the post-Covid-19 recovery. However, there was no progress on import dependency and GHG intensity for energy. Both increased in 2022 in comparison to the year before, with import dependency rising to 64.4 % from 57.1 %, while the GHG intensity of energy increased by 3.3 %.
- The EU renewable share in gross final energy consumption rose to 24.5% in 2023. The share of renewables in gross electricity consumption increased by 3.5 to 44.7 % EU. However, progress will need to continue to accelerate to meet future targets. In parallel, the EU's electrification rate (26%) needs to start increasing. This value has remained almost unchanged over the decade leading to 2023 and suggests that decarbonisation of the transport and heating sectors is still at an early stage.
- The analysis of levelised cost of electricity per country and technology in 2023 confirmed that wind, solar and hydropower continue to be the most cost competitive technologies, while CCGT became the most competitive thermal technology. .
- The EU renewable energy industry saw continued growth in turnover and gross value added in 2023, outperforming the overall economy. The manufacturing production value of clean energy technologies reached approximately EUR 80 billion, but only batteries, heat pumps and fuel cells saw significant growth, while bioenergy, PV and hydrogen electrolyser production declined by 10% or more compared to 2022. The overall trade deficit persisted in 2023, driven by high imports of the solar PV and batteries. The wind and district heating sectors had positive trade balances.
- Public investment in clean energy R&I is increasing, but not fast enough: The EU has been increasing its public investment in research and innovation (R&I) for clean energy technologies, with a 23% increase in 2022 compared to 2021. However, the share of clean energy R&I in overall energy research is stagnating, and the EU still lags behind other major economies in terms of private R&I investment.
- Private investment provides the majority of R&I funding for clean energy technologies, but the EU faces challenges in mobilizing sufficient private investment, particularly in areas such as solar PV and electrolyser technologies, where China is advancing rapidly. The EU needs to attract more strategic growth deals and improve access to finance for its clean energy start-ups and scale-ups.
- The EU has strengths in certain clean energy technologies, but needs to improve in others: The EU has a lead in scientific output on smart, green, and integrated transport, and is specialized in technologies such as wind energy, hydrogen, and green transportation. However, it lags behind the US and China in digital domains and needs to improve its specialisation in areas such as solar, nuclear, hydropower, batteries, and geothermal.

- Unlocking the potential of the EU's clean energy entrepreneurial ecosystem requires targeted public intervention: To mobilize private investors and equity financing, the EU needs to deepen its banking and capital markets, improve exit options for scale-ups, and allocate financial support to clean energy technologies. The EU's Strategic Technology for Europe Platform regulation, the European Tech Champions Initiative, and the proposed European Green Guarantee are steps in the right direction, but more needs to be done to address the EU's scale-up gap and unlock investments in clean energy technologies.
- Employment in the renewable energy sector reached 1.7 million in 2022, growing at a faster rate than the economy as a whole, and driven by the heat pump and solar PV sectors. The clean energy sector has the potential to continue to create medium-skilled jobs, but in many areas there are shortages for specific profiles. For manufacturing, the current market remains challenging. Labour productivity was EUR 119 thousand per employee in 2021, 44% higher than the average in manufacturing and growing faster than that of the economy as a whole.
- Up to now efforts to develop a common methodology to disaggregate the key socio-economic parameters of clean technology value chains have not reached a sufficient level of reliability. Nonetheless the data gathered in the individual CETO reports provides useful insights regarding the challenges to scale-up of manufacturing and of the need to exploit synergies between technologies, in particular in regard to hybridised deployment solutions. The electric grid and heating and cooling networks will play a key enabling role.
- CETO applied a new sustainability assessment framework for clean energy technologies, with energy security, environmental and social sustainability as the main overall dimensions. The cross-technology comparison for global warming potential (GHG emissions) illustrates a range of approaches and analysis boundaries, ranging from fully regulated methods (biofuels under the RED-III directive), prescribed component-specific methods (product environmental footprint category rules for batteries), to more self-defined LCA approaches. With the foreseen increased use of the carbon accounting in legislation, further efforts are needed to create a harmonised basis for comparing results for different clean energy technologies.

Lastly, the studies and analyses performed for CETO in 2024 have again underlined the need to improve the quality and timeliness of publicly available data for clean energy technology sector, in particular regarding investments, the industrial value chain and socio-environmental aspects. This can bring benefits to policy makers, prospective investors and sector participants.

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List of abbreviations and definitions

Item	Definition
CEAP	Circular economy action plan
CET	Clean Energy Technology
CETP	Clean Energy Transition Partnership
CPC	common patent classification
CRMA	Critical Raw Materials Act
DHCN	District heating and cooling networks
ESG	Environmental and social governance
ETS	Emission Trading System
FiT	feed-in tariff
FOAK	First–of-a-Kind
GW	Giga Watt
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 (EUR/MWh)
LCoH	levelised cost of heat (EUR/MWh)
MENA	Middle East and North Africa
MS	[EU] Member State
NZIA	Net-Zero Industry Act
OCGT	Open cycle gas turbine
OEM	Original equipment manufacturer
O&M	Operations and maintenance
PEFCR	Product environmental footprint category rule
PEMFC	Proton exchange membrane fuel cell

Item	Definition
PPA	power purchase agreement
PV	photovoltaic
RED	renewable energy directive
RES	Renewable Energy Source
R&I	Research and innovation
SDG	[United Nations] sustainable development goal
SET-Plan	[EU] Strategic Energy Technology Plan
SG	Steering Group [of the SET-Plan]
SOFC	Solid oxide fuel cell
SRIP	[EU] Science, research and innovation performance
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 2024

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

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