Assessment of the competitiveness of clean energy technologies

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Final Report

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List of abbreviations

A-CAES	Adiabatic compressed air energy storage
AEM	Anion exchange membrane
AWE	Alkaline water electrolysis
CAGR	Compound annual growth rate
CCUS	Carbon capture, utilisation and storage
CETO	Clean Energy Technology Observatory
CINEA	European Climate, Infrastructure and Environment Executive Agency
CPR	Progress Report on Competitiveness of Clean Energy Technologies
CSP	Concentrated solar power
DG ENER	Directorate-General for Energy of the European Commission
EBA	European Biogas Association
EEA	European Economic Area
EU	European Union
FID	Financial Investment Decision
GVA	Gross value added
GW	Gigawatt
GWh	Gigawatt hour
IEA	International Energy Agency
ISCC	International Sustainability & Carbon Certification
JRC	Joint Research Centre
LAES	Liquid air energy storage
LNG	Liquified natural gas
MW	Megawatt
MSTES	Molten salt thermal energy storage
NACE	Statistical Classification of Economic Activities in the European Community
OTEC	Ocean thermal energy conversion
PEM	Proton exchange membrane

Prodcom	PRODuction COMmunautaire (Community production)
PV	Photovoltaic energy
RFNBO	Renewable fuels of non-biological origin
SBS	Official Structural Business Statistics
SOEC	Solid oxide electrolysis cells
TRL	Technology Readiness Level
TWh	Terawatt hour

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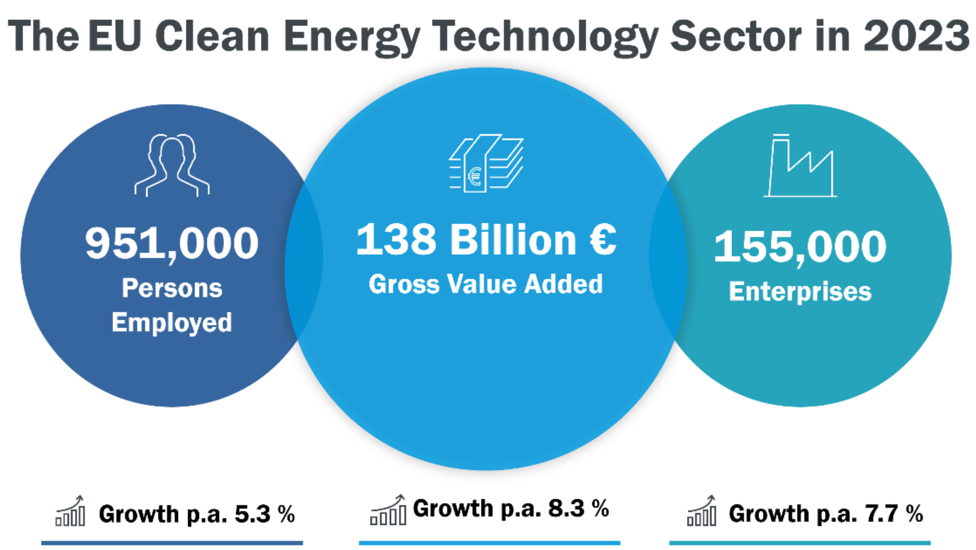
Executive summary

This report contributes to the assessment of the competitiveness of clean energy technology by presenting the key results of an analytic study and model based on publicly available data sources.

Since 2010, the clean energy technology sector in the EU has grown substantially – In terms of direct employment, gross value added (GVA) and number of enterprises. In 2023 around 951,000 persons were directly employed in 155,000 enterprises, generating a gross value added of EUR 138 billion. The gross value added of the sector grew at an annual rate of 8.3%.

In recent years however, the EU's competitive position in clean energy technologies has come under increasing pressure from other regions. At the same time, as also emphasised in the Draghi report,[1] the pronounced global trend towards decarbonisation presents significant opportunities for the EU's clean tech sector. Securing a strong European competitive position in the growing global clean energy technology markets offers economic and employment opportunities to Europe, while also supporting the objective of achieving climate neutrality by 2050 – an ambition first outlined in the European Green Deal of 2019. Reflecting this, the Clean Industrial Deal of February 2025 supports both the goal of securing competitiveness as a driver of growth, and decarbonisation towards the 2050 climate neutrality target. Clean tech is one of the two focal sectors under the Clean Industrial Deal.[2]

Figure 1 Comparison of economic metrics for the EU clean energy technology sector in 2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) for the period 2010–2023. The results are presented as nominal values, reflecting the respective annual price level. The following technologies are covered: wind energy, photovoltaic energy, bioenergy, hydropower, heat pumps, batteries, geothermal energy, concentrated solar power (CSP) and solar thermal energy. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

[1] The Draghi report: A competitiveness strategy for Europe The Draghi report on EU competitiveness.

[2] Clean Industrial Deal - European Commission. Energy-intensive industries comprise the other focal sector.

This study has supported the European Commission and its Clean Energy Technology Observatory in the work of identifying and developing relevant competitiveness indicators.[3] Comprehensive and updated indicators enable an assessment of competitiveness and are essential for informing policymaking. An extensive, robust data foundation allows for overall and detailed insights, disaggregated by country, technology and value chain segment. A model-based approach was developed and applied, covering the technologies illustrated in the figure overleaf. The figure presents the most recent values for the key headline indicators. The indicators are also useful for identifying country-specific specialisations and examining the relative importance of different value chain segments.

Some technologies – such as hydrogen production via electrolysis or CCUS – could not be captured by the model due to data limitations. To enable an evidence-based assessment that also encompasses these areas, a quantitative evaluation of the European start-up landscape could be undertaken in the future. Such data on the start-up landscape could provide further insights into the development and progress of emerging clean energy technologies.

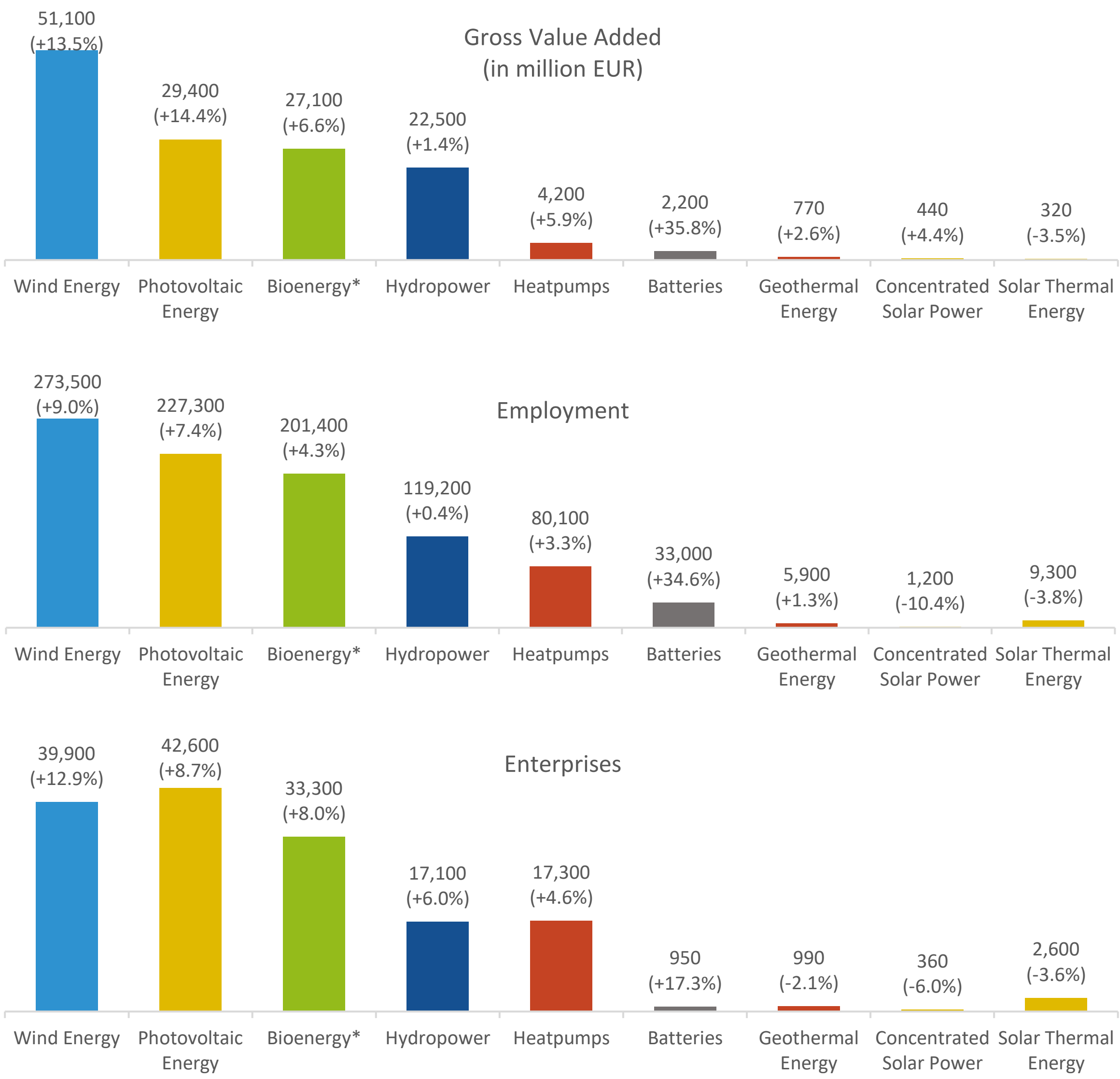
The analysis shows that the economic impact across value chain segments is largely driven by downstream activities such as construction and operation,[4] reflecting the continued expansion of generation capacities. A key driver behind the economic performance of the clean energy technology industry is the operation segment, owing to low electricity and heat generation costs combined with high market revenues. This underscores the strong cost-competitiveness of clean energy technologies. In contrast, the manufacturing segment exhibits divergent trends. While the market for heat pumps and batteries remained small in 2023, production showed very dynamic growth. However, growth rates are below average for solar thermal energy, concentrated solar power and geothermal energy. The manufacturing segment in the photovoltaic (PV) sector has lost significant market share to China in solar module production, while EU manufacturing shows some growth in other components, including inverters.

At Member State level, the analysis shows different specialisations across clean energy technologies and value chain segments. Germany has established strong manufacturing capacities, particularly in the fields of wind energy, heat pumps and batteries. In the wind energy sector, Denmark exhibits a comparatively high level of specialisation in manufacturing. Sweden has established substantial manufacturing capacities in the heat pump sector, positioning itself as a leading producer within the EU. In Hungary, the government has provided extensive support to establish the country as a key hub for battery production – these efforts resulted in a substantial value-added contribution in 2023, the highest among all EU Member States.

[3] Since 2020, the Commission has published annual reports on the competitiveness of clean energy technologies. These reports are also informed by the annual technology-specific reports of the Clean Energy Technology Observatory (CETO).

[4] The analysis covers six value chain segments, each representing a distinct category based on specific delineations: resource sourcing (only for bioenergy), manufacturing, research and project development, construction, operation and recycling (only for batteries).

Figure 2 Economic metrics for clean energy technologies in the EU in 2023[5]



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) for the period 2010–2023. The results are presented as nominal values, reflecting the respective annual price level. The figures on bioenergy exclude resource sourcing. The figures on batteries do not cover operational activities. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

The analysis is based on the most detailed and coherent economic data from Eurostat, available at the European level: the Structural Business Statistics and PRODCOM. Both datasets are derived from surveys of European enterprises, providing a valid and empirically robust data foundation. In addition, the use of official statistics, aligned with standardised classification systems, offers a detailed and methodologically consistent basis for generating differentiated insights – both thematical and geographical – across various clean energy technologies. However, given the varying levels of detail in economic classification systems, not all relevant activities related to clean energy technologies can be directly identified. Some must be inferred from broader, heterogeneous categories of goods and services, requiring estimation methods that differ in approach and robustness. This limitation is expected to diminish over time, as classification systems continue to evolve and

[5] Data were much more limited for other technologies (CCUS, novel thermal storage, RFNBO, advanced biofuels, water electrolysis and ocean energy). Accordingly, these technologies were covered through a more limited desk-based gathering of publicly available information relevant to assessing competitiveness.

increasingly reflect goods and services that have gained economic relevance – particularly in the field of clean energy technologies. For future analyses, such models would benefit from improvements in classification revisions and estimation methods, as well as from incorporating more recent secondary statistics, e.g. on clean energy capacities installed, as they become available. As the economic footprint of technologies not yet covered by the model grows, future updates should also aim to include these clean energy technologies in the analysis.

1. Introduction

Background. The Clean Industrial Deal, presented in February 2025 sets out actions to turn decarbonisation into a driver of growth for European industries. The clean tech sector is one of two focal sectors under the Clean Industrial Deal. This aligns with the concerns and recommendations set out in the Draghi report on the future of European competitiveness published in 2024. The report identifies three overarching areas for action, one of which is decarbonisation and competitiveness. The report highlights the opportunities for a Europe that succeeds in leveraging the opportunities of the global decarbonisation trend. Building on the Draghi report, the Competitiveness Compass presented in January 2025 outlines a strategic vision to strengthen the EU's competitiveness. In this context, a continued monitoring of the competitiveness of the EU in clean energy technologies is of critical importance to assess the effectiveness of relevant initiatives and policies and, ultimately, to evaluate the extent to which decarbonisation and competitiveness go hand in hand. The objective of this report is to contribute to this monitoring.

Scope and structure of this report. This report presents the results of the study assessing the competitiveness of clean energy technologies. It begins by outlining the methodologies applied,[6] along with a discussion of their strengths and limitations. The subsequent 2 chapters present the technology-specific key findings, first for technologies covered by the evidence-based-statistical model and subsequently for technologies covered by desk research. The final chapter of the report presents key conclusions, focusing on discussion of relevant competitiveness indicators and their availability, as well as potential future improvements to the applied methodology. Appendix 1 provides a more detailed overview of implementation of the project, including the deliverables produced. Appendix 2 presents a list of all economic activities covered per technology in the statistical analysis. Appendix 3 presents the robustness and sensitivity assessment. Appendix 4 elaborates the scope and methods used to produce the fact sheets and policy briefs developed under the project.

Contract objectives. This report constitutes the final report marking the conclusion of the 29-month contract that supported 'the European Commission in the preparation and dissemination of the annual Competitiveness Progress Reports (CPR) of clean energy technologies, the European Commission's annual report that aims to map the competitiveness of the EU clean energy industry and to assess whether clean energy technology development is on track to deliver the EU's long-term energy and climate goals, while addressing new emerging challenges'.[7] The key objective was to enhance the quantitative and qualitative data foundation by applying an evidence-based methodology for value chain analysis of clean energy technologies. Where possible, a value chain-based approach was used to identify and analyse the relevant economic indicators. Throughout the study, data collected and used to supplement the model-based analysis were required to be freely and publicly available.

Implementation of the contract. The contract was implemented by a consortium consisting of Viegand Maagøe (lead) and Prognos for the European Climate, Infrastructure and Environment Agency (CINEA) of the European Commission. Implementation commenced in December 2022. The Directorate-General for Energy (DG ENER) of the Commission and the Joint Research Centre (JRC) played a key role in managing and coordinating the project. The responsibility for project deliverables, including the content of this report, lies solely with the implementing consortium (Viegand Maagøe and Prognos).

[6] According to the Tender Specifications: The methodology and delineations developed during project implementation to deliver up-to-date and comprehensive indicators on competitiveness, including the main challenges and limitations of the methodology when relevant.

[7] Quote from section 1.2 (on Subject: 'what is this call for tenders about') of the Tender Specifications for the contract.

Workstreams. Support under this contract was delivered through four separate work streams,[8] two of which focused on analytical and methodological content and the other two on assisting communication of the CPR. The former is the focus of this report. However, Annex 1 includes a description of activities undertaken to support communication and Annex 2 provides a description of the fact sheets and policy briefs produced to facilitate communication of the CPR report.

[8] The study tasks comprised Task 1: Data collection of competitiveness indicators of the clean energy technology value chains; Task 2: Data analysis and reporting; Task 3: Editorial support for the CPR; and Task 4: Communication and Dissemination Plan and supporting activities following adoption of the CPR, including drafting of policy briefs and communication fact sheets.

2. Methodology

The present analysis compiles economic indicators to strengthen the assessment of competitiveness across a range of clean energy technologies. Based on the selected indicators persons directly employed, gross value added and the number of enterprises, it is possible to analyse recent developments in clean energy technologies, identify country-specific specialisations and examine the relative importance of different value chain segments.

Analysis of the clean energy technologies varies depending on data availability. For technologies with sufficient data, a quantitative evidence-based statistical model was developed. This model enables the assessment of economic indicators at the level of individual value chain segments. For technologies with limited data, a more restricted literature based economic and market analysis was conducted to explore the availability of data for informing an assessment of technological competitiveness.

Table 1 Method used to analyse competitiveness for each clean energy technology

Technology	Analysis type
Wind energy	Evidence-based statistical model
Photovoltaic energy	Evidence-based statistical model
Bioenergy	Evidence-based statistical model
Hydropower	Evidence-based statistical model
Heat pumps	Evidence-based statistical model
Batteries	Evidence-based statistical model
Geothermal energy	Evidence-based statistical model
Concentrated solar power (CSP)	Evidence-based statistical model
Solar thermal energy	Evidence-based statistical model
Carbon capture, utilisation and storage (CCUS)	Literature based analysis
Novel thermal energy storage	Literature based analysis
Renewable fuels of non-biological origin (RFNBOs)	Literature bared analysis
Advanced biofuels	Literature based screening
Ocean energy	Literature based screening
Water electrolysis	Literature based screening

The chapters on clean energy technologies covered by the evidence-based statistical model provide a comprehensive overview of the quantitative results and highlight key trends for the following indicators: gross value added,[9] number of persons directly employed and enterprises. In contrast, the chapters covering the remaining technologies adopt a more

[9] Gross Value Added (GVA) is an established indicator for measuring value creation within an economy. Unlike other indicators, GVA captures the actual added value generated by a statistical unit, excluding the value of intermediate goods included in metrics such as turnover. Gross value added is calculated using the following formula: turnover + capitalised production + other operating income (including operating subsidies) ± changes in stocks − purchases of goods and services − other taxes on products linked to turnover but not deductible − duties and taxes linked to production.

narrative format, bringing together relevant information that can support an assessment of technological competitiveness. While the structure and content of these chapters have been aligned as far as possible, some variation remains reflecting differences in data availability and depth of investigations.

2.1. Modelling

The methodological approach applied in this project differs from those underpinning other publications. Such publications often rely on a broad spectrum of economic methods to analyse and assess the socio-economic aspects of different environmental sectors. These methodologies range from micro-level (survey-based) approaches to (macro-level) input-output models. The EurObserv'ER approach, for example, can be considered among the latter.[10] Such macro-level approaches contend with the coarse level of detail of input-output data, limited availability of time series data across geographies, high complexity and numerous modelling assumptions. While such models highlight the direct and indirect effects of an activity or the degree of connectiveness across the entire economic system, they do not lend themselves to a clear disaggregate analysis at the value chain level. Moreover, these approaches do not collect data across the different segments of the value chain.

The modelling approach of this study is based on the most detailed socio-economic data available from Eurostat. Compared to other methods, the approach chosen for this project has several key distinguishing features. The clear delineation of clean energy technologies provides a solid foundation for identifying the goods and services included in their respective value chains. Based on comprehensive market research, all relevant economic activities along the value chain for each clean energy technology were compiled. These identified goods and services were systemically matched to existing economic classification systems – in particular the PRODCOM classification for goods and products and the NACE classification for services – at the most granular level possible. The principal data source for the derivation of the indicators gross value added, persons employed, and enterprises was the Structural Business Statistics available from Eurostat, that provides data for the years 2010 to 2023. By maintaining consistency between the defined scope and the underlying raw data, the results can be presented at the level of value chain segments for each clean energy technology, encompassing multiple economic indicators per year and Member State. This modelling approach allows for assessment of the direct economic effects of these technologies.

[10] EurObserv'ER provides a comprehensive database offering detailed data on clean energy technologies, including metrics such as employment figures and turnover. Based on newly installed capacities and the corresponding CAPEX and OPEX costs, the EurObserv'ER model estimates total investments per economic sector. These figures are then converted to derive estimates of gross employment per economic sector. The data are available under https://www.eurobserv-er.org/online-database/.

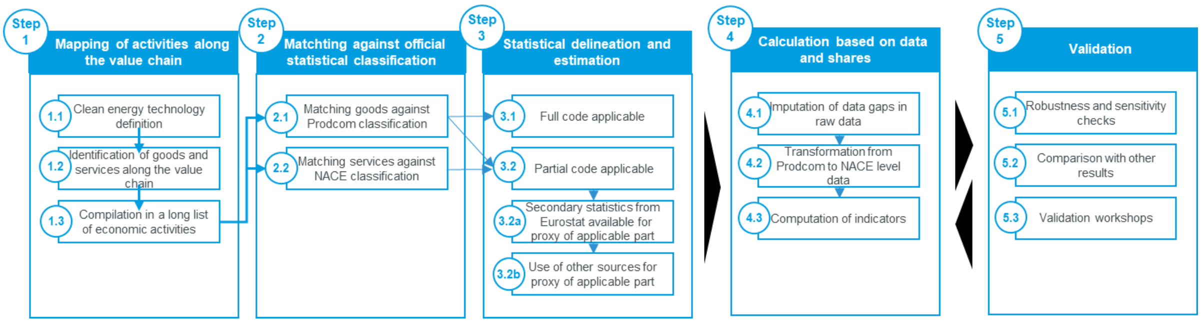
The following value chain segments[11] are covered for each technology:

- Resource sourcing (only for bioenergy): captures the cultivation of energy crops as well as forestry logging activities.
- Manufacturing: includes, as far as can be delineated, both the production of components (such as solar modules) and the production of advanced components relevant to the deployment of clean energy technologies (such as inverters).
- Research and project development encompasses activities related to research on developing new advanced technologies, consulting services, as well as activities aimed at the design, approval, planning and feasibility of new projects.
- Construction: captures construction activities and the installation of clean energy technologies.
- Operation: depending on the technology, this includes the generation and marketing of electricity or heat.
- Recycling (only for batteries): covers the material recovery of used batteries.

In total, nine different technologies are covered by the modelling approach: wind energy, photovoltaic energy, bioenergy, hydropower, heat pumps, batteries, geothermal energy, concentrated solar power (CSP), solar thermal energy. For batteries, the value chain segment operation is not covered.

An overview of the methodological steps applied in the modelling approach is provided in the figure below. For an overview of the NACE and PRODCOM codes covered in the statistical analysis see Appendix 2.

Figure 3 Principal methodological steps for the statistical model



Source: Prognos 2025.

A methodological assessment confirms the robustness of key statistical estimates. A sensitivity analysis was conducted to assess how variations in estimated shares impact results for each clean energy technology. Key statistical entries for the results of each clean energy technology were identified and analysed. For these and all relevant activities, the proxy estimation methods were qualitatively assessed and classified into three robustness levels (low, medium, high), based on derivation method, assumptions, data availability and quality and code heterogeneity. A cross-examination of sensitivity and robustness levels

[11] Based upon the definitions of the clean energy technology in the Clean Energy Technology Observatory (CETO) reports, a long list of economic goods and services of each clean energy technology was identified based on desk research and grouped in different principal value chain segments, covering the associated services and 1st and 2nd tier components for the manufactured products. In this manner, more general applicable components (e.g. nuts, bolts, metal plating) are excluded and the value chain focuses on the distinct value generated by the clean energy technology.

enabled prioritisation of critical checks. Overall, the model demonstrates good robustness. All high-impact codes are based on medium or high-quality estimation methods. Lower robustness is primarily associated with economically marginal activities, which have limited influence on the overall results (see Appendix 3).

The results of the statistical model are robust but subject to limitations. The granularity of Eurostat data and the international economic classification system present challenges for the precise identification of specific clean energy activities, necessitating some assumptions. More detailed national data (such as NACE 5-digit and PRODCOM 9-digit) could improve precision but are not always available. Confidentiality requirements and classification updates may introduce minor distortions in time series. Additionally, discrepancies between Structural Business Statistics and National Accounts affect the consistency of the data. In addition, there is a time lag in the analysis, as it only covers data up to 2023.

A key limitation arises from estimating shares within heterogeneous economic classification classes that do not fully represent specific clean energy technologies. Proxy data must be used, assuming proportional structures that may not reflect actual economic output. Mapping secondary statistics to relevant classes is complex, especially when classes are highly heterogeneous, and may require aggregation or exclusion. Furthermore, official statistics often lack differentiation by technology type, such as renewable versus non-renewable energy. While proxies like energy balances can improve estimates, they simplify differing cost structures and add complexity. Finally, some activities and technologies (such as CCUS and RFNBO) were excluded due to their marginal market presence or limited data availability.

Specific countries were excluded due to a lack of sufficient data. The raw data from the Structural Business Statistics contain significant data gaps for Cyprus, Malta and Luxembourg, which could not be reliably closed through estimation methods. All EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

In cases where limitations to the modelling approach prevented the generation of robust results, a qualitative analysis was conducted to provide insights. The level of detail of activity mapping by value chain segment requires the statistical classification systems to be aligned with the identified goods and services, at least at an aggregate level. Additionally, the economic activities must be significant, i.e. sufficiently large to be reflected in the reported data of the Member States. For specific technologies, such as water electrolysis or ocean energy, these conditions are not yet met.

2.2. Assessment for technologies not covered by model

Desk-based investigations of available and relevant data were undertaken for technologies lacking coverage in the statistical model, using open-source literature. The technologies concerned are overall less mature than the technologies covered by the model. Therefore, data limitations prevent them from being included in the model-based analysis. However, the study has investigated the extent to which publicly available and relevant data could be found that would be relevant to an assessment of the competitiveness of the technologies. However, while increasing transparency, the reliance on open-source information also introduces certain limitations. While such data can provide a broad overview of market trends and technologies, they may not always capture the most recent developments or proprietary insights that are only available through commercial or confidential sources. Accordingly, it is important to acknowledge that the depth, timeliness and specificity of the data varies, potentially affecting the comprehensiveness of our analyses.[12]

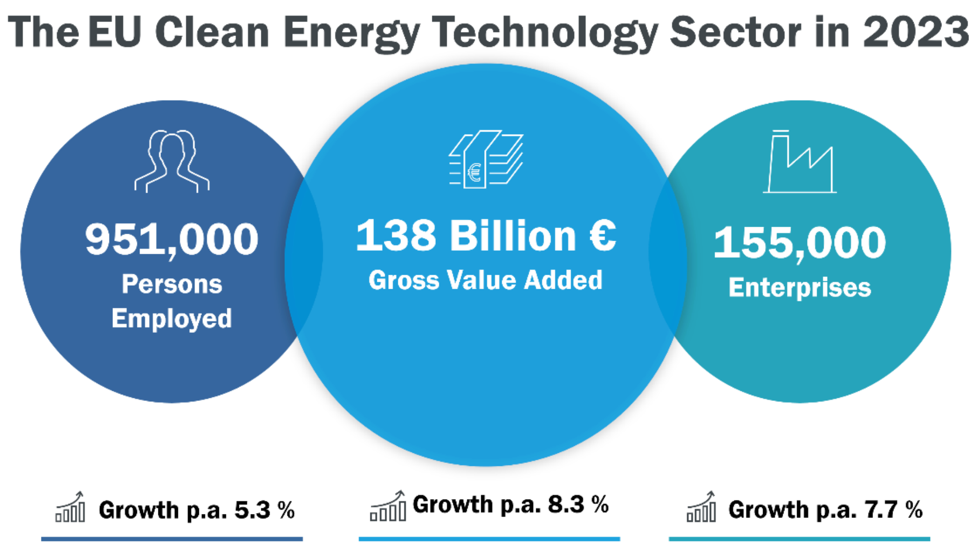
[12] Three technologies – water electrolysis, ocean energy and biofuels – were initially included in the modelling, however it was jointly decided during implementation to discontinue this effort as the statistical analysis proved unfeasible. Instead, it was decided to include them in the data investigations exercise described here, however with a less comprehensive scope focusing mainly on identifying the most significant advancements and progress. This also applied to biofuels as this could not be integrated into the modelling either.

3. Key findings: Economic and market analysis of the EU clean energy technology sector

Based on the evidence-based-statistical model, the number of companies, persons directly employed, and gross value added were calculated for the following technologies: wind energy, bioenergy, hydropower, photovoltaic energy, solar thermal energy, concentrated solar power (CSP), geothermal energy, heat pumps and batteries.

The EU clean energy technology sector has evolved as a key and highly dynamic industry. Since 2010, the number of companies and persons directly employed has increased annually by 7.7% and 5.3%, respectively. In 2023 the sector employed 951,000 persons across 155,000 enterprises.[13] Growth in nominal gross value added – a measure of economic value creation – has been even more pronounced, rising by 8.3% per year, generating EUR 138 billion in 2023. In recent years, this growth has accelerated further. Between 2020 – the year of onset of the COVID-19 pandemic – and 2023, the annual growth rate of gross value added reached 11.7%. When gross value added is put in relation to the number of persons employed, it also becomes evident that the sector's productivity is increasing significantly.

Figure 4 Comparison of economic metrics for the EU clean energy technology sector in 2023



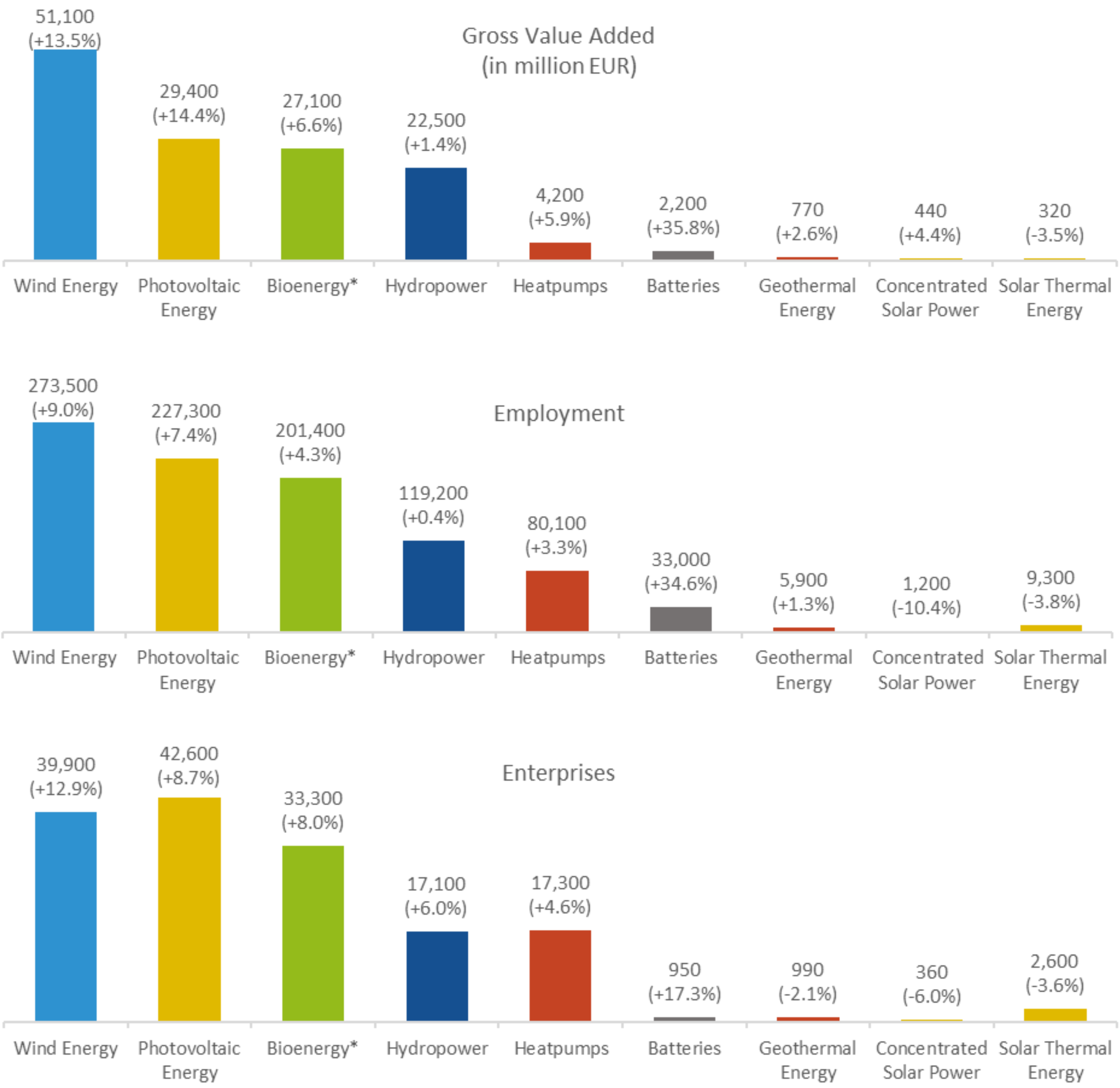
Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The results are presented as nominal values, reflecting the respective annual price level. The technologies covered are: wind energy, photovoltaic energy, bioenergy, hydropower, heat pumps, batteries, geothermal energy, concentrated solar power (CSP) and solar thermal energy. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Analysis at the value chain segment level reveals an important insight: the operation segment is a major driver behind the economic performance of the clean energy technology industry. This is due to low electricity and heat generation costs combined with high market revenues, underscoring the strong competitiveness of clean energy technologies. Other downstream activities, such as system installation, have also experienced significant growth in response to the increasing importance of clean energy for

[13] Other studies report even higher employment effects, as they include not only direct employment but also indirect effects. See for example IRENA (2024): Renewable energy and jobs: Annual review 2024 https://www.irena.org/Publications/2024/Oct/Renewable-energy-and-jobs-Annual-review-2024.

the future decarbonised energy system. In contrast, the manufacturing segment shows more mixed trends: the production of heat pumps and batteries is experiencing dynamic growth, while the wind energy sector shows positive trends in Germany and Denmark. The photovoltaic energy manufacturing sector has lost significant market share to China. A more differentiated picture emerges across the various clean energy technologies analysed.

Figure 5 Economic metrics for clean energy technologies in the EU in 2023



Source: Prognos 2025. Annual growth is calculated as compound annual growth rate (CAGR) over the period 2010–2023. The results are presented as nominal values, reflecting the respective annual price level. Bioenergy figures exclude resource sourcing. The batteries figures do not cover operational activities. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

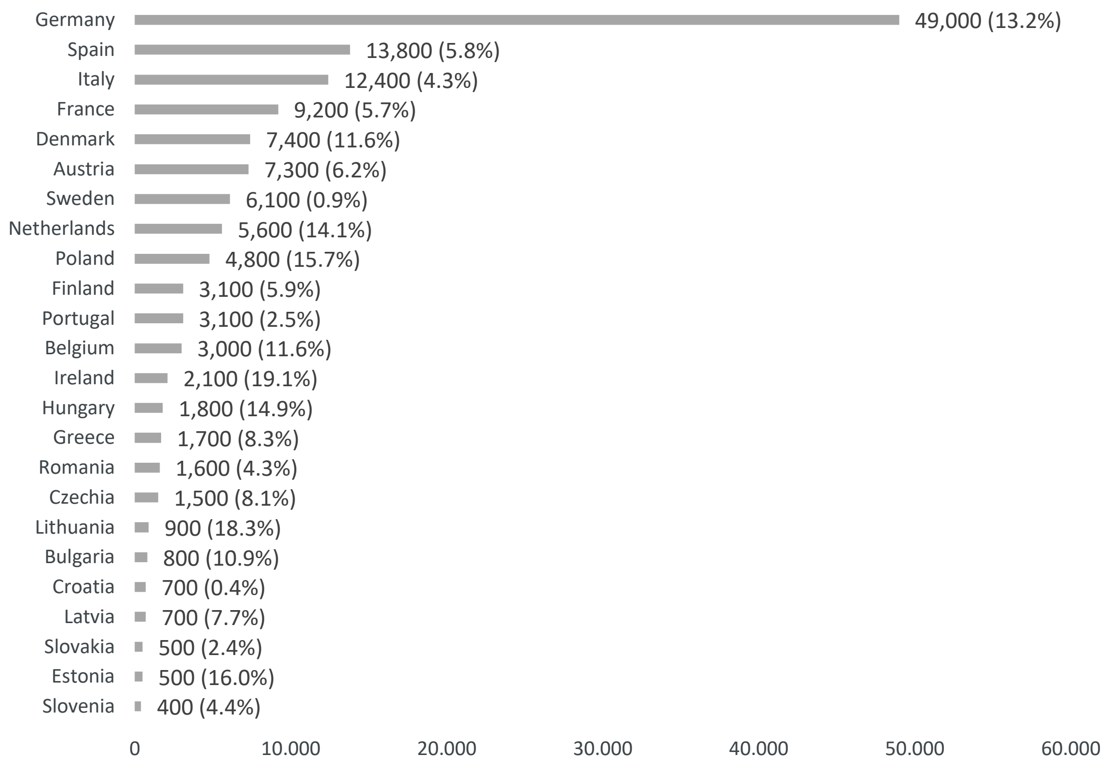
Both the wind energy and photovoltaic energy sectors have experienced particularly dynamic growth, with substantial capacity additions in recent years. This has led to significant economic contributions, especially in the construction and operation segments. EU manufacturing of PV and wind technologies, however, is increasingly exposed to international competition, albeit to different degrees. For instance, PV module production has declined sharply.

In contrast, manufacturing in the heat pump and battery sectors has shown above-average growth, although the overall market size remains relatively small. Gross value added in heat pump manufacturing, for example, doubled between 2016 and 2023. The gross value added of manufacturing in the battery sector increased from EUR 530 million in 2019 to over EUR 2.1 billion in 2023, with growth expected to continue.

A direct comparison also reveals the relatively minor significance of some technologies. For the three clean energy technologies – solar thermal energy, concentrated solar power (CSP) and geothermal energy – the current economic performance and growth trends are still negligible compared to those of major clean energy technologies.

Across the EU Member States, the clean energy industry is heavily shaped by the German market, which accounts for over one-third of total gross value added. With annual growth of 13.2%, Germany is set to remain a key player in the future. However, several other countries are also experiencing dynamic development: the Netherlands reports annual growth of 14.1% and Ireland 19.1%.

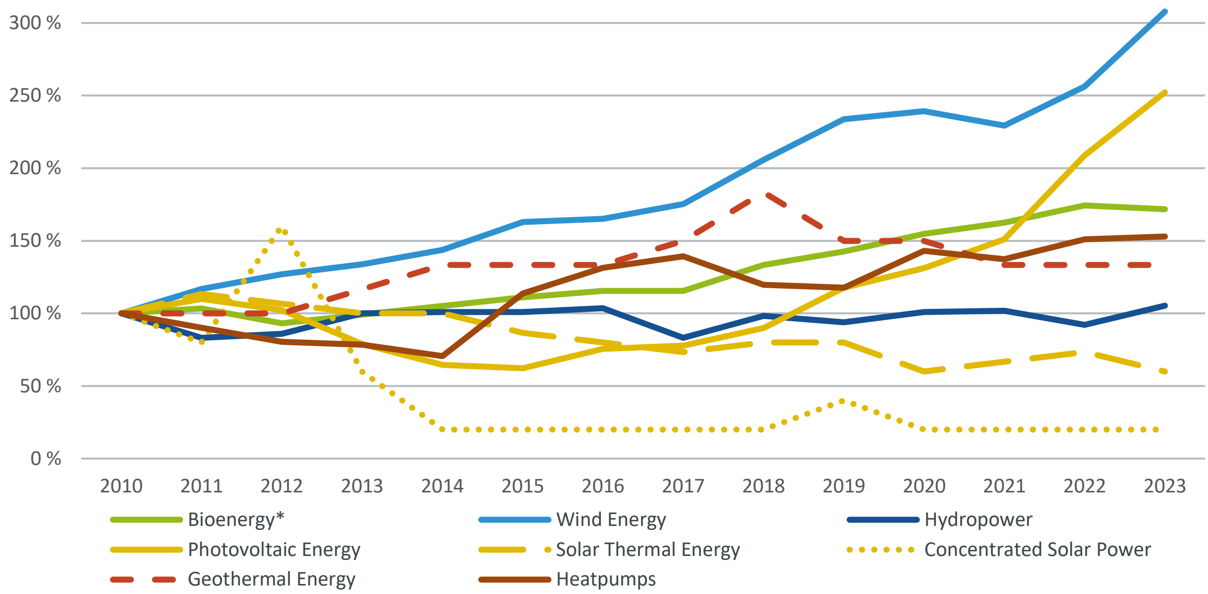
Figure 6 Gross value added across the analysed EU Member States in 2023 (in MEUR)



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The results are presented as nominal values, reflecting the respective annual price level. The technologies covered are: wind energy, photovoltaic energy, bioenergy, hydropower, heat pumps, batteries, geothermal energy, concentrated solar power (CSP) and solar thermal energy. Cyprus, Malta, and Luxembourg are not covered due to significant data gaps.

The number of persons directly employed also shows clear growth trends, reaching 951,000 in 2023. In the wind energy and photovoltaic energy sectors, employment has more than doubled. The bioenergy and heat pump sectors have also seen a marked upward trend over the years. In contrast, the analysis indicates stagnation in employment for hydropower and even a decline for solar thermal energy and concentrated solar power.

Figure 7 Trends of persons employed per clean energy technology in the EU (Trend 2010 = 100%)



Source: Prognos 2025. *Bioenergy figures exclude Resource sourcing. The figure does not include the trend for batteries. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

4. Economic and market analysis

4.1. Wind energy

Wind generation of electricity has a relatively long tradition in Europe, with the first commercial testing sites dating back to the 1970s. Today, wind energy is a key pillar of the European and global transition to green energy generation.

Between 2010 and 2023, gross electricity production from wind energy in the EU rose from 140 TWh to over 378 TWh. By 2023, onshore and offshore wind turbines accounted for 17% of total electricity generation.[14]

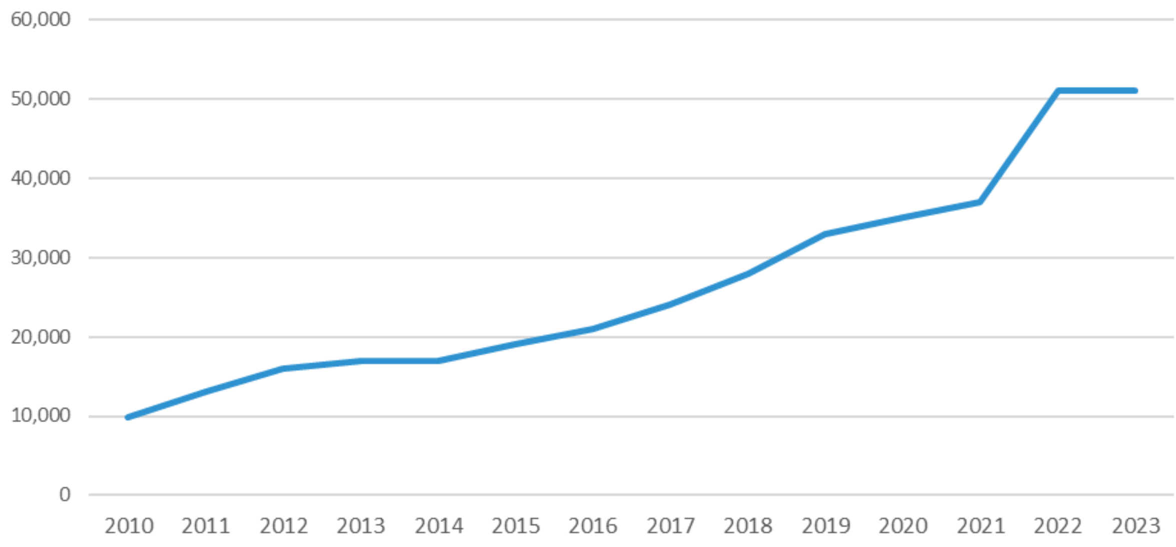
With the growth of wind energy, a range of economic services and production of goods has emerged. The value chain can be subdivided into four principal stages: research and project development, manufacturing, construction, and operation. In practice, however, the schematic distinction between value chain segments is often blurred. Wind turbine manufacturers are typically international companies, producing various types of wind turbines and installing wind farms for both offshore and onshore operation. Many of them cover large parts of the value chain, from product development and manufacturing of wind turbines to wind farm management, performance monitoring, analysis and maintenance. Furthermore, the range of economic activities is richer than can be depicted by the model, with the model capturing the main economic activities along the value chain.

Gross value added

The EU wind energy sector shows steady and dynamic growth between 2010 and 2023. The analysis uses the official Structural Business Statistics (SBS) to estimate the direct gross value added for relevant NACE activities across the four value chain segments: manufacturing, research and project development, construction, and operation. In 2023, the EU wind energy market recorded EUR 51.1 billion in gross value added. Operational activities largely determine the overall gross value added.

[14] Eurostat (2025). Complete energy balance [nrg_bal_c].https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_c/default/table?lang=en.

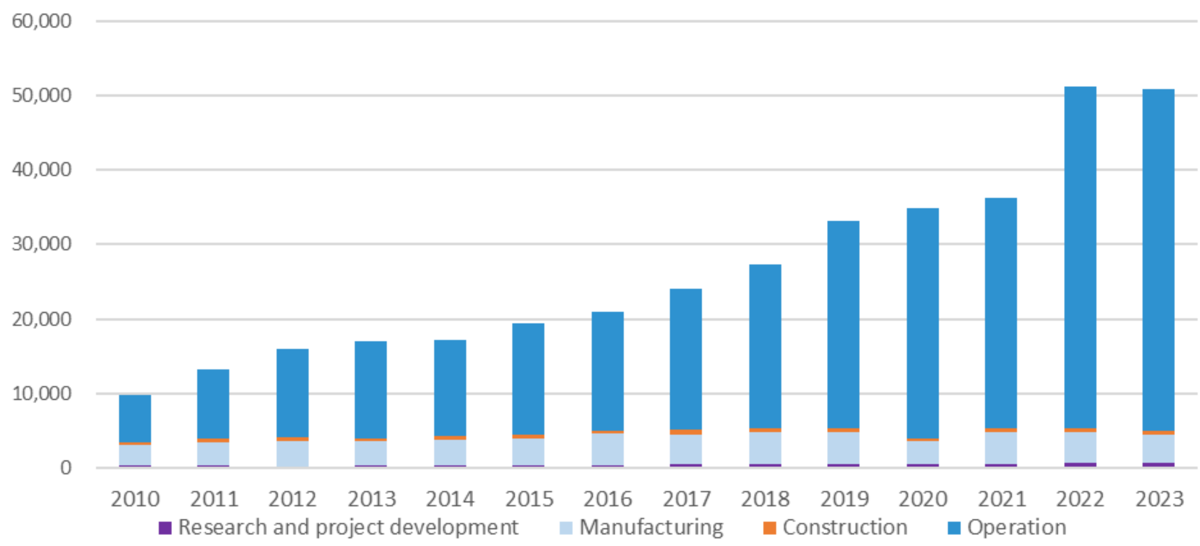
Figure 8 Gross value added of the EU wind energy value chain (in MEUR) over the period 2010–2023



Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

The growth in gross value added is strongly driven by the increasing electricity production of wind power plants, low variable costs and high market revenues due to merit order pricing. The data shows a boom in gross value added for the EU wind energy sector. The 2023 gross value added levels represent a fivefold increase compared to 2010, with a growth rate of 13.5% per year since 2010. The highest growth rates can be observed in the decisive value chain segment operation. The price surges in the electricity sector in 2022 provided additional momentum, significantly boosting gross value added.

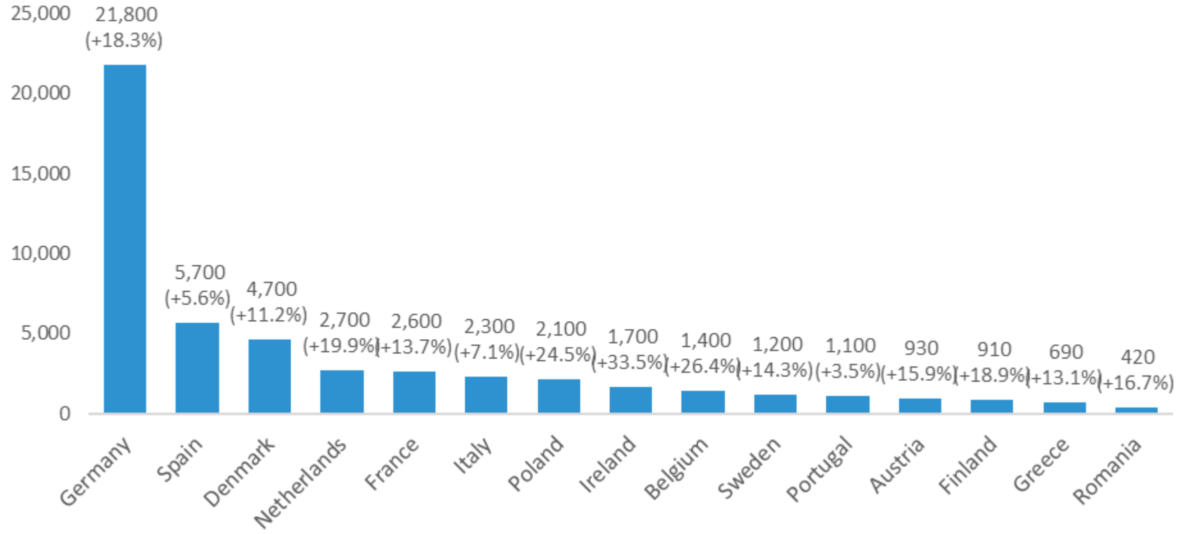
Figure 9 Gross value added by value chain segment in the EU wind energy sector (in MEUR) over the period 2010–2023



Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Across EU Member States, Germany has the highest level of gross value added, mainly due to its substantial installed wind capacity. Between 2010 and 2023, its gross value added grew at an annual rate of 18.3%. In 2023, Germany generated EUR 21.8 billion, followed by Spain (EUR 5.7 billion), Denmark (EUR 4.7 billion) and the Netherlands (EUR 2.7 billion).

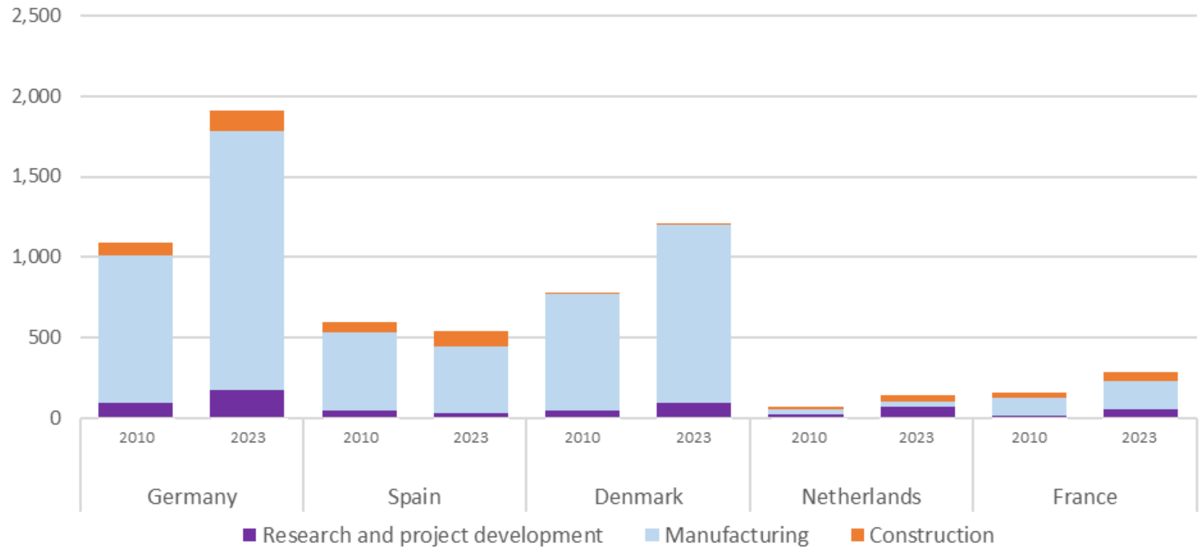
Figure 10 Gross value added of the wind energy value chain in selected EU Member States in 2023 (in MEUR) and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The results are presented as nominal values, reflecting the respective annual price level. The graph displays only those EU Member States that report the highest result values.

As wind installations grew consistently, value creation within the manufacturing segment also gained traction. The gross value added for manufacturing in Germany increased from EUR 920 million in 2010 to EUR 1.6 billion in 2023. In Denmark, the respective figure increased from EUR 720 million to EUR 1.1 billion in the same period.

Figure 11 Gross value added by value chain segment, excluding operation, in the top five Member States in 2010 and 2023 (in MEUR)



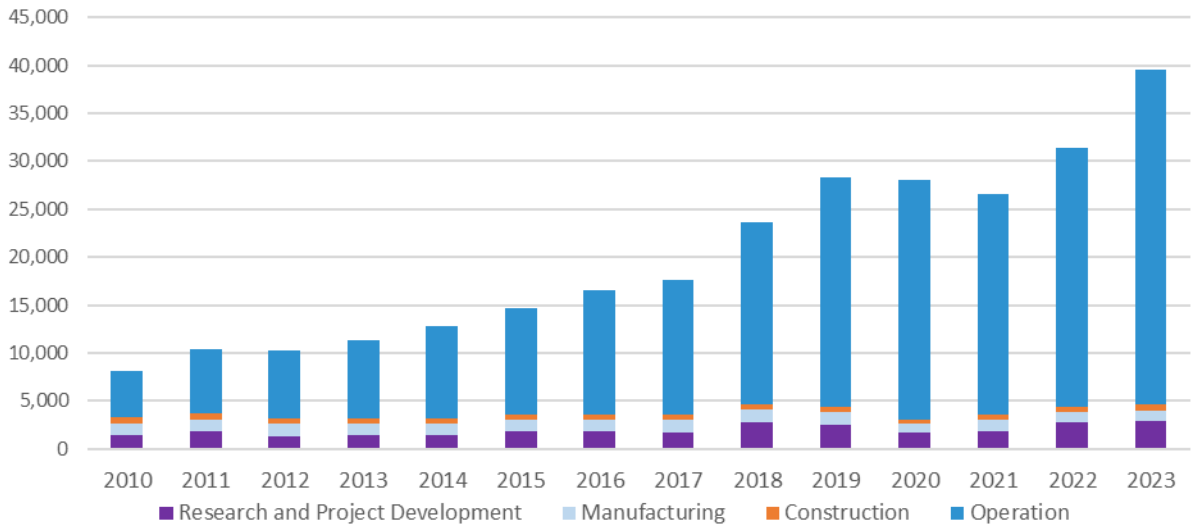
Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level.

Enterprises

In line with the steep growth in gross value added, the number of companies increased significantly between 2010 and 2023. Across all value chain segments, nearly 40,000 enterprises operated in 2023, mainly engaged in operation activities.

The findings suggest that an increasing number of smaller operators are entering the market to produce and market electricity. In 2023, the number of companies increased sharply compared to the previous year. This development can be attributed to two parallel trends in operation activities. First, the overall number of companies generating and selling electricity has grown across all generation types. Second, the significance of wind power has increased considerably.

Figure 12 Number of wind energy enterprises by value chain segment at EU level over the period 2010–2023

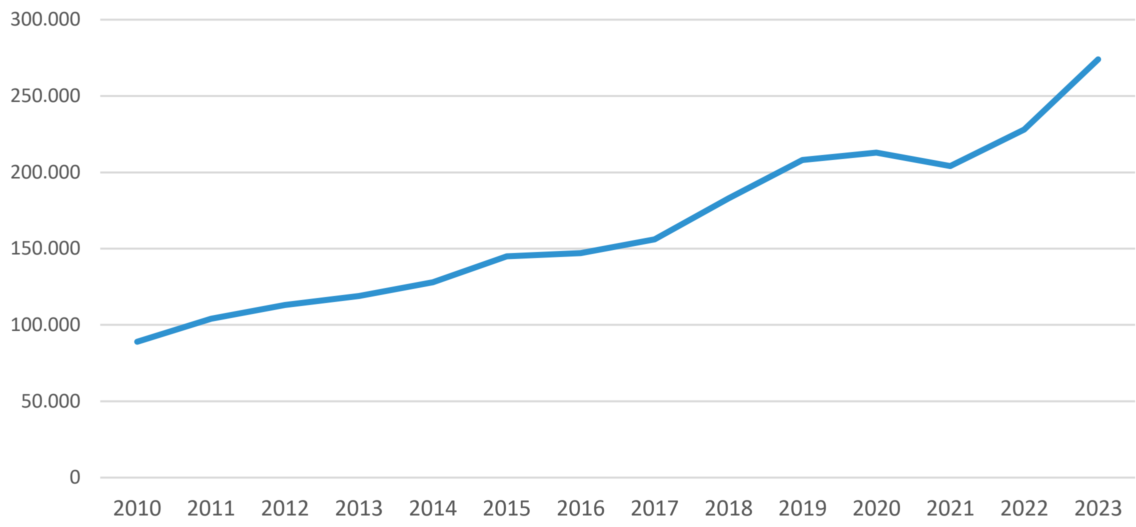


Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Employment

The increased installations in the wind energy sector have also driven continued growth in employment, reaching record levels in 2023. The analysis provides data based on the Structural Business Statistics (SBS) until 2023, estimating that 273,500 persons were directly employed in the wind energy sector.

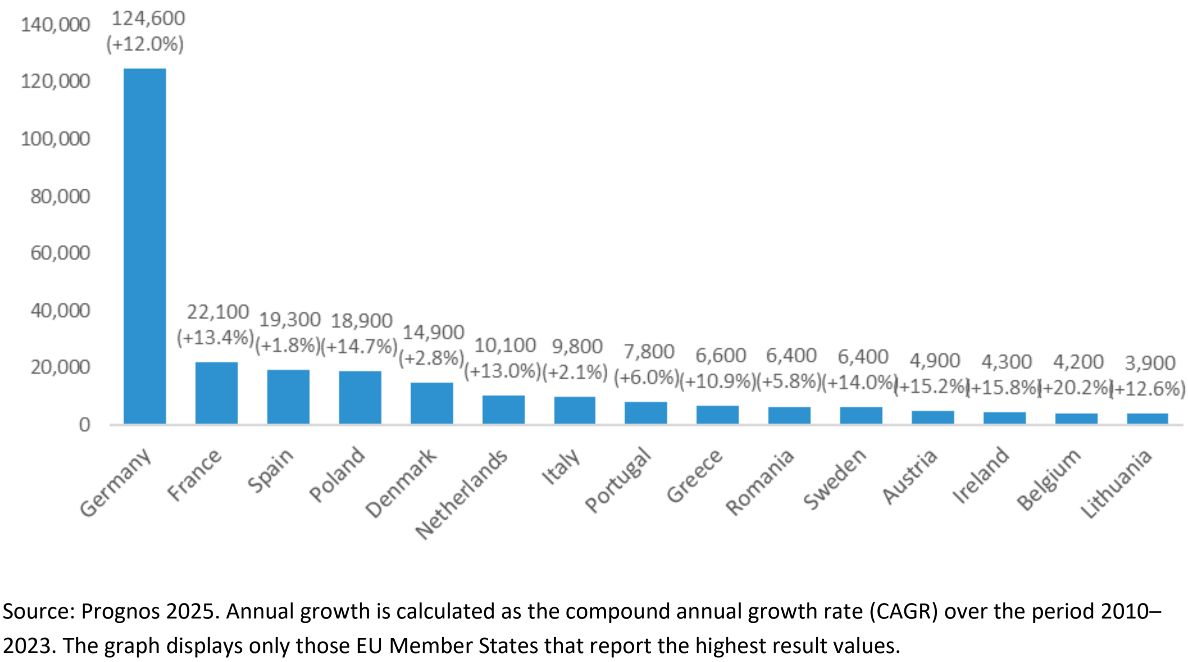
Figure 13 Employment in the EU wind energy sector over the period 2010–2023



Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Germany has the highest employment level among the EU Member States, with a total of 124,600 persons employed and an annual growth rate of 12.0%. Significant increases in persons employed are also observed in France and Poland, with annual growth rates of 13.4% and 14.7%, respectively. Spain and Denmark have seen lower employment growth, but still account for 19,300 and 14,900 persons employed, respectively.

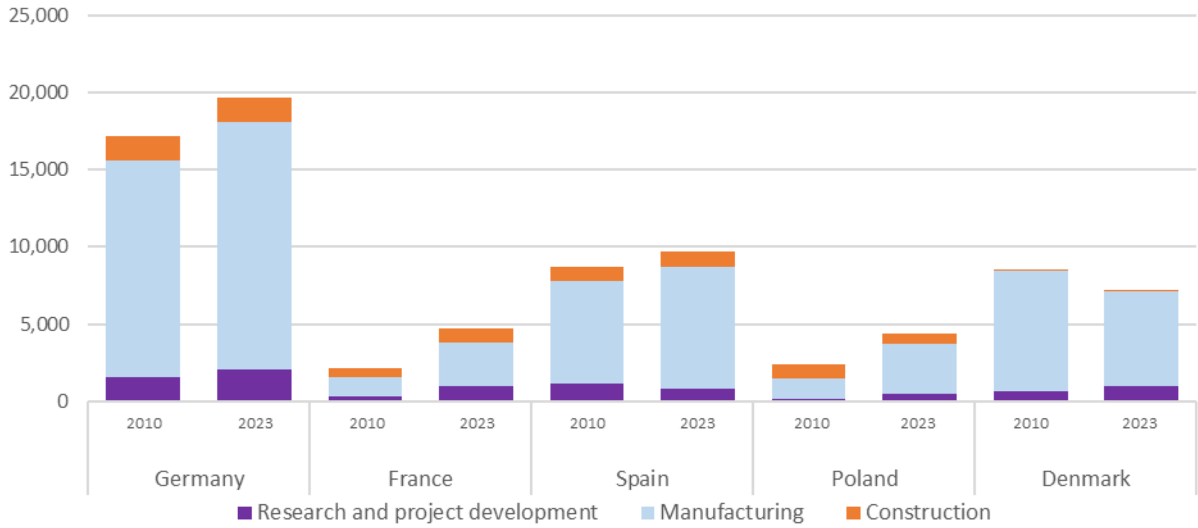
Figure 14 Employment in the wind energy value chain in selected EU Member States in 2023 and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The graph displays only those EU Member States that report the highest result values.

The strong employment growth is primarily attributable to operation activities, while the other value chain segments are also expanding, but at a significantly slower pace. In Germany, France, Spain and Poland, the number of persons employed in the manufacturing segment increased slightly between 2010 and 2023. Denmark – one of Europe's leading wind power manufacturers – saw a reduction in that segment from 7,800 persons employed to 6,200. The number of persons employed increased in both research and project development, as well as in construction. Due to falling costs for wind turbines, the construction segment recorded only a slight increase, despite a significant rise in new installations.

Figure 15 Employment by value chain segment, excluding operation, in the top five Member States in 2010 and 2023



Source: Prognos 2025.

4.2. Photovoltaic energy

Solar photovoltaic (PV) energy experienced remarkable development over the last 15 years. The technology provides one of the cheapest forms of electricity generation today, as the prices for photovoltaic modules have plummeted over the past years.

At 247 TWh in 2023, electricity generation from photovoltaic energy has increased more than tenfold compared to 2010. In 2023, PV systems accounted for approximately 9% of total electricity generation.[15]

Large-scale application of photovoltaic technologies is a key pillar of the EU's clean energy targets. While the EU was initially at the forefront of the development of photovoltaic energy, intensified global competition in subsequent years has led to a relocation of production capacities and a significant decline in EU's PV manufacturing segment. Today, the production of photovoltaic modules is mainly located in China. However, the significantly reduced costs per module have strengthened the overall competitiveness of photovoltaic electricity generation, paving the way for continuous growth in demand for the modules and corresponding growth in the construction and operation segments in the EU.

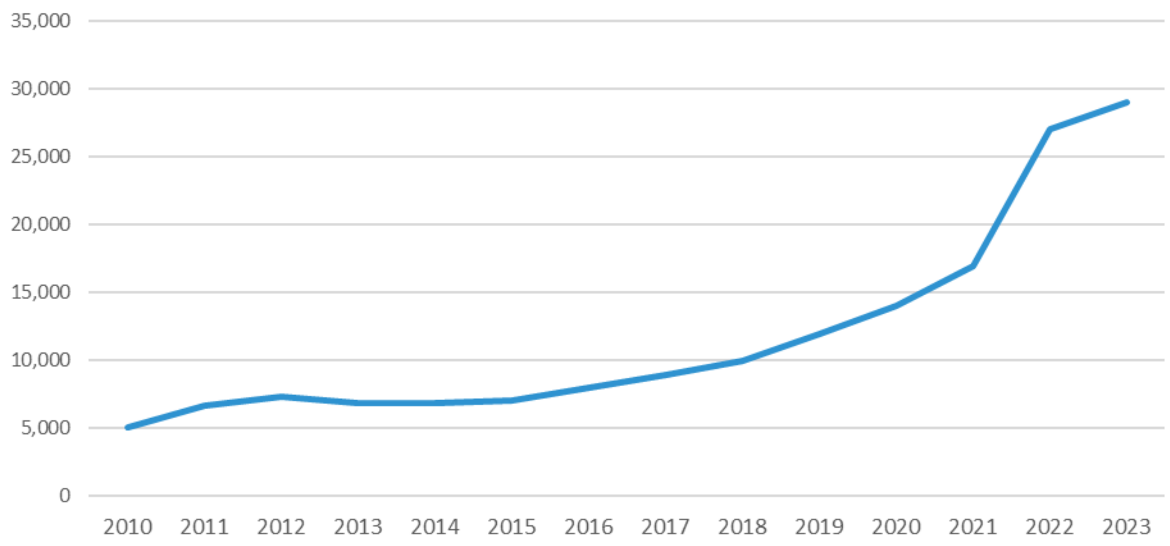
Gross value added

The gross value added of the EU PV sector shows exponential growth since 2015. In 2023, the EU PV sector generated approximately EUR 29.4 billion in gross value added, compared to around EUR 5.1 billion in 2010. In contrast to other clean energy technologies, a large share of photovoltaic electricity is generated by private households and consumed

[15] Eurostat (2025). Complete energy balance [nrg_bal_c].https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_c/default/table?lang=en.

directly, without being fed into the grid. Accordingly, the trend shown reflects only the gross value added generated by companies, as electricity consumed directly by private households does not contribute to gross value added.

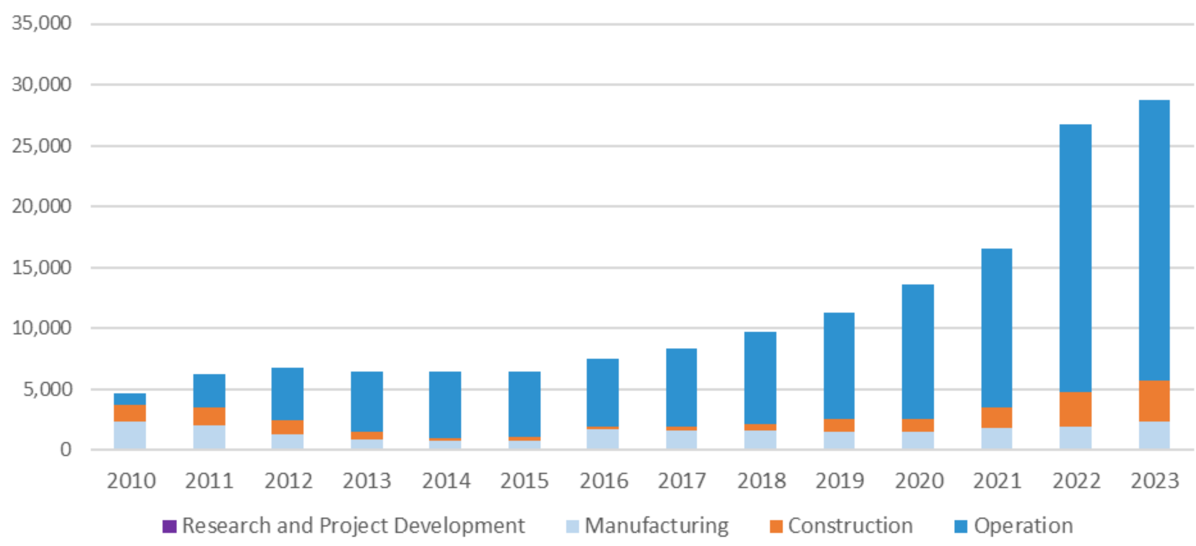
Figure 16 Gross value added of the EU PV energy value chain (in MEUR) over the period 2010–2023



Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

The PV sector experienced particularly strong growth around the turn of the year from 2021 to 2022, partly driven by rising electricity market prices. The gross value added of operation increased from EUR 13.1 billion in 2021 to EUR 21.7 billion in 2022. In 2023, operation represented the most important segment along the value chain, accounting for approximately 80% of gross value added. Since 2010, construction has also played an increasingly significant role, benefiting from strong growth in capacity additions.

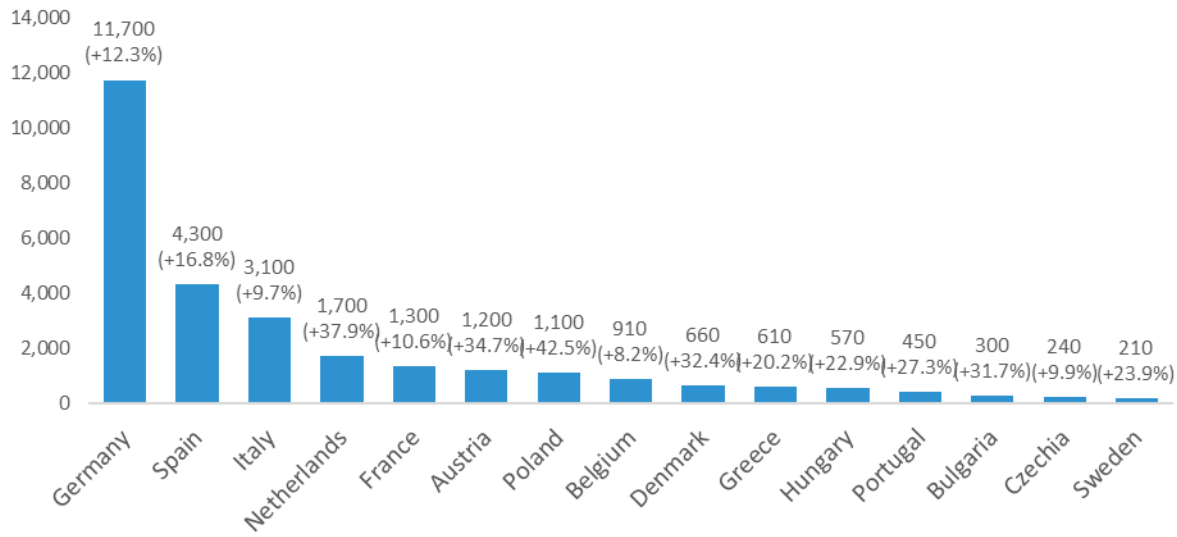
Figure 17 Gross value added by value chain segment in the EU PV energy sector (in MEUR) over the period 2010–2023



Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

The EU PV market is highly concentrated in Germany. However, all EU countries are experiencing dynamic growth. Germany generated over EUR 11.7 billion in gross value added in 2023 – nearly three times that of Spain, the second-ranked country. The German market grew at a dynamic annual rate of 12.3%, while Spain saw even faster growth at 16.8% per year. Since 2010, all 15 leading PV markets in the EU have expanded rapidly, with some countries, such as the Netherlands and Poland, recording annual growth rates exceeding 30%.

Figure 18 Gross value added of the PV energy value chain in selected EU Member States in 2023 (in MEUR)



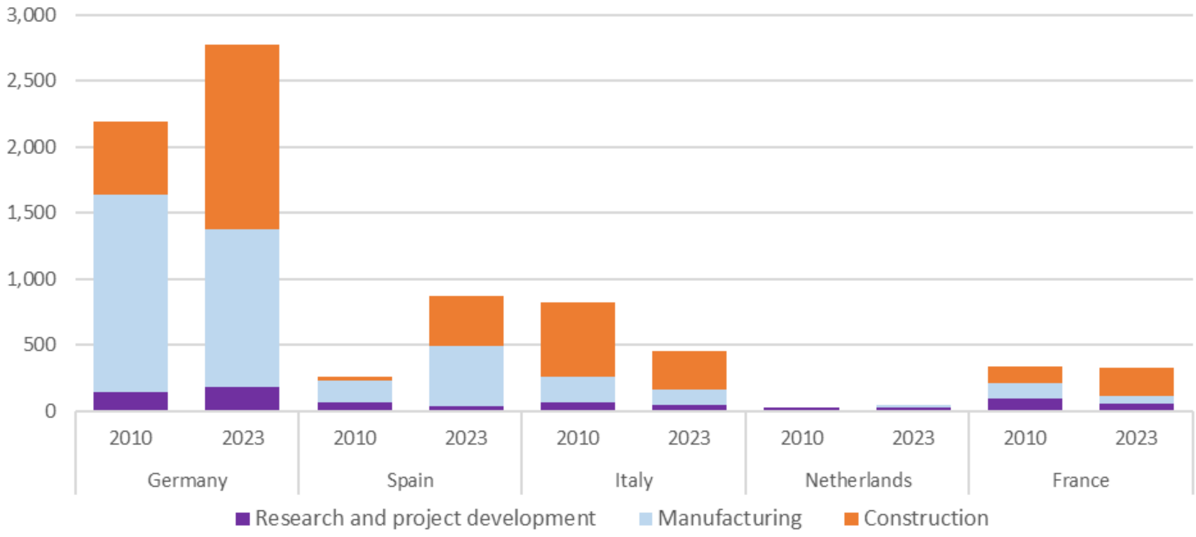
Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The results are presented as nominal values, reflecting the respective annual price level. The graph displays only those EU Member States that report the highest result values.

In the five countries with the highest gross value added, differing trends over the period 2010–2023 can be observed across the value chain segments. In all five, the gross value added from operation increased significantly, driven by rising PV capacities. The below figure illustrates the trends in the remaining segments. Research and project development remained relatively stable across all countries.

The gross value added of manufacturing declined in Germany and Italy, while Spain recorded growth. Several trends can be observed in the manufacturing sector. In photovoltaic module production, the EU has experienced a significant loss in gross value added. After 2011, module manufacturing underwent a sharp decline, reaching a low point in 2020, from which the industry has yet to recover. This decline is primarily due to intense competition from China, where massive expansions in production capacity and increasing energy performance have led to cost reductions. This has resulted in a significant competitive advantage for China. In contrast, a somewhat more stable trend can be observed in the manufacturing of other key components for solar systems, such as inverters and mounting systems. Here, manufacturing companies, such as in Germany and Spain, have benefited from the strong growth in installed capacity, recording slight gains.

In Germany and Spain, the increase in installed capacities has also led to significant growth in the construction segment. Gross value added for construction activities increased in Germany from EUR 550 million in 2010 to over EUR 1.4 billion in 2023, while in Spain it reached EUR 380 million.

Figure 19 Gross value added by value chain segment, excluding operation, in the top five Member States in 2010 and 2023 (in MEUR)

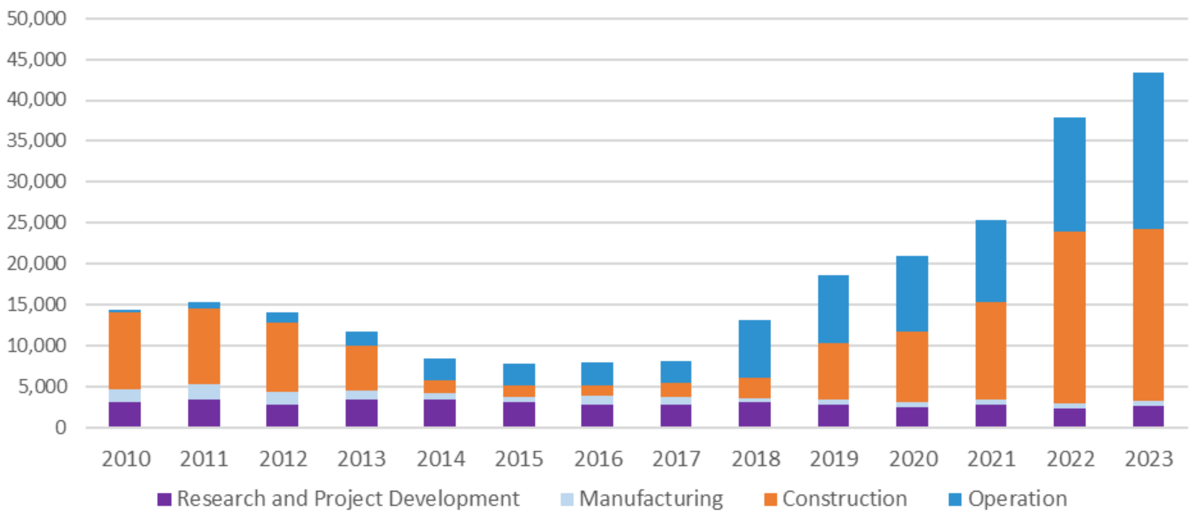


Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level.

Enterprises

The number of companies has likewise been shaped by the disruptions over the past decade, showing a downward trend after 2011 and a strong recovery from 2017 onwards. In 2023, around 42,600 companies were engaged in the PV sector in the EU, mostly in the operation and the construction segments. In 2010, most companies were active in the construction segment, but their number dropped sharply by 2014. From 2017 onwards, there has been a strong recovery. By contrast, the number of companies engaged in operation has steadily increased, reflecting the growing importance of this segment within the value chain.

Figure 20 Number of PV energy enterprises by value chain segment in the EU over the period 2010–2023

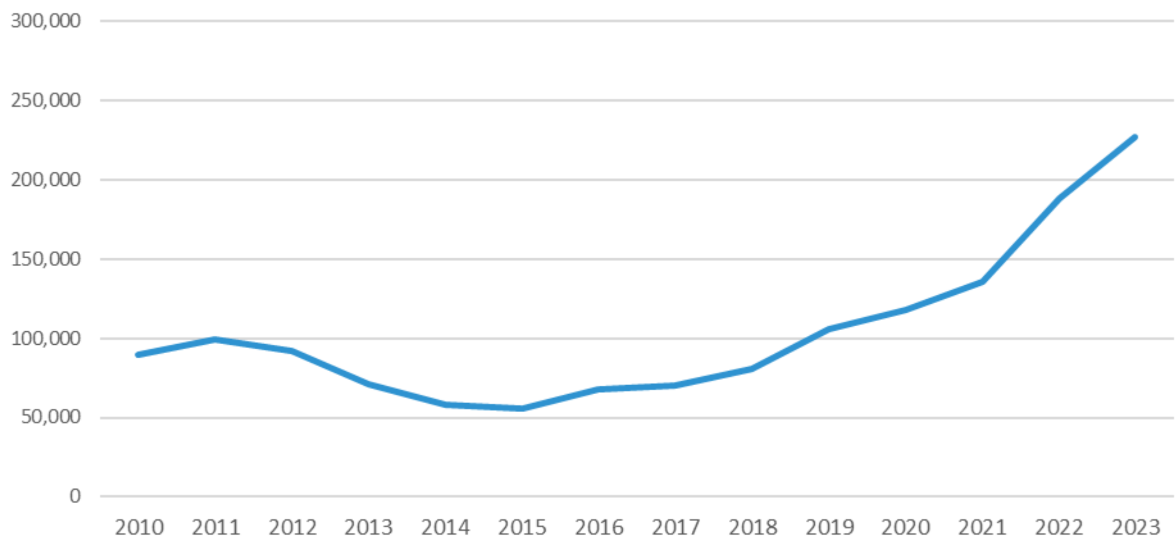


Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Employment

The number of persons employed shows significant growth, with an annual increase of 7.4% between 2010 and 2023. The analysis estimates the number of persons employed in the PV sector at around 227,300 for 2023.

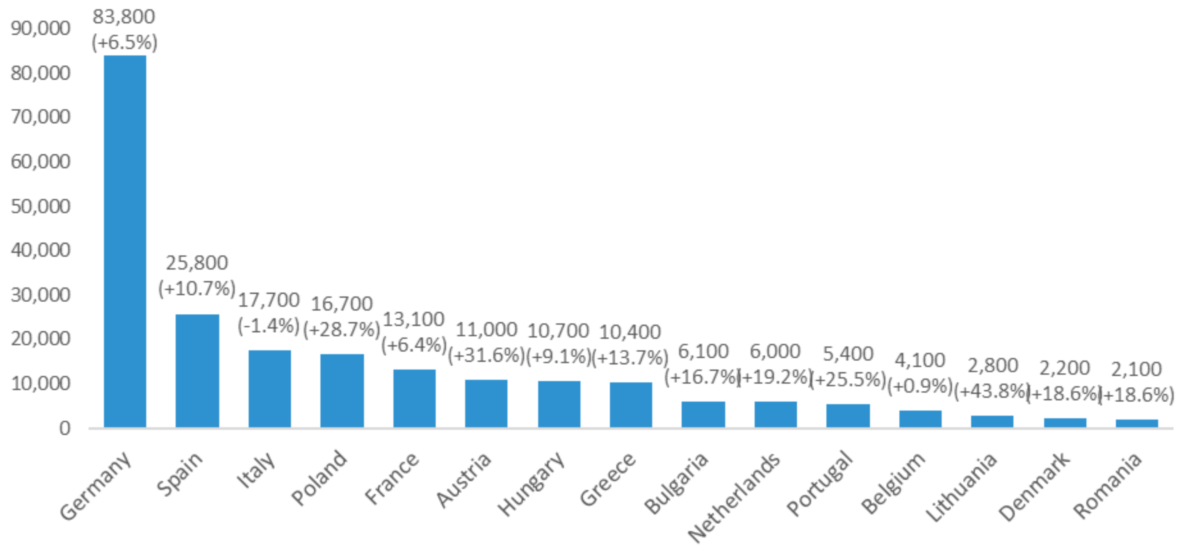
Figure 21 Employment in the EU PV energy sector over the period 2010–2023



Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Germany records the highest number of persons employed across EU countries, with over 83,800 people working in the photovoltaic energy sector. While the German market shows a strong upward trend, with an average annual growth rate of 6.5%, several other countries are experiencing even faster employment growth. Spain, for example, recorded a growth rate of 10.7% and Poland saw an exceptional increase of 28.7%. Italy is the only major market to exhibit a negative employment trend over the same period.

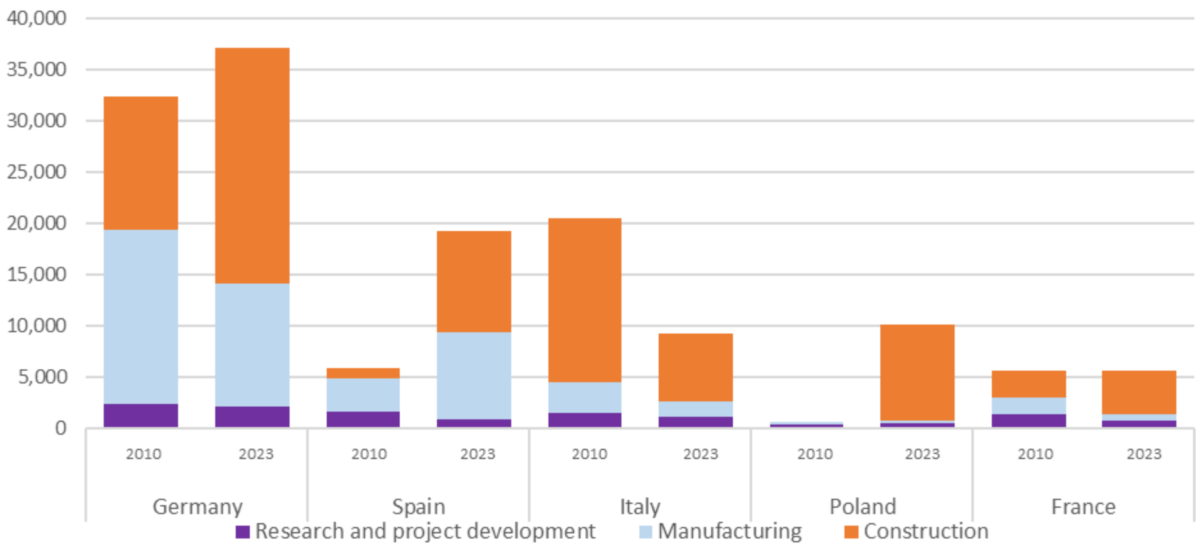
Figure 22 Employment in the PV energy value chain in selected EU Member States in 2023 and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The graph displays only those EU Member States that report the highest result values.

When operation is excluded, the trends across the value chain segments closely mirror those of gross value added, partly showing a decrease in manufacturing but growth in construction. The number of persons employed in manufacturing has decreased in Germany and Italy, while in Spain it has risen slightly. Employment in construction, by contrast, shows a clear upward trend except for Italy. A comparison between 2010 and 2023 reveals a decline. In 2010 and 2011, Italy experienced a rapid expansion of capacity, which then dropped sharply in the subsequent years. Since 2015, new constructions have led to increased employment, although the levels have yet to return to those observed in 2010 and 2011.

Figure 23 Employment per PV energy value chain segment, excluding operation, in the top five Member States in 2010 and 2023



Source: Prognos 2025.

4.3. Bioenergy

Bioenergy plays a key role in the European energy system. Through various conversion processes, natural energy carriers can be used to generate electricity, heat and transport fuels. Bioenergy holds additional significance for the energy system, as it contributes to the security of supply due to its storability and flexible deployment.

The technology relies on pre-processed energy carriers, such as biofuels or biomass. These typically undergo several processing steps before they can be used for energy production. For example, fuel crops need to be sown, grown and harvested before being converted into fuel for energy generation. Once the energy carrier is produced, bioenergy is versatile and can be used in both small-scale or large-scale applications for heating, electricity production and mobility purposes.

Although all clean energy technologies require resources – for example, to produce technological components – the provision and conversion of energy carriers such as wood, corn, grain, rape, slurry, biowaste, sludge and used cooking oils is unique to bioenergy. The associated agricultural and forestry activities constitute a significant economic activity and are included in the value chain segment resource sourcing.

Electricity generation from bioenergy totalled 155 TWh in 2023, representing an increase of nearly 40% compared to 2010. It accounted for just under 6% of the total electricity generation in the EU. Heat generation plays a significantly larger role: output rose from 115 TWh to around 184 TWh, accounting for over 32% of gross heat production.[16]

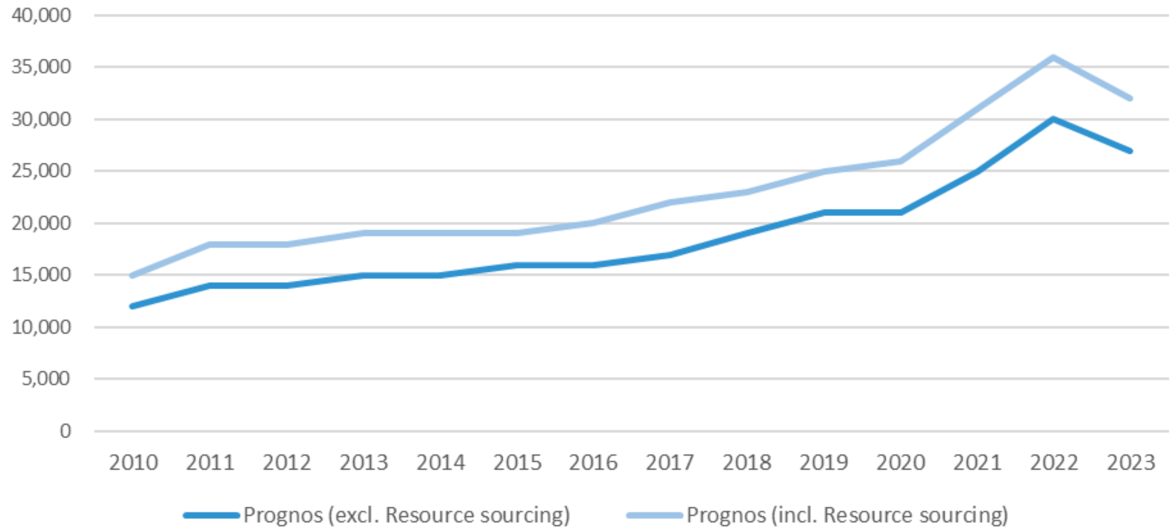
The bioenergy value chain consists of five segments: resource sourcing, research and project development, manufacturing, construction, and operation. Unless otherwise stated, all figures refer to the bioenergy value chain segment excluding resource sourcing, as this segment is only indirectly linked to energy production.

Gross value added

The model shows consistent growth in gross value added over the past decade, both with inclusion and exclusion of resource sourcing. A sharp increase is observed between 2019 and 2022, followed by a decline in 2023. For 2023, the analysis estimates gross value added – excluding resource sourcing – at EUR 27.1 billion.

[16] Eurostat (2025). Complete energy balance [nrg_bal_c].https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_c/default/table?lang=en.

Figure 24 Gross value added of the EU bioenergy value chain (in MEUR) over the period 2010–2023



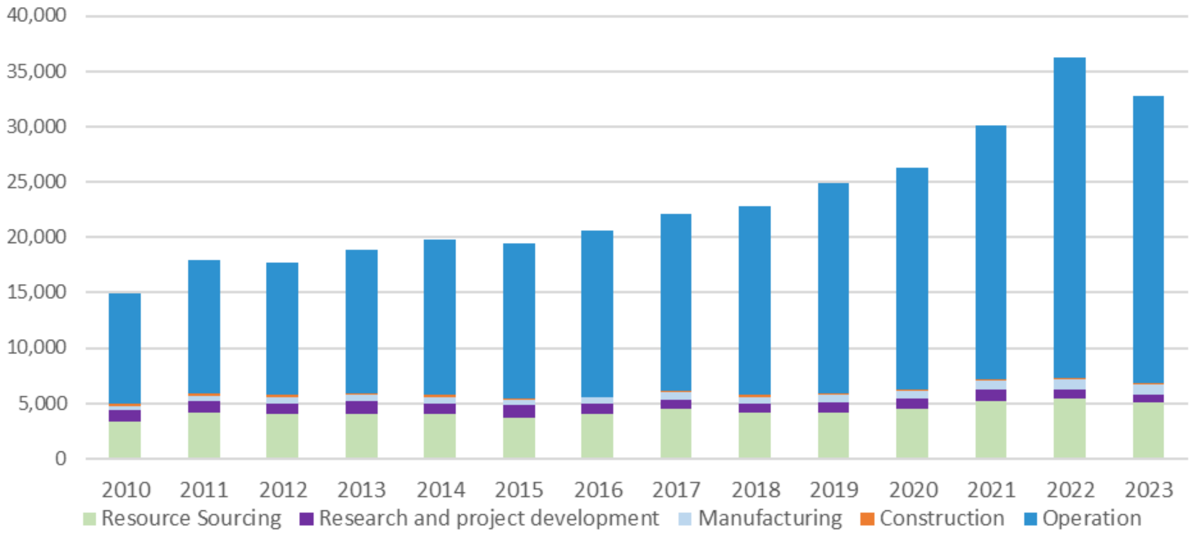
Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Operation remains the dominant segment, showing both high relative growth and substantial absolute values. It also accounts for the largest share of gross value added in the value chain. In 2023, the gross value added of the operation segment amounted to EUR 25.5 billion. In the remaining value chain segments, changes have been less dynamic. For example, construction activities gradually lost importance after 2012, whereas Manufacturing increased slightly, albeit at a low absolute level.

Gross value added figures show a peak in 2022, followed by a decline, which is primarily attributable to a sharp increase in day-ahead electricity prices in the wake of Russia's war of aggression.[17] Unlike other clean energy technologies, electricity output in 2023 decreased slightly compared to the previous year, while electricity prices also fell modestly. Both factors contributed to a slight decline in gross value added in 2023. Research and project development, as well as manufacturing, remain relatively constant over time. Overall, the entire value chain has experienced a growth rate of 6.6% p.a.

[17] FfE (2025). European day-ahead electricity prices in 2024. https://www.ffe.de/en/publications/european-day-ahead-electricity-prices-in-2024/.

Figure 25 Gross value added by value chain segment in the EU bioenergy sector (in MEUR) over the period 2010–2023 (including resource sourcing)

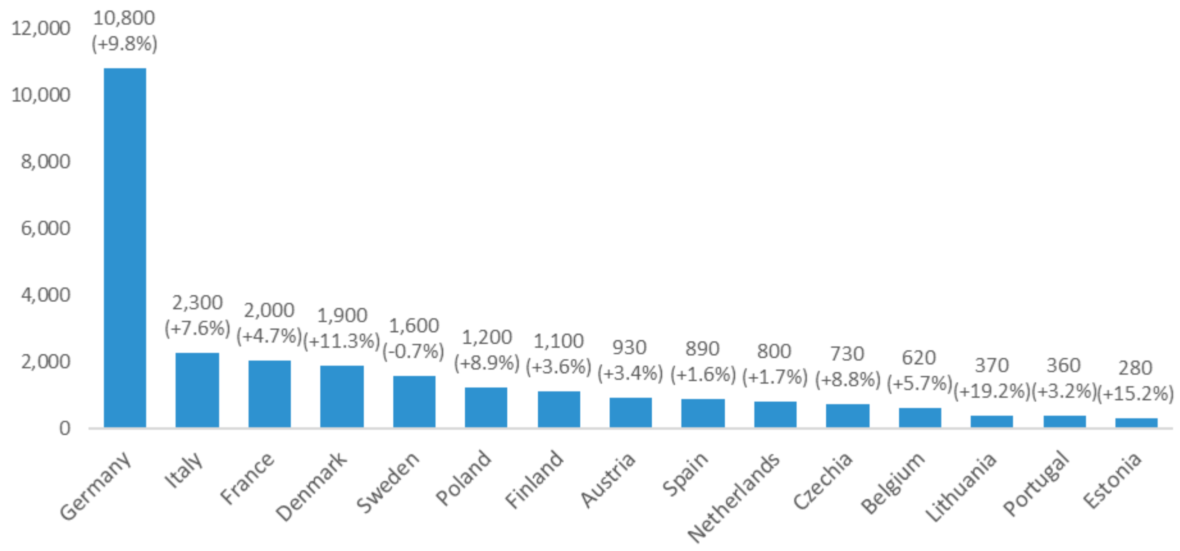


Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Germany records the highest absolute gross value added among all EU Member States, at EUR 10.8 billion. This is because around one-third of gross electricity production from bioenergy in the EU is generated by installations in Germany.[18] It is followed by Italy at EUR 2.3 billion, ahead of France at EUR 2.0 billion and Denmark at EUR 1.9 billion. Among the top five countries, Denmark shows the highest annual growth rate at 11.3%.

[18] Eurostat (2025). Complete energy balance [nrg_bal_c].https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_c/default/table?lang=en].

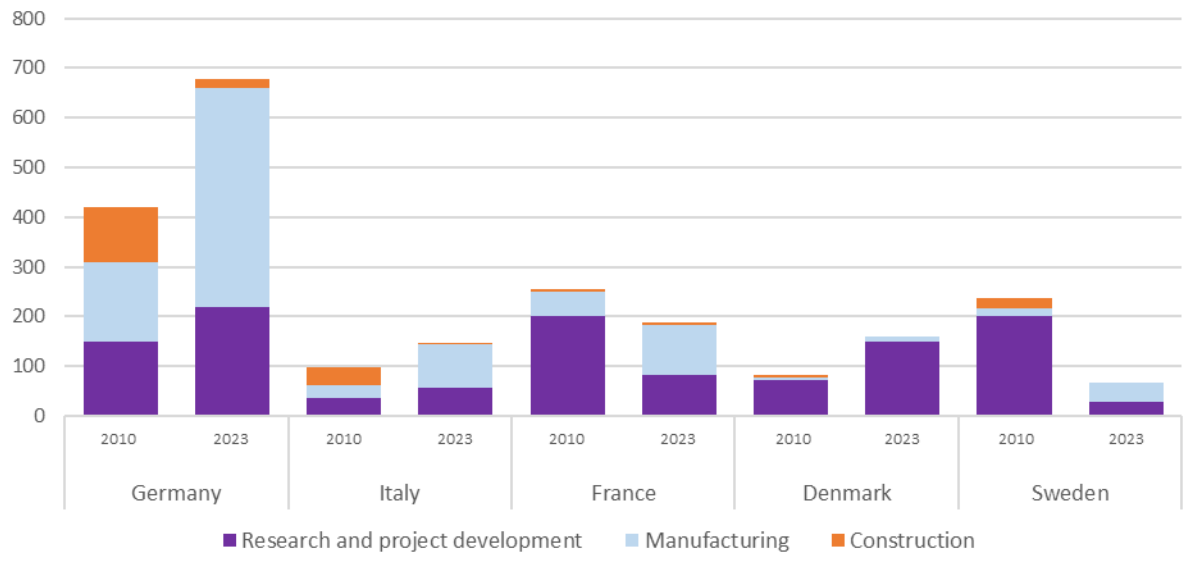
Figure 26 Gross value added of the bioenergy value chain in selected EU Member States in 2023 (in MEUR) and annual growth over the period 2010–2023 (excluding resource sourcing)



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The results are presented as nominal values, reflecting the respective annual price level. The graph displays only those EU Member States that report the highest result values.

When the operation segment is excluded, the five largest bioenergy markets in the EU exhibit diverging trends: while Germany, Italy and Denmark are experiencing growth, France and Sweden are contracting. Germany shows growth in the manufacturing and research and project development segments, while construction shows a downward trend. Italy records a slight growth in manufacturing and research and project development. In contrast, France shows a significant decline in research and project development, a pattern also observed in Sweden, but both countries show growth in the manufacturing segment. Denmark, on the other hand, continues to grow, particularly in the research and project development segment of the value chain.

Figure 27 Gross value added by value chain segment, excluding operation, in the top five Member States in 2010 and 2023 (in MEUR) (excluding resource sourcing)

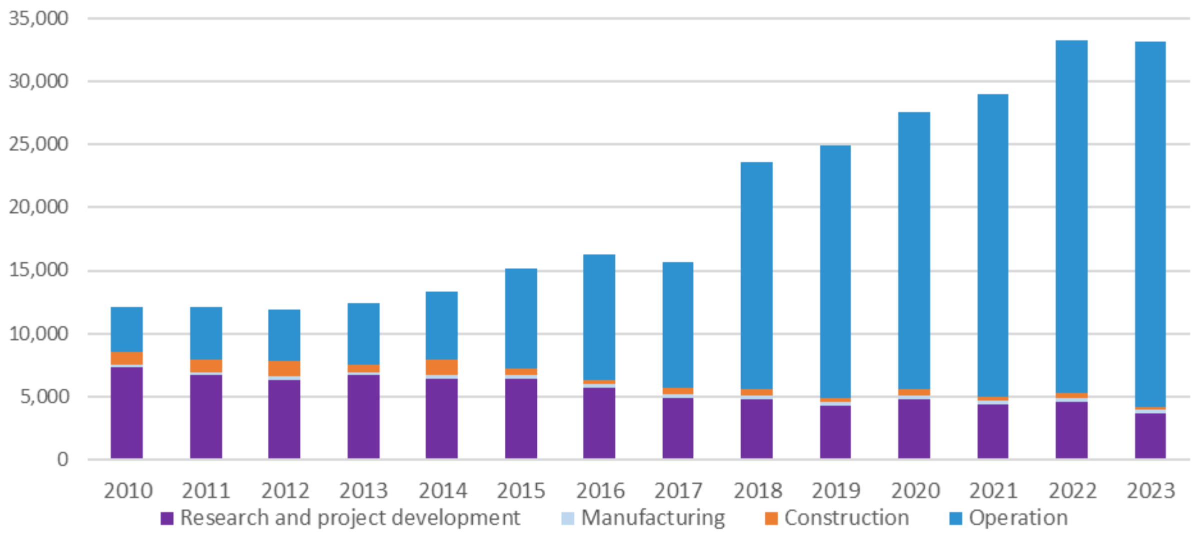


Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level.

Enterprises

Growth in the number of enterprises is primarily driven by operation with the total number of enterprises rising from 12,200 in 2010 to more than 33,300 in 2023. Similar to gross value added, the number of enterprises has grown significantly since 2010. Manufacturing remains relatively small, research and project development and construction declined in the same period.

Figure 28 Number of bioenergy enterprises by value chain segment in the EU over the period 2010–2023 (excluding resource sourcing)

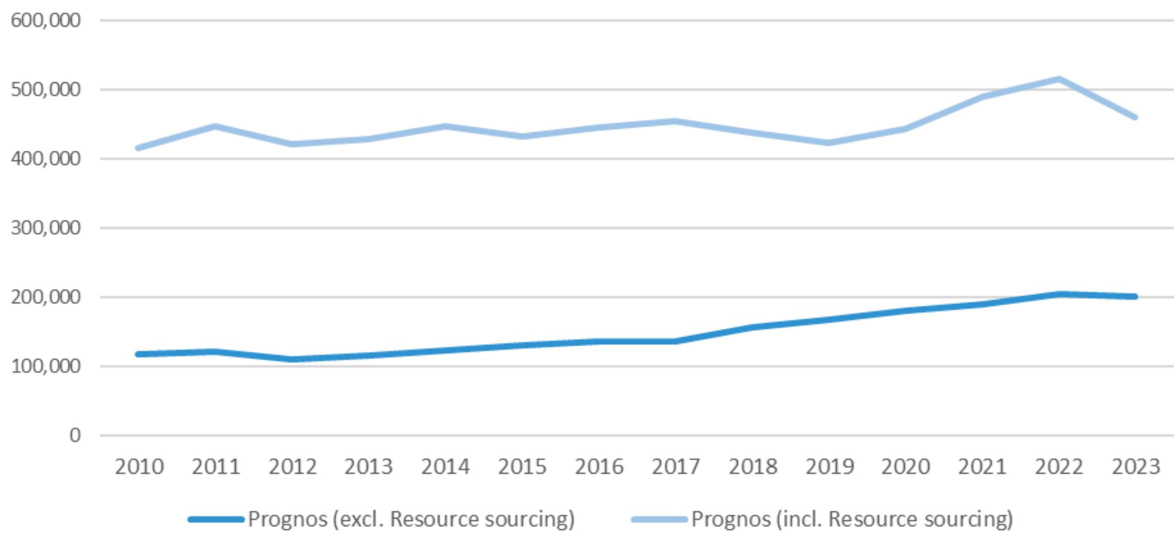


Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Employment

The model estimates that employment growth is less dynamic than gross value added, with an annual growth rate of 4.3% (excluding resource sourcing). With 201,400 persons employed in 2023, employment nearly doubled compared to 2010. In comparison, the value for gross value added more than doubled in the same period. When including resource sourcing, the growth rate is 0.8% per year due to a significant decline from 2022 to 2023, resulting in a total value of 459,800 in 2023.

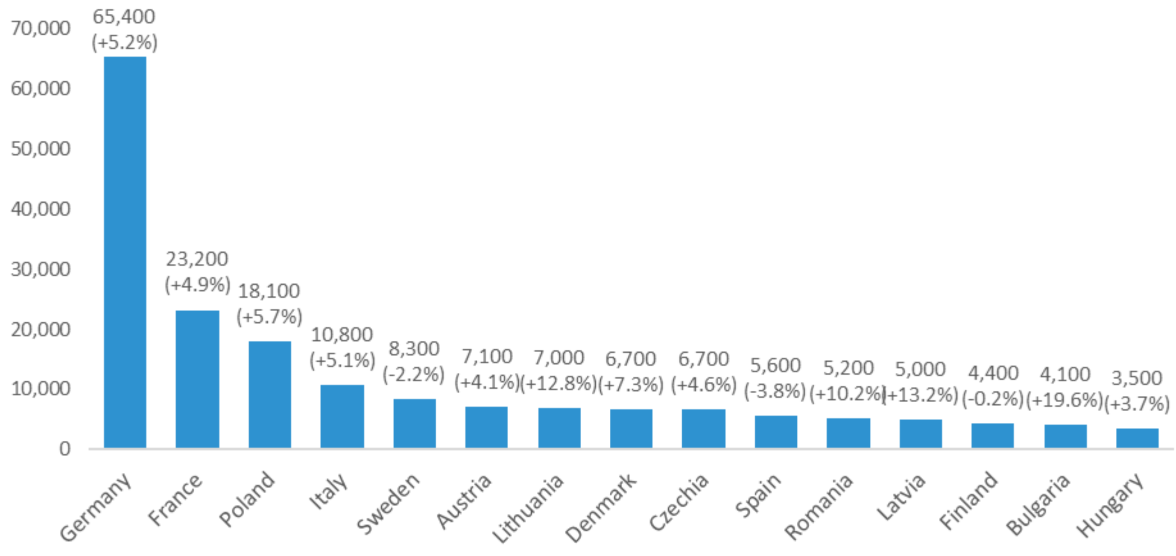
Figure 29 Employment in the EU bioenergy sector over the period 2010–2023



Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Among the top five Member States, Poland and Lithuania show the highest annual growth at 5.7% and 12.8%, respectively. Similarly to gross value added, the highest level of employment is recorded in Germany, with 65,400 persons employed and an annual growth rate of 5.2%. France follows with 23,200 persons employed and Poland with 18,100.

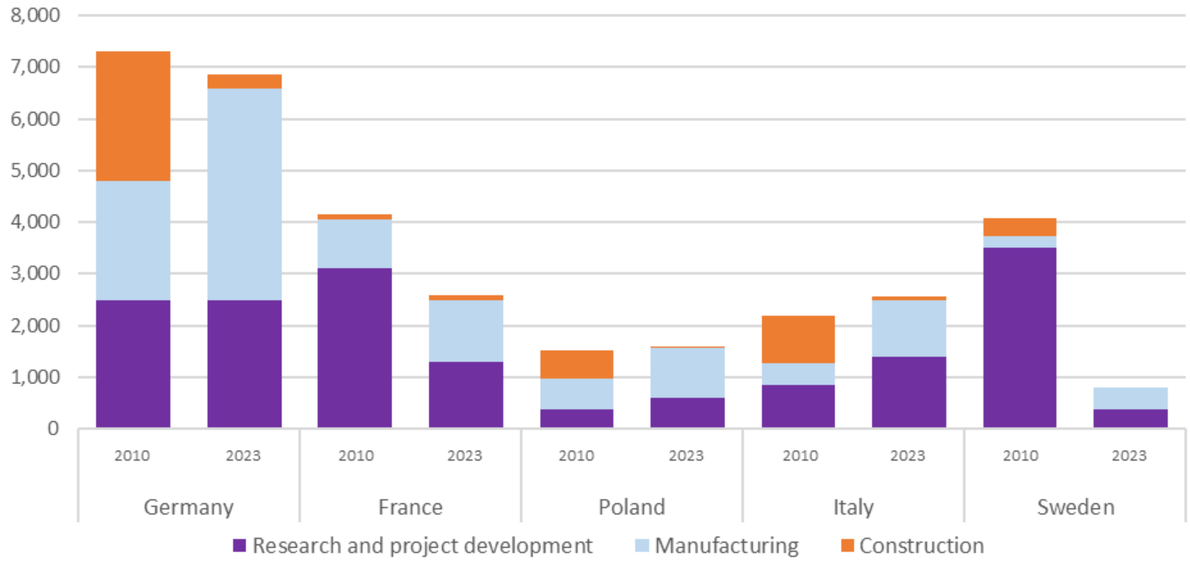
Figure 30 Employment in the bioenergy value chain in selected EU Member States in 2023 and annual growth over the period 2010–2023 (excluding resource sourcing)



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The graph displays only those EU Member States that report the highest result values.

When the operation segment is excluded, Germany, France and Sweden show a decline in employment, while Poland and Italy show an increase. In Germany, for example, the number of persons employed decreased significantly in the construction segment from 2,500 to 250 between 2010 and 2023. A similar trend is evident in France, and more pronounced in Sweden, where the decline is primarily attributable to reductions in research and project development. Poland and Italy are both experiencing positive dynamics, primarily driven by the manufacturing segment.

Figure 31 Employment per bioenergy value chain segment, excluding operation, in the top five Member States in 2010 and 2023 (excluding resource sourcing)



Source: Prognos 2025.

4.4. Hydropower

Hydropower has a long history of energy generation. The first plants were installed in the 19th century, while the use of watermills can be dated back to before the Roman Empire. Today, hydropower serves as a reliable source of electricity generation, making it one of the most important clean energy sources globally.

In the EU, installed hydropower capacity increased slightly from 143 GW in 2010 to around 153 GW in 2023.[19] Actual electricity generation declined over the same period, from approximately 372 TWh to 329 TWh. As a result, hydropower accounted for around 12% of total electricity generation in the EU in 2023.[20]

The hydropower value chain has remained relatively unchanged over the last decade. No significant technological breakthroughs have occurred. Developments are primarily focused on the modernisation of existing capacities. However, pumped hydro storage may still gain further in significance. This technology operates using two reservoirs; when there is a surplus of electricity, water is pumped into the upper reservoir; when electricity is needed, the water is released back down through turbines to generate power. It plays a crucial role in grid stability by balancing short-term fluctuations and covering peak loads.

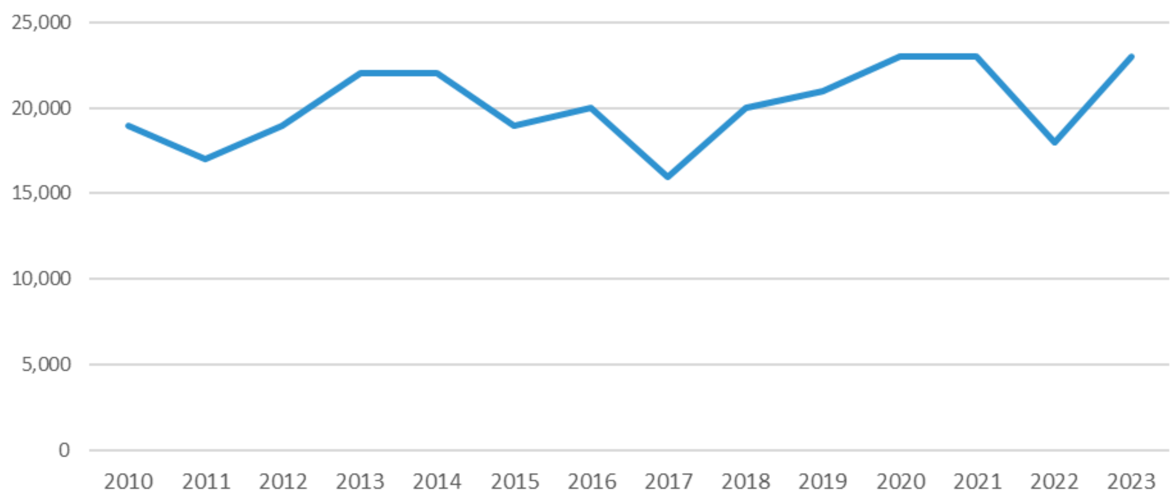
[19] Eurostat (2025). Electricity production capacities for renewables and wastes [nrg_inf_epcrw]. https://ec.europa.eu/eurostat/databrowser/view/nrg_inf_epcrw$defaultview/default/table?lang=en.

[20] Eurostat (2025). Complete energy balance [nrg_bal_c].https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_c/default/table?lang=en.

Gross value added

Unlike other clean energy technologies, hydropower has shown little dynamism since 2010. Based on the Structural Business Statistics (SBS), the model shows gross value added of EUR 22.5 billion for 2023. In comparison, gross value added amounted to around EUR 18.9 billion in 2010. Installed capacities in EU countries have remained relatively stable, with minimal expansion due to limited natural potential and the considerable environmental implications of large-scale projects.

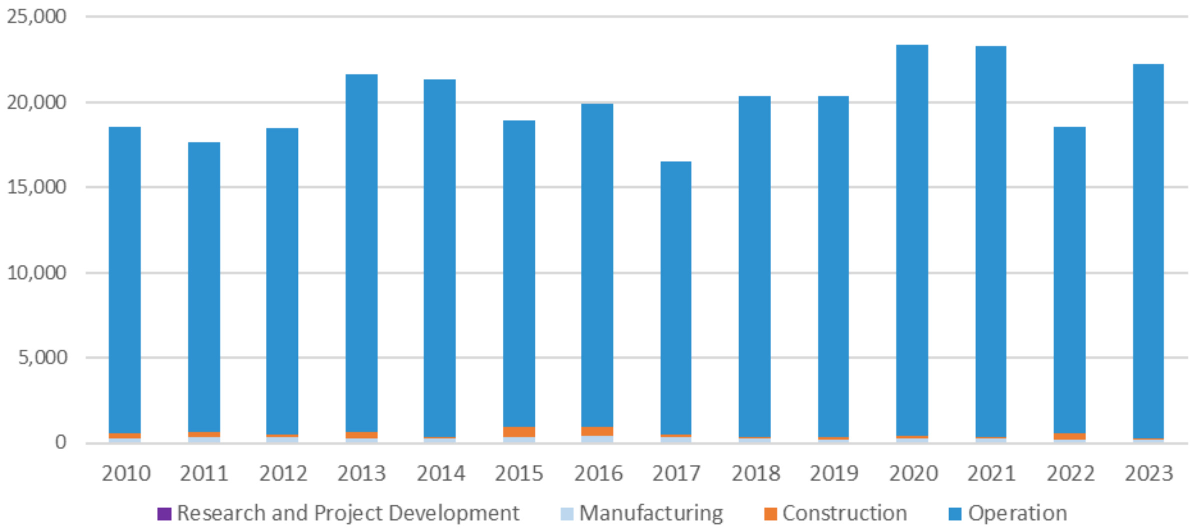
Figure 32 Gross value added of the EU hydropower value chain (in MEUR) over the period 2010–2023



Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Since 2010, nearly all value added has been generated through the operation of existing hydropower capacities. Of the EUR 22.5 billion in total gross value added recorded in 2023, approximately EUR 22.2 billion was generated by the operation segment of the value chain. Value chain segments such as manufacturing and construction have played a minimal role due to the limited expansion of production capacity. Notably, electricity production from installed hydropower capacity has fluctuated. This volatility is reflected in the revenues of companies in the operation segment and explains the fluctuating gross value added figures.

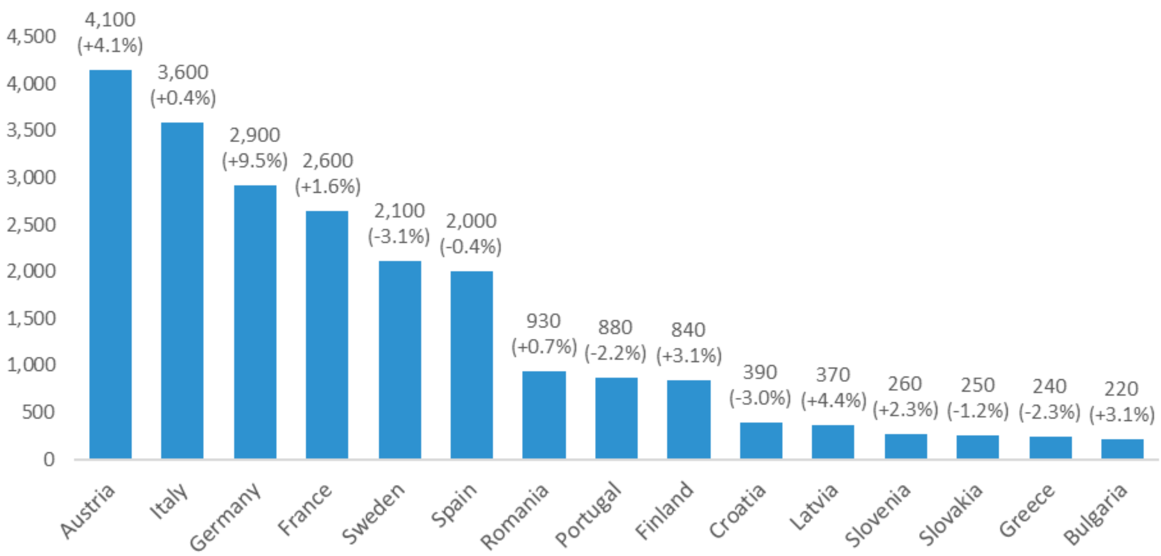
Figure 33 Gross value added by value chain segment in the EU hydropower sector (in MEUR) over the period 2010–2023



Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

The EU hydropower market is primarily concentrated in Austria, Italy, Germany and France, though these countries exhibit differing growth trends. At EUR 4.1 billion, Austria leads the EU hydropower market, ahead of Italy at EUR 3.6 billion and Germany at EUR 2.9 billion. With respective annual growth rates of 4.1% and 9.5%, Austria and Germany increased their gross value added, while the remaining EU countries recorded significantly lower growth.

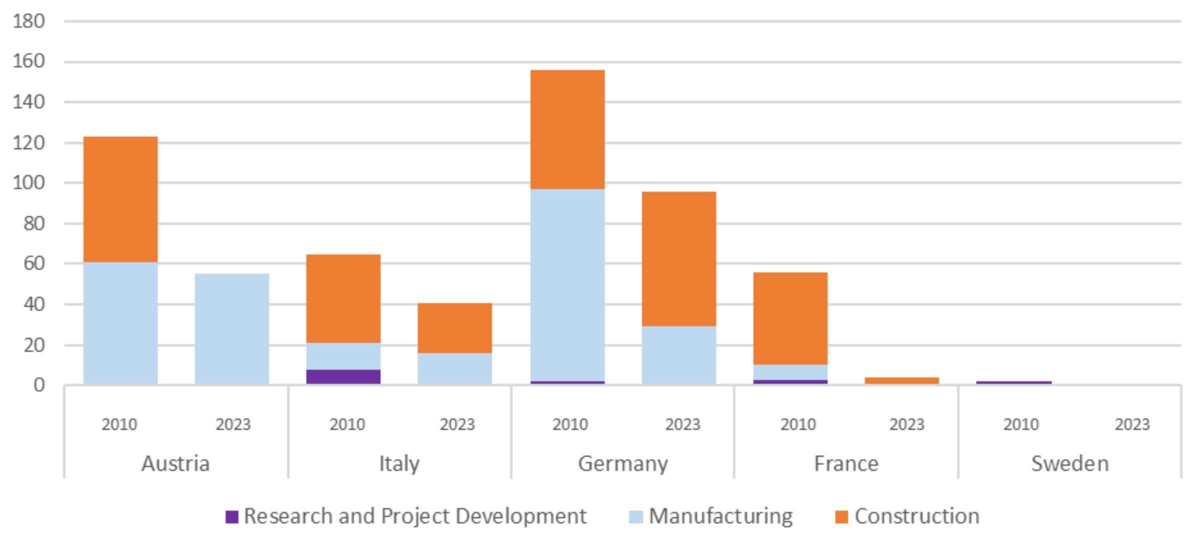
Figure 34 Gross value added of the hydropower value chain in selected EU Member States in 2023 (in MEUR) and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The results are presented as nominal values, reflecting the respective annual price level. The graph displays only those EU Member States that report the highest result values.

In the five largest EU hydropower markets, gross value added declined significantly when the value chain segment operation is excluded. Across the leading markets, the gross value added of research and project development, manufacturing and construction decreased, with only two exceptions: in Germany a minor capacity expansion occurred between 2018 and 2023, resulting in corresponding effects on the construction segment. In Italy, gross value added in the manufacturing segment slightly increased.

Figure 35 Gross value added by value chain segment, excluding operation, in the top five Member States in 2010 and 2023 (in MEUR)

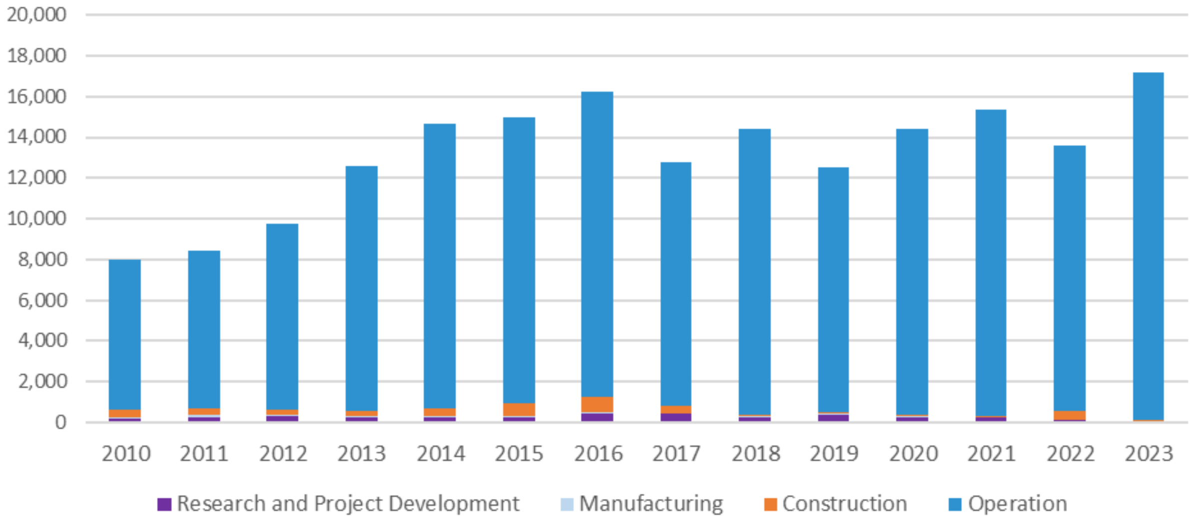


Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level.

Enterprises

The hydropower market shows a growing number of companies, most of which are likely engaged in electricity marketing and distribution. Despite almost stagnant capacity levels, the number of companies active in the operation segment grew from 7,400 in 2010 to 17,000 in 2023. This suggests that market entry has been particularly strong in the areas of electricity distribution and trading. The remaining value chain segments saw virtually no increase.

Figure 36 Number of hydropower enterprises by value chain segment in the EU over the period 2010–2023

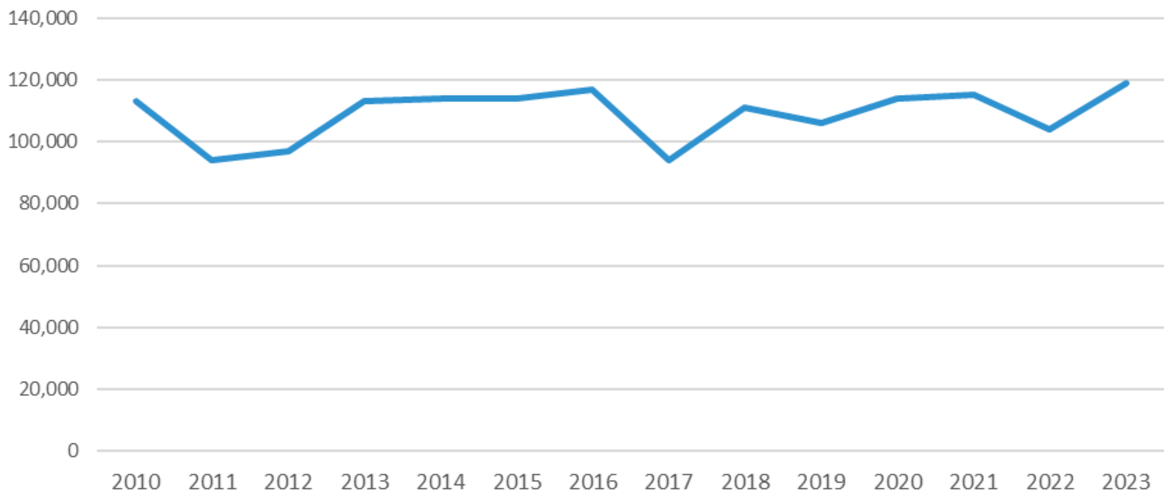


Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Employment

EU employment figures have remained nearly constant since 2010, reflecting the stable installed hydropower capacities and generated power outputs. In 2023, around 119,200 persons were directly employed in the hydropower sector, compared to around 113,000 in 2010.

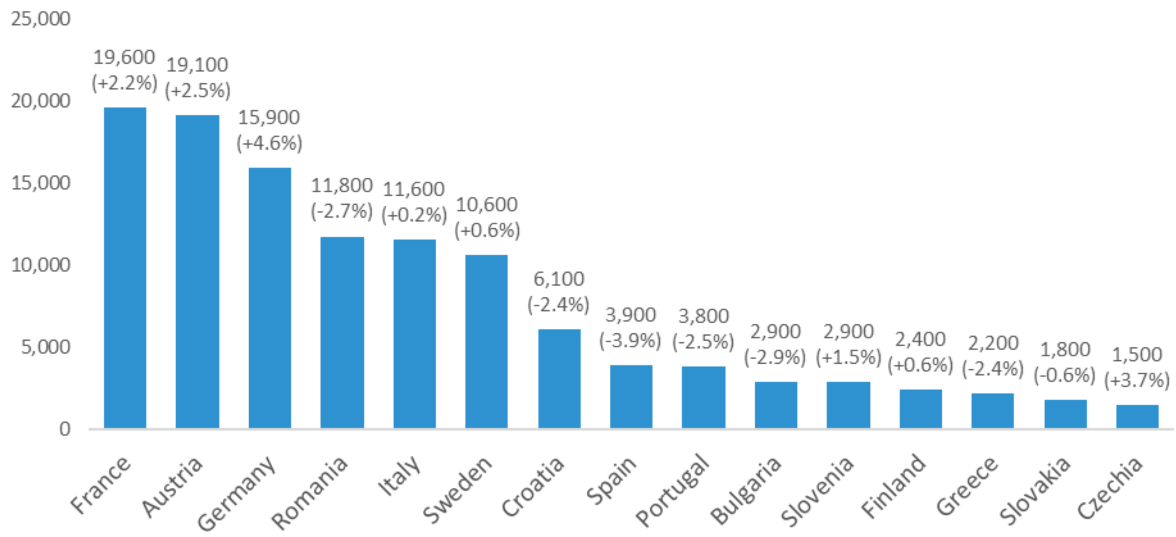
Figure 37 Employment in the EU hydropower sector over the period 2010–2023



Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

The comparison of persons employed and gross value added reveals that EU countries exhibit varying levels of labour intensity in the market. France reports the highest number of persons employed, at 19,600, followed closely by Austria, at around 19,100. Austria recorded the highest gross value added among all EU countries, potentially suggesting that the French hydropower sector is disproportionately labour-intensive.

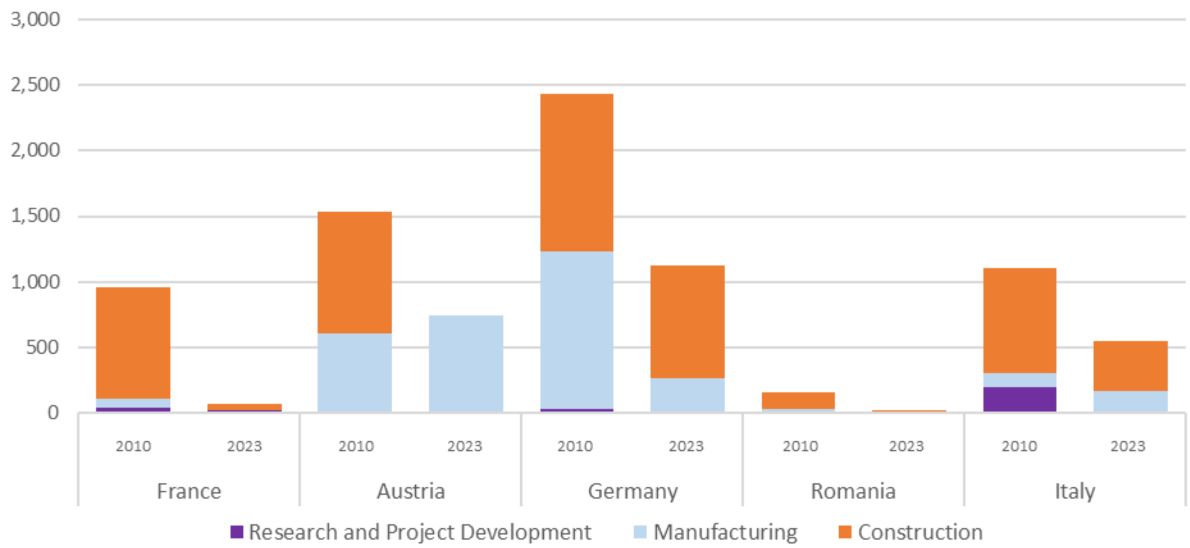
Figure 38 Employment in the hydropower value chain in selected EU Member States in 2023 and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The graph displays only those EU Member States that report the highest result values.

Similar to gross value added, the employment indicator also shows a decline when the operation segment is excluded. Between 2010 and 2023, the number of persons employed decreased across value chain segments, with only minor growth observed in manufacturing in Austria and Italy. This trend is mainly attributable to the limited expansion of hydropower capacity since 2010, which has led to declines in research and project development, as well as construction, across most countries.

Figure 39 Employment per hydropower value chain segment, excluding operation, in the top five Member States in 2010 and 2023



Source: Prognos 2025.

4.5. Heat pumps

The use of heat pumps, particularly in buildings, has gained significant attention and momentum in recent years. They offer a solution for decarbonising heat supply in a decentralised manner. Heat pumps are typically used in standalone configurations in buildings as well as in the industry.

Heat pumps extract thermal energy from their surroundings, such as the air, and make it usable for space or water heating. A refrigerant absorbs the ambient heat and evaporates. The resulting gas is then compressed in a compressor, significantly increasing the temperature. This heat is transferred to the heating system. Industrial heat pumps recover low-temperature waste heat from industrial processes and upgrade it to a higher temperature for reuse.

The importance of heat pumps for heat supply in the EU has steadily increased since 2010. Ambient heat generation reached around 9.1 TWh in 2023, up from just 388 GWh in 2010. Despite this strong growth, heat pumps accounted for only 1.6% of total heat generation in the EU in 2023.[21]

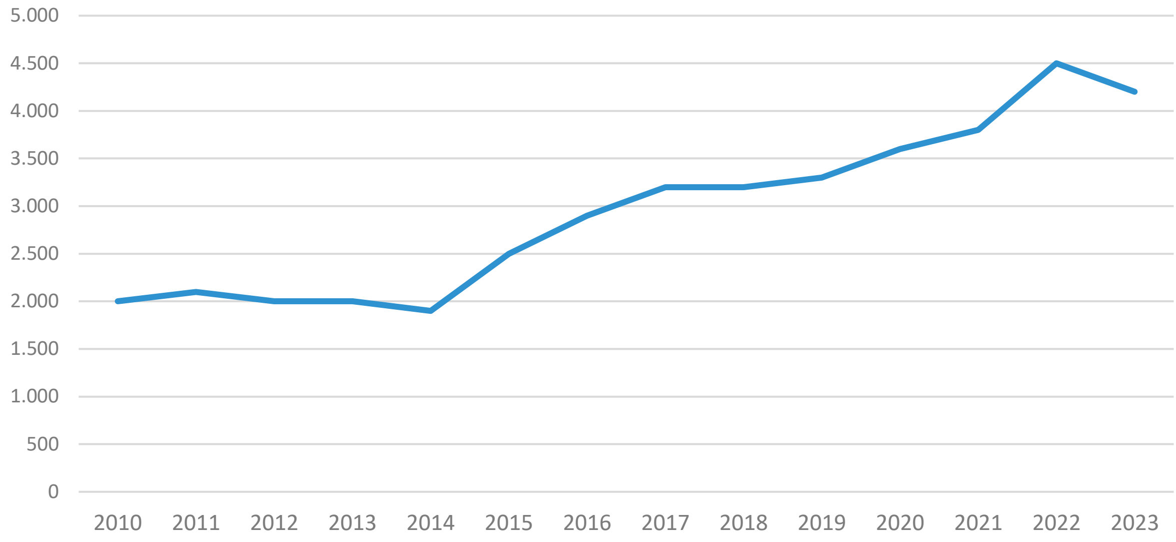
The four value chain segments along the heat pump value chain are research and project development, manufacturing, construction and operation. Due to the decentralised use of heat pumps and the direct on-site use of the heat they produce, this form of energy production is not reflected in the energy markets. As a result, the operation segment within this value chain remains limited, as it does not typically generate measured economic effects.

Gross value added

The steadily increasing number of installations in the heat pump market has resulted in a doubling of gross value added. The gross value added rose from around EUR 2.0 billion in 2010 to over EUR 4.2 billion by 2023. In 2023, the last reporting year for this project, a slight decline is observed, as sales of heat pumps decreased in some countries. For example, in Italy, sales dropped by approximately 250,000 units.

[21] Eurostat (2025). Complete energy balance [nrg_bal_c]. https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_c/default/table?lang=en.

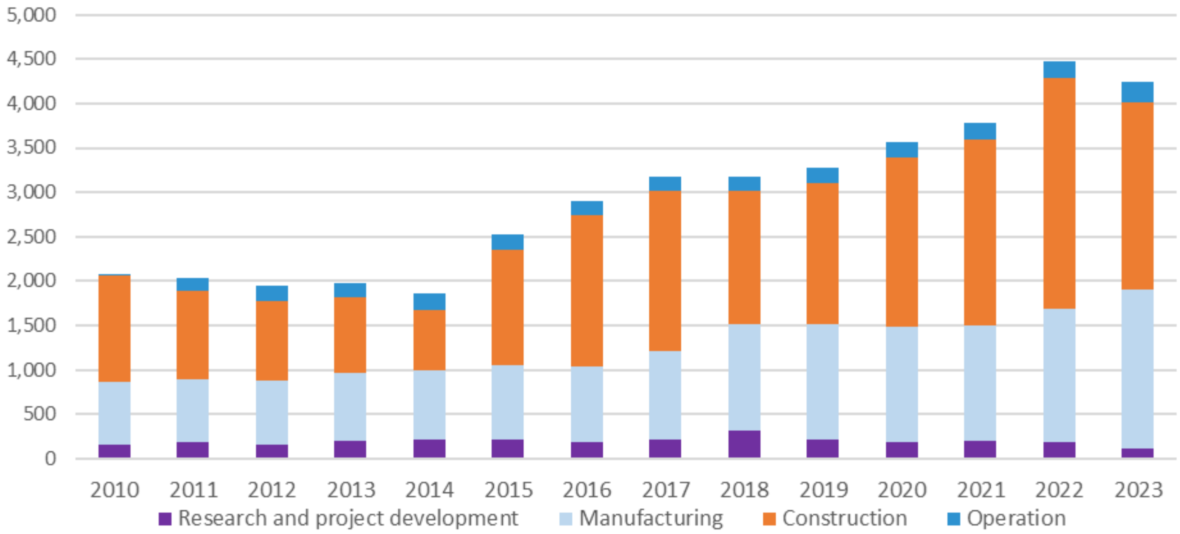
Figure 40 Gross value added of the EU heat pump value chain (in MEUR) over the period 2010–2023



Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Gross value added increased steadily over the period concerned, peaking in 2022 before slightly declining in 2023. The decline in gross value added can be explained by slightly lower heat pump sales, for example in Italy. The largest contribution consistently comes from the construction segment, followed by manufacturing, which shows stable growth. Research and project development, as well as operation, play lesser roles, with operation increasing gradually in recent years. The growth across segments highlights the sector's rising economic relevance, particularly driven by construction activities. Similarly to solar thermal systems, heat pumps are most often used for heating or cooling buildings without involving sales-type transactions. The operations segment is relatively small compared with technologies that involve large electricity transfers.

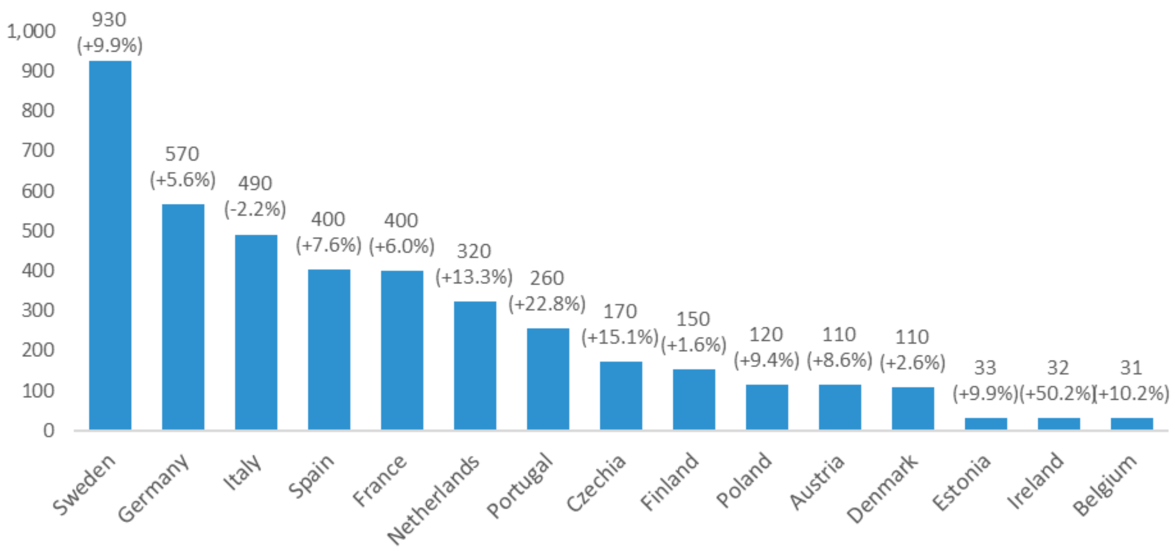
Figure 41 Gross value added by value chain segment in the EU heat pump sector (in MEUR) over the period 2010–2023



Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Across EU countries, gross value added shows dynamic growth trends, with Italy being the only exception. Sweden leads the heat pump sector at EUR 930 million, with annual growth of 9.9%, followed by Germany (EUR 570 million, +5.6%) and Italy (EUR 490 million, –2.2%). Spain and France show similar levels at around EUR 400 million, with both countries recording solid growth rates. Portugal stands out with EUR 260 million and the highest growth rate of 22.8%. Other notable players include the Netherlands and Czechia, with modest values and growth.

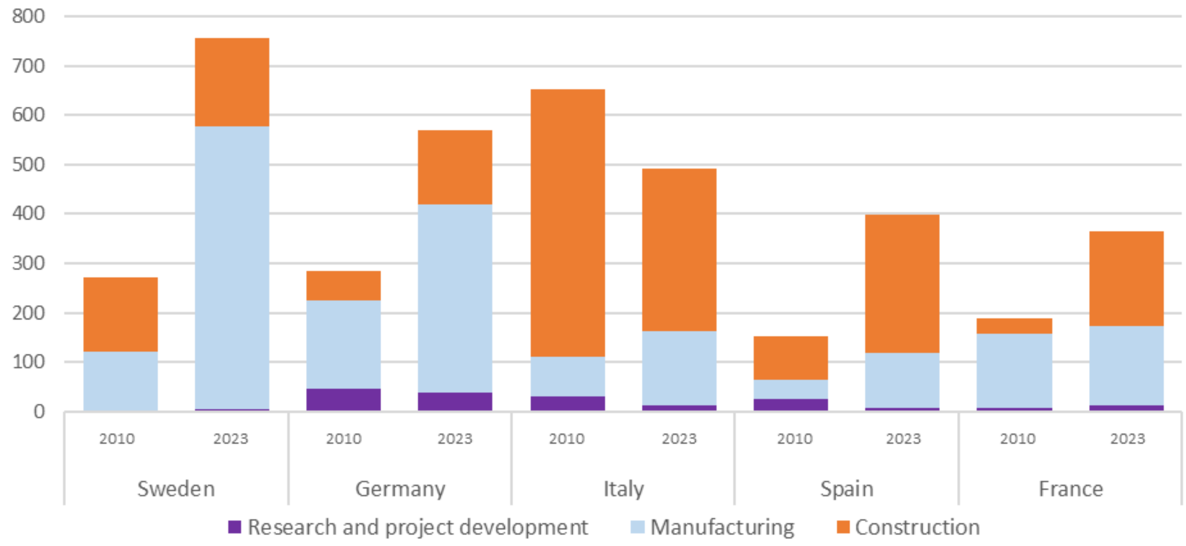
Figure 42 Gross value added of the heat pump value chain in selected EU Member States in 2023 (in MEUR) and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The results are presented as nominal values, reflecting the respective annual price level. The graph displays only those EU Member States that report the highest result values.

When operation activities are excluded, Sweden records the highest gross value added among all Member States, primarily driven by the manufacturing segment. The operation segment plays a less significant role in the heat pump sector than in other value chains. Germany shows notable growth, with an increase from EUR 280 million to EUR 570, largely due to manufacturing. In contrast, Italy's gross value added has declined overall, despite growth in manufacturing, with both research and project development and Construction having decreased significantly. Spain and France show similar development to Germany, with growth primarily driven by the construction segment.

Figure 43 Gross value added by value chain segment, excluding operation, in the top five Member States in 2010 and 2023 (in MEUR)

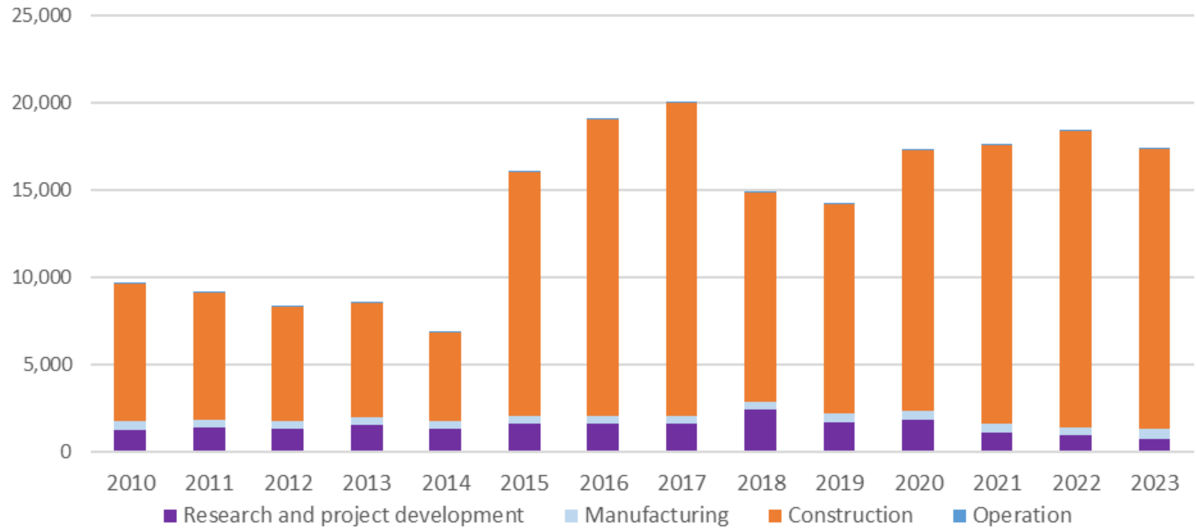


Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level.

Enterprises

In the heat pump market, most enterprises operate in the construction segment, primarily in the installation of heat pump systems. The construction segment has experienced substantial growth; in 2023, more than 17,300 enterprises were part of the heat pump value chain. The analysis also highlights the limited economic significance of the operation segment within this value chain. The number of enterprises involved in research and project development and manufacturing has remained relatively stable, showing limited dynamic growth between 2010 and 2023.

Figure 44 Number of heat pump enterprises by value chain segment in the EU over the period 2010–2023

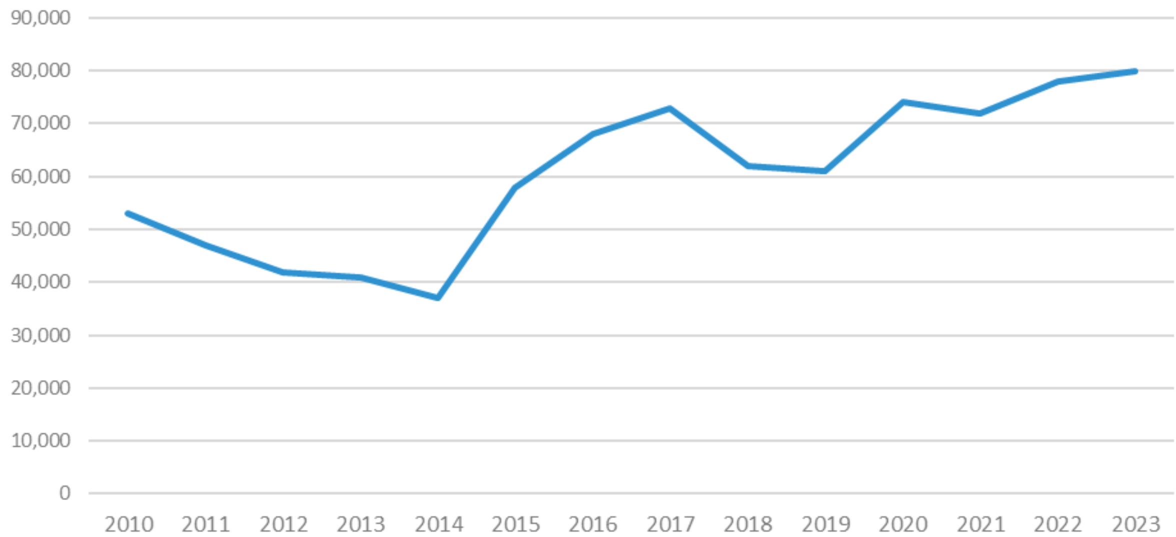


Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Employment

The number of persons employed shows an annual growth rate of 3.3%, reaching 80,100 persons in 2023. After a decline until 2014, the heat pump sector has continued to grow, reflecting the increasing number of heat pumps installed.

Figure 45 Employment in the EU Heat Pump sector over the period 2010–2023

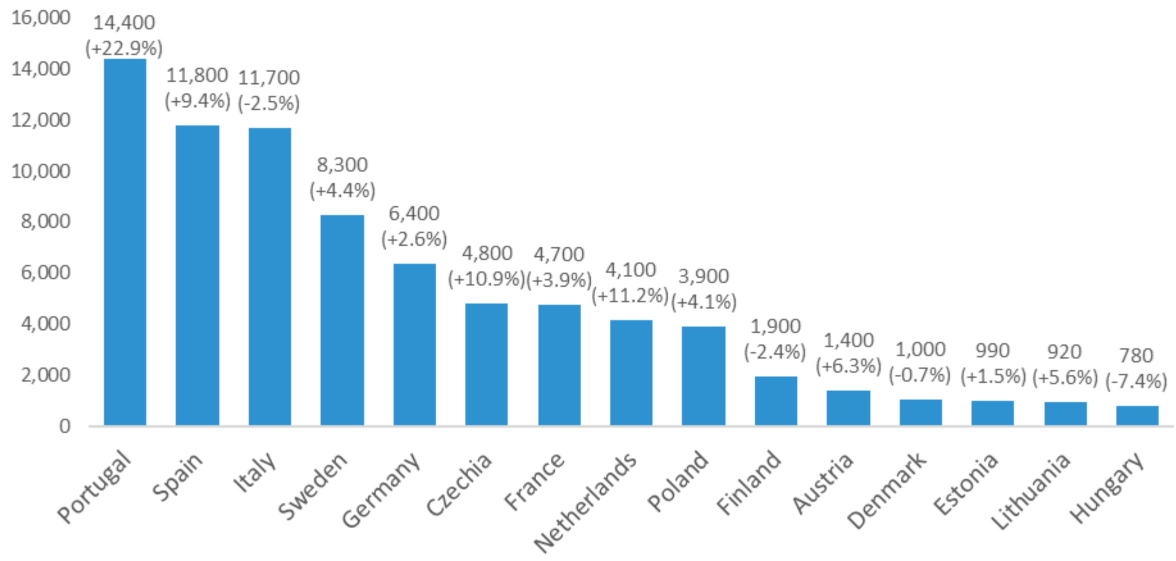


Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Portugal recorded the highest number of persons employed in the heat pump sector, at over 14,400 in 2023, reflecting strong momentum and an annual growth rate of 22.9%. In 2023, Portugal ranked fourth among all EU Member States in terms of the absolute number of heat pump installations. The employment figure for Portugal might partly be explained by low labour productivity. Portugal's prominent role highlights a notable difference between the indicators of gross value added and employment. While the country records the highest employment among all EU Member States, it ranks only seventh in terms of gross value added. Construction activities tend to be relatively labour-intensive but generate lower gross value added. In contrast, the manufacturing sector shows higher value creation, though with lower employment levels.

Portugal is followed by Spain and Italy, each with nearly 12,000 persons employed, though with diverging trends: Spain showed a positive dynamic, while Italy experienced a decline. Other Member States show lower values, such as Sweden and Germany, each reporting between 8,300 and 6,400 persons.

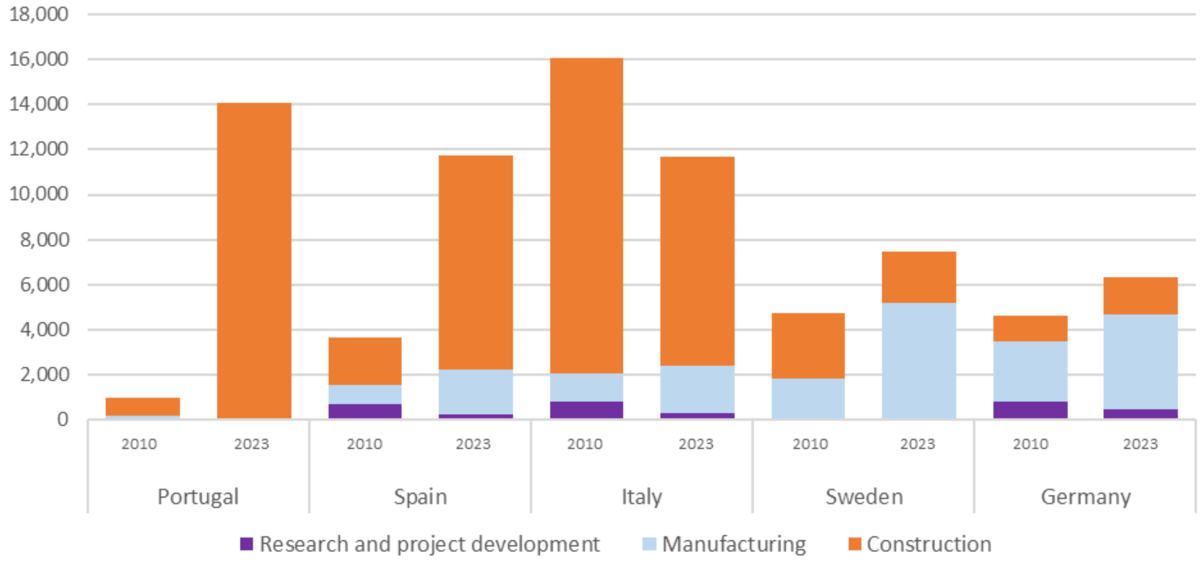
Figure 46 Employment in the heat pump value chain in selected EU Member States in 2010 and 2023 and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The graph displays only those EU Member States that report the highest result values.

For the five largest EU markets, except for Italy, the analysis shows an increase in persons employed. Especially Portugal and Spain exhibit a very dynamic trend, primarily driven by the construction segment. In contrast, Italy reports a decrease in the number of persons employed due to lower sales in the heat pump market. In addition, Sweden and Germany report significant growth in the manufacturing segment.

Figure 47 Employment by value chain segment, excluding operation, in the top five Member States in 2010 and 2023



Source: Prognos 2025.

4.6. Batteries

Battery technologies are playing a growing role in the efforts to achieve climate neutrality. Decarbonisation of the transport sector largely depends on the transition to electric drivetrains, with battery systems installed in vehicles being pivotal to this goal. Additionally, the use of battery systems is becoming increasingly important for balancing supply and demand in the future energy system. The systems range from large utility-scale battery projects to smaller private battery systems, including for storing excess electricity produced through privately owned solar PV systems.

Lithium-ion batteries dominate the battery market. Since 2010, their costs have fallen by approximately 90%, while energy density and lifespan have steadily increased.[22]

Analysis of the battery value chain covers the research and project development, manufacturing and End-of-Life/recycling segments. Given the scarcity of rare earth elements and the environmental impact associated with batteries, recycling plays a crucial role. The objective is to recover as much material as possible, reduce environmental harm and lower the costs of producing new batteries. Since batteries, as an energy storage technology, still play a minor role in the energy market, the operation segment is not included in this value chain analysis.

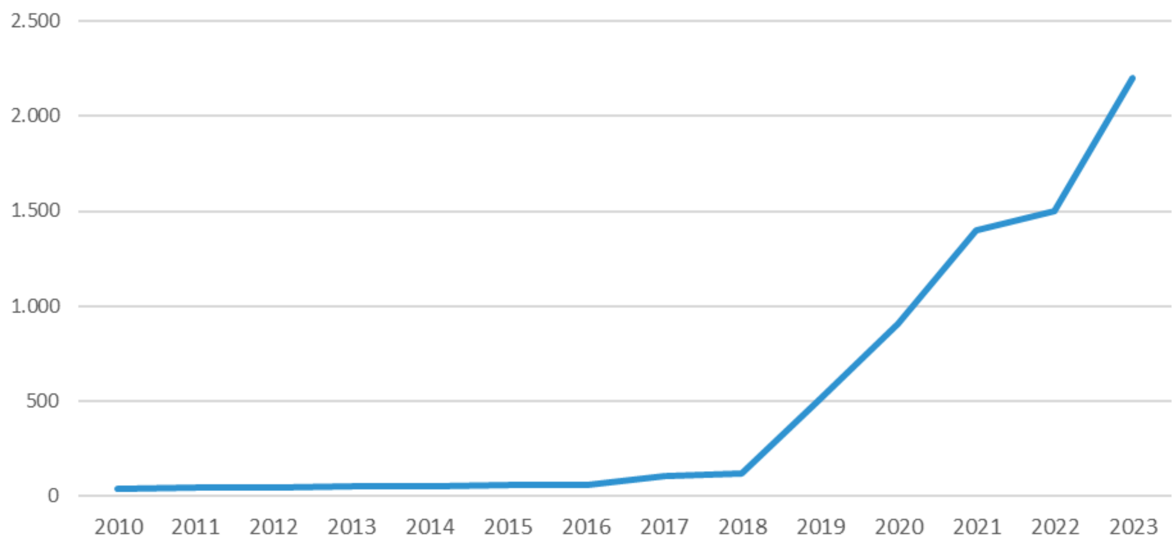
Gross value added

The battery market shows an upward trend unmatched by any other clean energy sector. The sector's gross value added has consistently demonstrated dynamic growth,

[22] IEA (2025). Executive summary. Batteries are an essential part of the global energy system today and the fastest growing energy technology on the market. https://www.iea.org/reports/Batteries-and-secure-energy-transitions/executive-summary.

increasing from nearly zero in 2018 to EUR 2.2 billion in 2023. This corresponds to an average annual growth rate of 35.8% over the period 2010–2023.

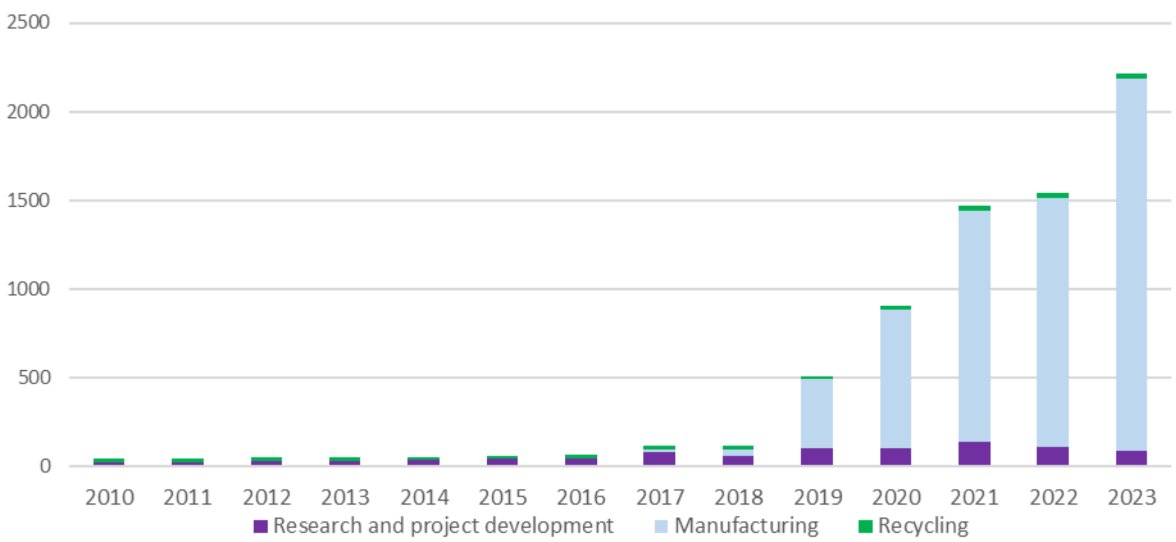
Figure 48 Gross value added of the EU battery value chain (in MEUR) over the period 2010–2023



Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

While research and project development and construction remain at relatively low absolute levels, manufacturing has grown substantially – from being economically insignificant to EUR 2.1 billion in 2023. As the value chain is still in the early stages of market penetration, end-of-life management has yet to show significant momentum but is expected to gain relevance in the coming years. Research and project development has already gained in importance in recent years, accounting for nearly EUR 100 million in 2023.

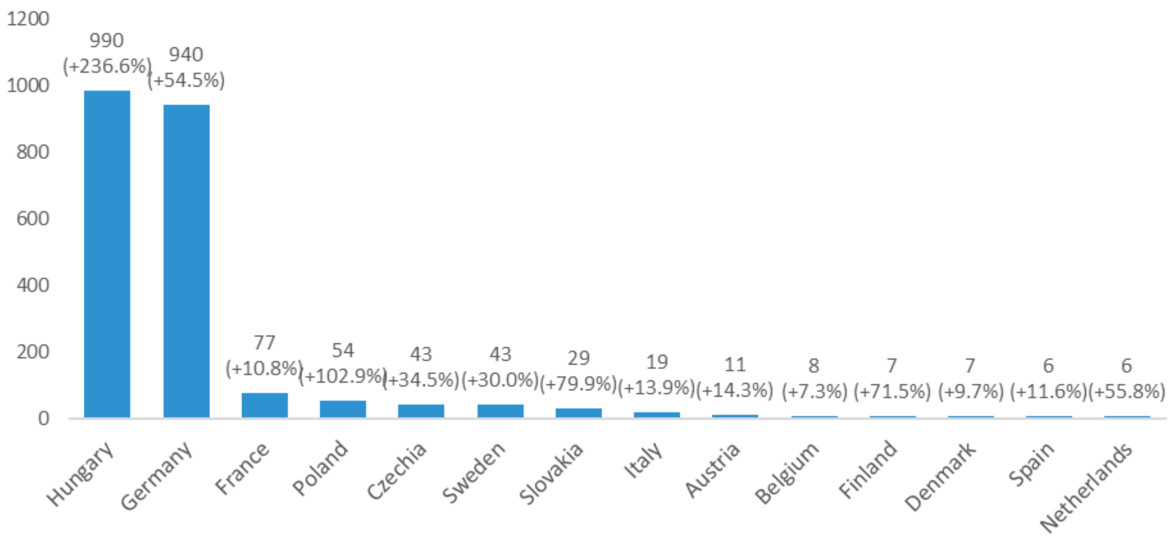
Figure 49 Gross value added by value chain segment in the EU battery sector (in MEUR) over the period 2010–2023



Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

The highest gross value added in the battery value chain was recorded in Hungary, at approximately EUR 990 million in 2023, followed by Germany, at around EUR 940 million. The value chain shows substantial dynamism, particularly in Hungary, which achieved an annual growth rate of 236.6% over the period 2010–2023. Other countries also reported significant growth rates, including Poland (102.9%), Germany (54.5%) and Slovakia (79.9%).

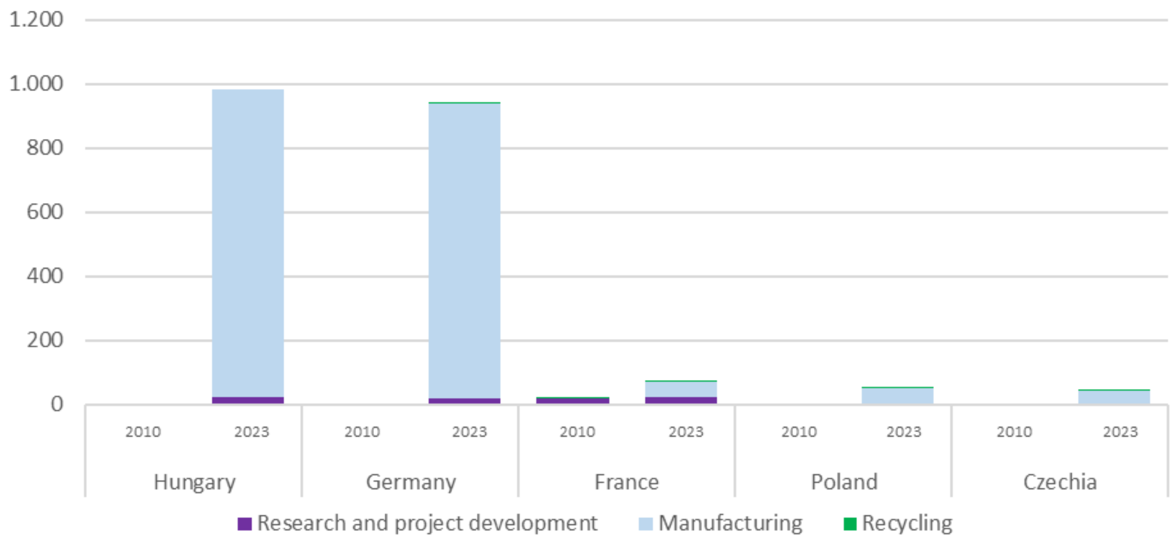
Figure 50 Gross value added of the batteries value chain in selected EU Member States in 2023 (in MEUR) and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The results are presented as nominal values, reflecting the respective annual price level. The graph displays only those EU Member States that report the highest result values.

While no economically measurable figures were recorded in 2010, by 2023, the manufacturing segment had become the most significant contributor to gross value added. Hungary and Germany lead this segment, followed by France, Poland and Czechia follow at a considerable distance, each with gross value added of less than EUR 100 million. Across the countries surveyed, research and project development, as well as recycling, currently have a small economic footprint, but are likely to grow in importance in the future.

Figure 51 Gross value added by value chain segment in the top five Member States in 2010 and 2023 (in MEUR)

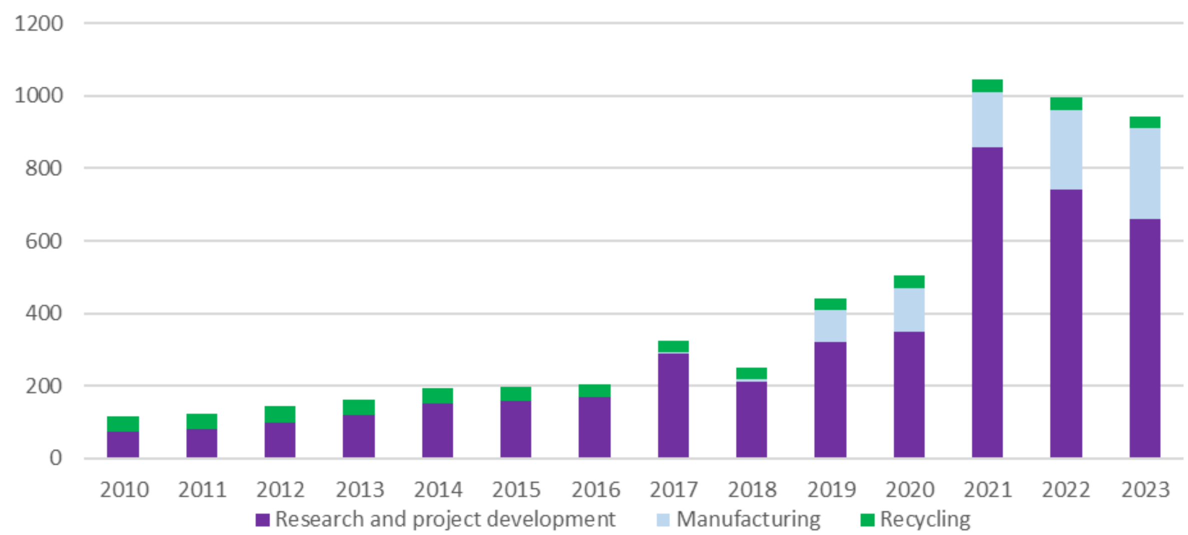


Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level.

Enterprises

In 2023, around 660 enterprises operated in the research and project development segment, while manufacturing and recycling together accounted for 284 enterprises. The comparatively low share of manufacturing in the total number of enterprises suggests that companies in this segment generate a disproportionately high level of value added and employment, reflecting a strong upscaling of manufacturing capacities.

Figure 52 Number of battery enterprises by value chain segment in the EU over the period 2010–2023

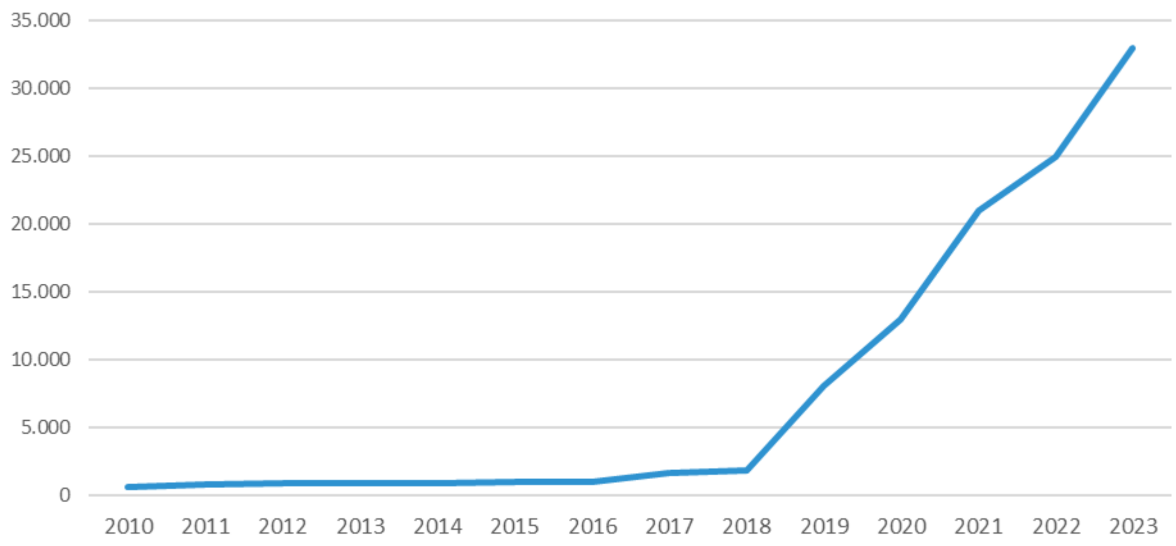


Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Employment

Employment figures follow the same trajectory as gross value added, remaining negligible until 2018 before experiencing marked growth. In 2023, the battery market accounted for 33,000 persons employed, corresponding to an average annual growth rate of 34.6% over the period 2010–2023.

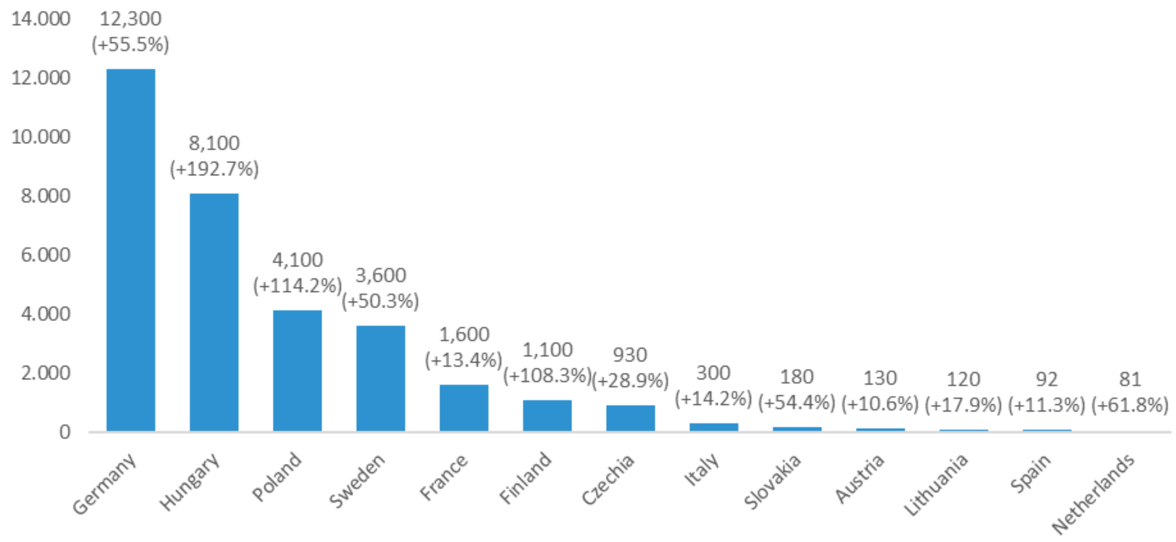
Figure 53 Employment in the EU battery sector over the period 2010–2023



Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Among the EU Member States, Germany recorded the highest number of persons employed in the battery value chain at 12,300 in 2023, followed by Hungary at 8,100 and Poland at 4,100. Mirroring the trends for gross value, Hungary reported the highest annual growth rate at 192.7%, followed by Poland at 114.2% and Finland at 108.3%. While Finland's growth stems from a low absolute base, Hungary and Poland have already established a substantial employment base in the battery value chain.

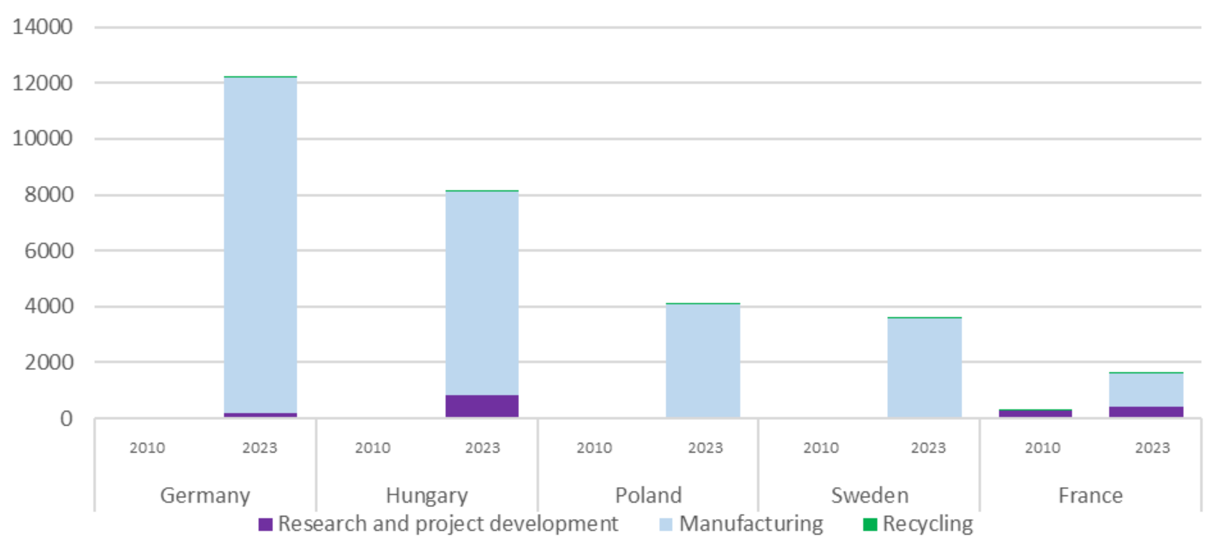
Figure 54 Employment in the battery value chain in selected EU Member States in 2023 and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The graph displays only those EU Member States that report the highest result values.

In Germany, Hungary and Poland, employment is almost exclusively concentrated in the manufacturing segment. Employment in the recycling segment shows little dynamism, while the research and project development segment exhibit only limited development.

Figure 55 Employment per battery value chain segment in the top five Member States in 2010 and 2023



Source: Prognos 2025.

4.7. Geothermal energy

Geothermal energy describes the use of heat derived from the subsurface of the earth. Warm water and/or steam carry the geothermal energy to the earth's surface, where it can be utilised. The heat is often used to drive a turbine, which generates electricity. Alternatively, the heat can be used directly, for example in district heating. Most geothermal applications are large-scale. After use, the cooled water is often reinjected into the subsurface to close the cycle. Geothermal energy is a reliable, weather-independent and low-emission energy source.

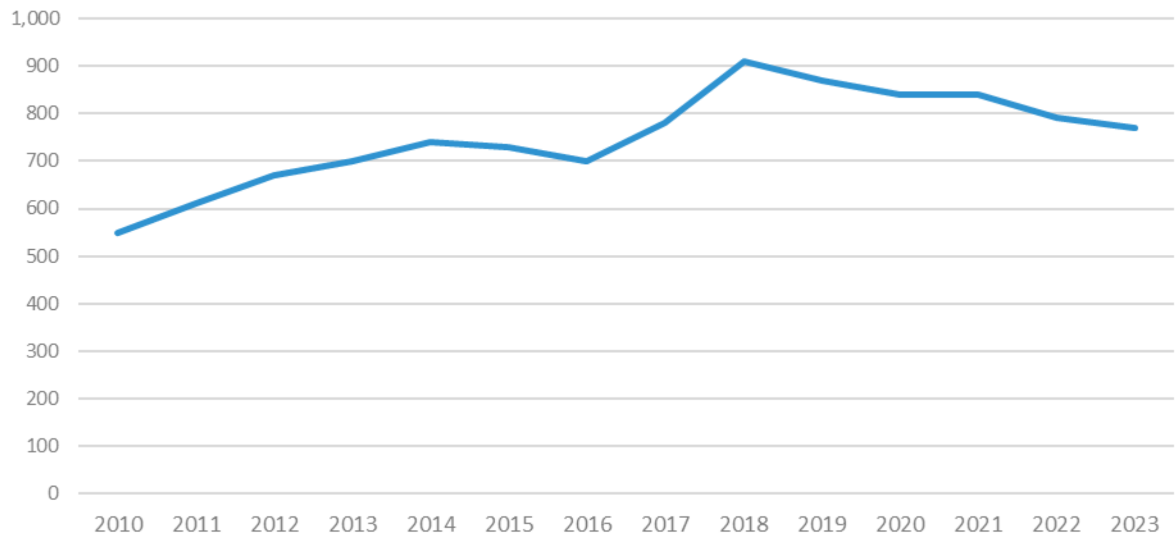
Geothermal power plants can operate at full capacity continuously, as the energy source is available around the clock. Accordingly, geothermal power plants exhibit comparatively high utilisation rates compared to wind or photovoltaic energy, for example. Moreover, geothermal plants offer operational flexibility, helping to stabilise electricity grids by ensuring reliable supply.

The EU has seen a slight increase in electricity and heat generation from geothermal technologies. Electricity production rose from 5.6 TWh in 2010 to 6.3 TWh, while heat generation increased from 1.4 TWh to around 4 TWh.[23]

Gross value added

The modest growth in the importance of heat generation from geothermal energy is also reflected in a marginal increase in gross value added. The analysis shows steady growth in gross value added, from EUR 550 million in 2010, peaking at EUR 910 million in 2018, before declining to EUR 770 million in 2023.

Figure 56 Gross value added of the EU geothermal energy value chain (in MEUR euros) over the period 2010–2023



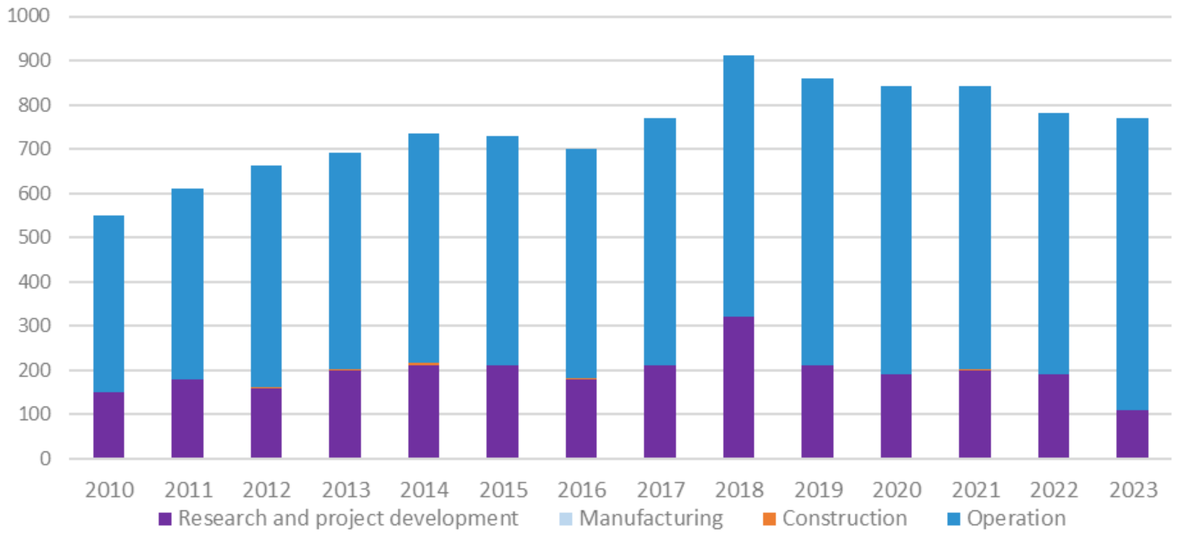
Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

In geothermal energy, operation represents the most significant value chain segment in terms of gross value added. In 2023, EU companies generated around EUR 660 million in gross value added in the operation segment, which covers the generation and marketing of heat. The research and project development segment has seen a decline in importance. Manufacturing as well as construction contribute only a negligible share and are not

[23] Eurostat (2025). Complete energy balance [nrg_bal_c]. https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_c/default/table?lang=en.

sufficiently economically significant to be measured, since almost no additional capacities have been installed.

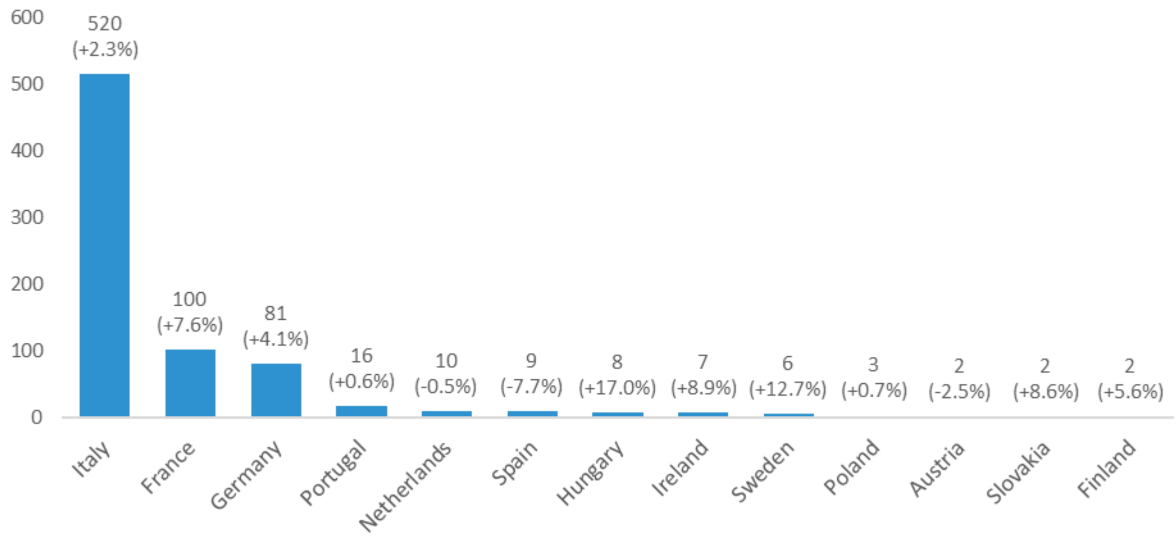
Figure 57 Gross value added by value chain segment in the EU geothermal energy sector (in MEUR) over the period 2010–2023



Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

The EU market for geothermal energy is heavily concentrated in just three countries, all of which show significant growth. Italy leads the EU Member States at EUR 520 million, accounting for over half of the EU's total gross value added in geothermal energy, with a solid growth rate of 2.3%. France and Germany follow, with figures of EUR 100 million, respectively EUR 81 million, and annual growth rates of 7.6% and 4.1%. All other Member States show significantly lower values.

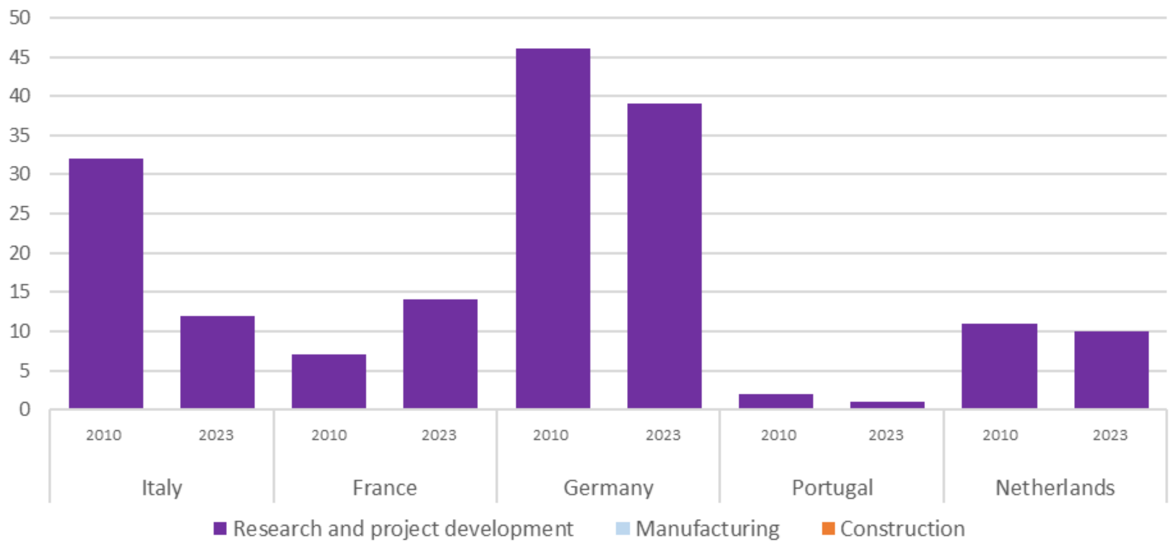
Figure 58 Gross value added of the geothermal energy value chain in selected EU Member States in 2023 (in MEUR) and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The results are presented as nominal values, reflecting the respective annual price level. The graph displays only those EU Member States that report the highest result values.

When the operation segment is excluded, the value chain is fully dominated by research and project development. Across the top five countries, manufacturing and construction activities are not relevant, since no new capacities have been installed in 2023. Except for France, the gross value added in research and project development has been decreasing in all countries since 2010.

Figure 59 Gross value added by value chain segment in the top five Member States in 2010 and 2023 (in MEUR)

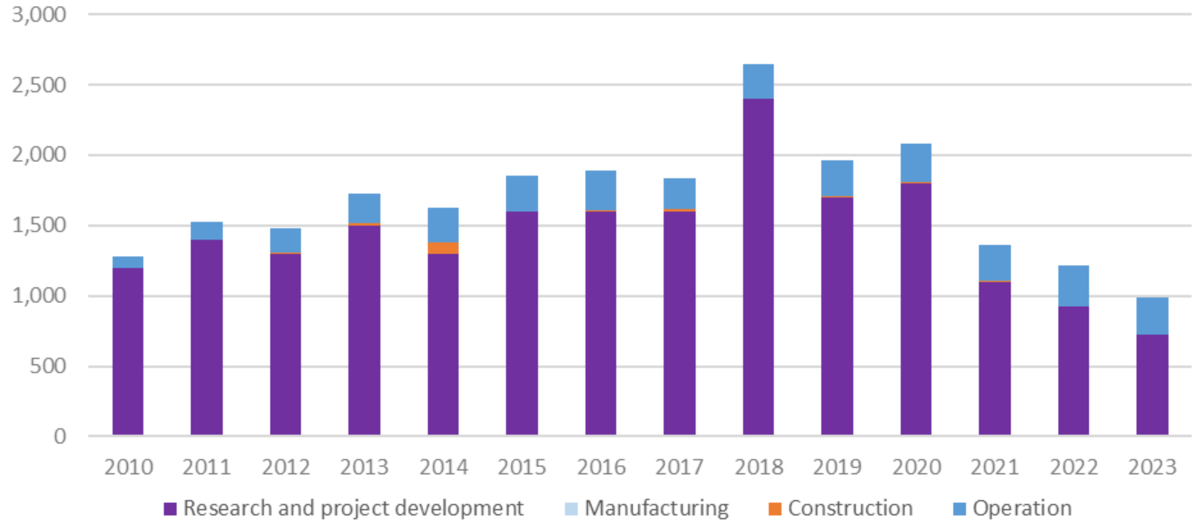


Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level.

Enterprises

In the geothermal energy sector, many small enterprises appear to be active in the field of research and project development, whereas the operation segment is concentrated among a few, but significantly larger, enterprises. In 2023, more than two-thirds of the approximately 1,000 enterprises were active in the research and project development segment. The number of enterprises peaked in 2018 at 2,600, followed by a sharp decline in subsequent years. Overall, the trend over the period 2010–2023 is negative, with an average annual decline of -2.1%.

Figure 60 Number of geothermal energy enterprises by value chain segment in the EU over the period 2010–2023

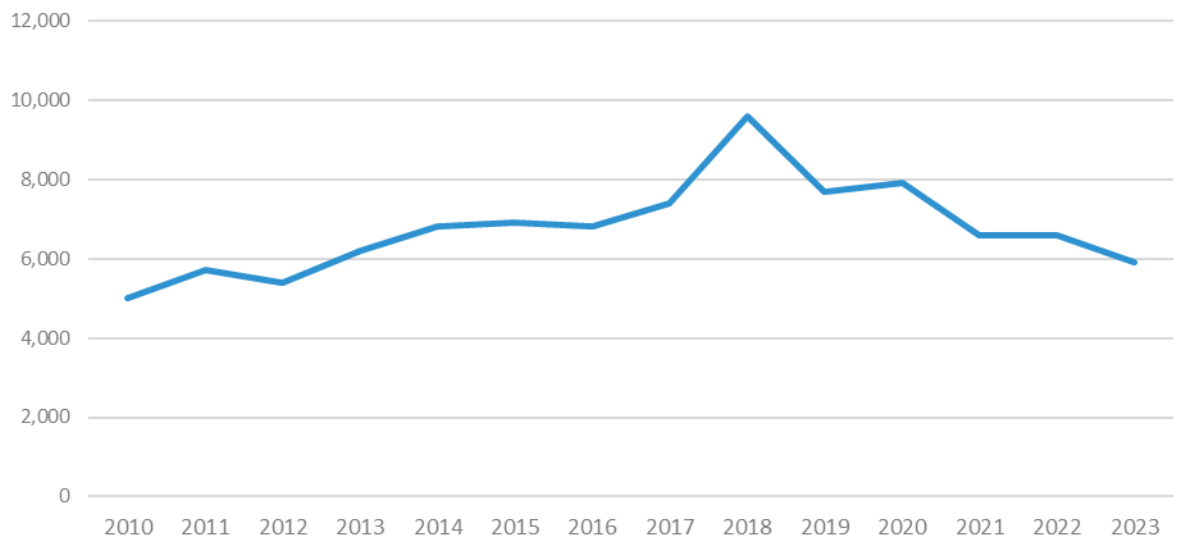


Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Employment

Following a prolonged upward trend, the number of persons employed has declined in recent years. A decrease is observed in the number of persons employed from 9,600 in 2018 to 5,900 in 2023. With approximately 5,000 persons employed in 2010, the overall trend over the longer term (from 2010 to 2023) indicates nearly no growth.

Figure 61 Employment in the EU geothermal energy sector over the period 2010–2023

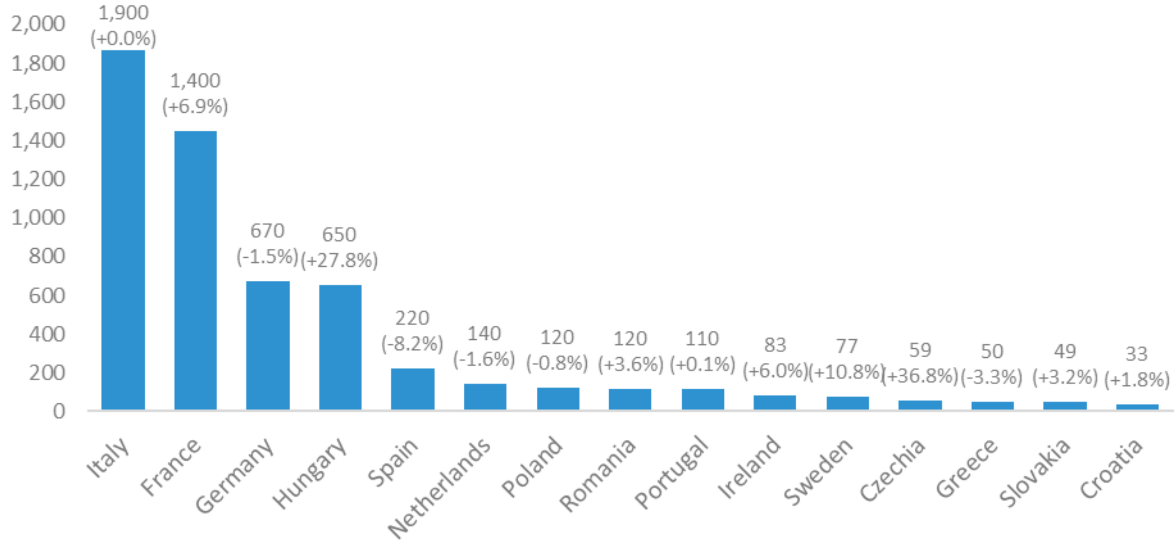


Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Similar to gross value added, the highest employment among all Member States is recorded in Italy, with around 1,900 persons employed. France follows with around 1,400 persons, while Germany and Hungary each report approximately 670 respectively

650 persons employed. Among the top five Member States, Hungary shows the highest annual growth rate at 27,8%.

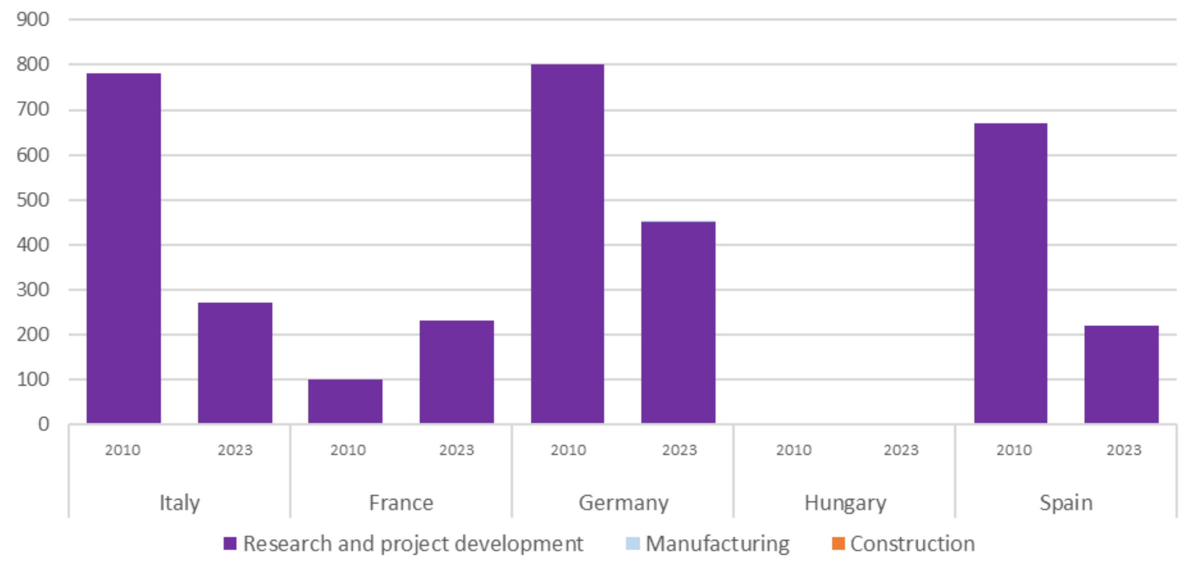
Figure 62 Employment in the geothermal energy value chain in selected EU Member States in 2010 and 2023 and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The graph displays only those EU Member States that report the highest result values.

Excluding operation activities, EU countries show some employment in research and project development. In Italy, Germany and Spain this number of persons employed has decreased since 2010, reflecting the limited importance of geothermal energy.

Figure 63 Employment by value chain segment, excluding operation, in the top five Member States in 2010 and 2023



Source: Prognos 2025.

4.8. Concentrated solar power

Concentrated Solar Power (CSP) is not a new technology. The first testing sites were built back in around 1910. In the mid-2010s, it experienced a brief renaissance, especially in Spain. However, CSP constitutes only a fraction of installed solar capacity.

Various CSP technologies are available, but they all share the fundamental principle of converting sunlight into high-temperature heat. CSP uses mirrors or lenses to focus sunlight onto a central point, generating high temperatures. This thermal energy can either be used directly or transferred via heat exchangers to a water-steam cycle where steam turbines are used to generate electricity. The technology is particularly well-suited to sun-rich regions with high direct solar irradiation.

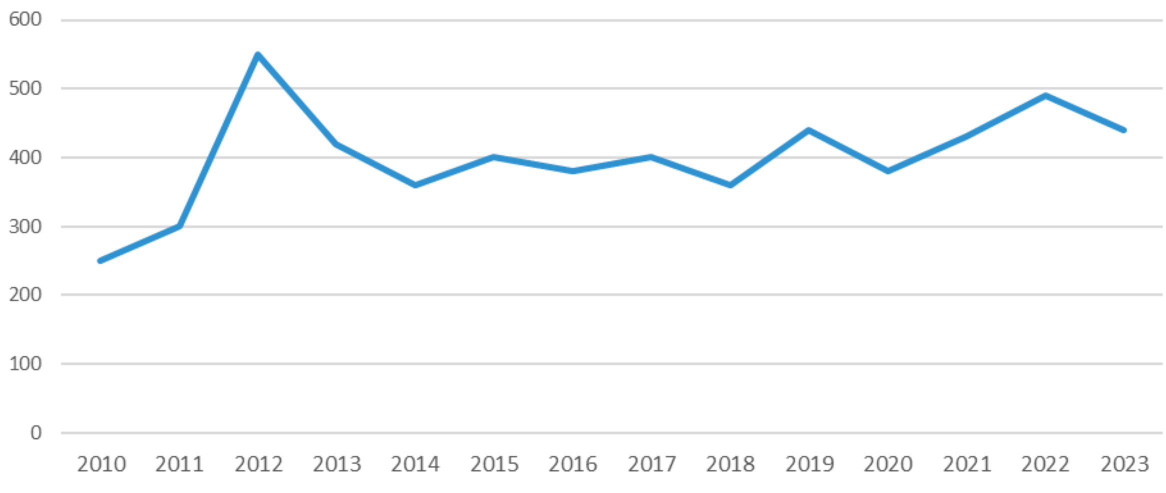
A key advantage of CSP is its ability to store thermal energy, thereby contributing to grid stability. Using molten salt as a storage medium, energy can be retained and dispatched, for example, during periods of low solar radiation.

According to Eurostat figures, installed capacities grew between 2010 and 2013, reaching 2.3 megawatts. From 2013, no more capacities were added in the EU.[24]

Gross value added

The stagnating capacity of CSP has resulted in minimal growth in gross value added within the EU. Between 2010 and 2012, CSP experienced a notable expansion in capacity, resulting in strong growth of gross value added. However, from 2012, gross value added has stagnated, amounting to approximately EUR 440 million in 2023.

Figure 64 Gross value added of the EU CSP energy value chain (in MEUR) over the period 2010–2023

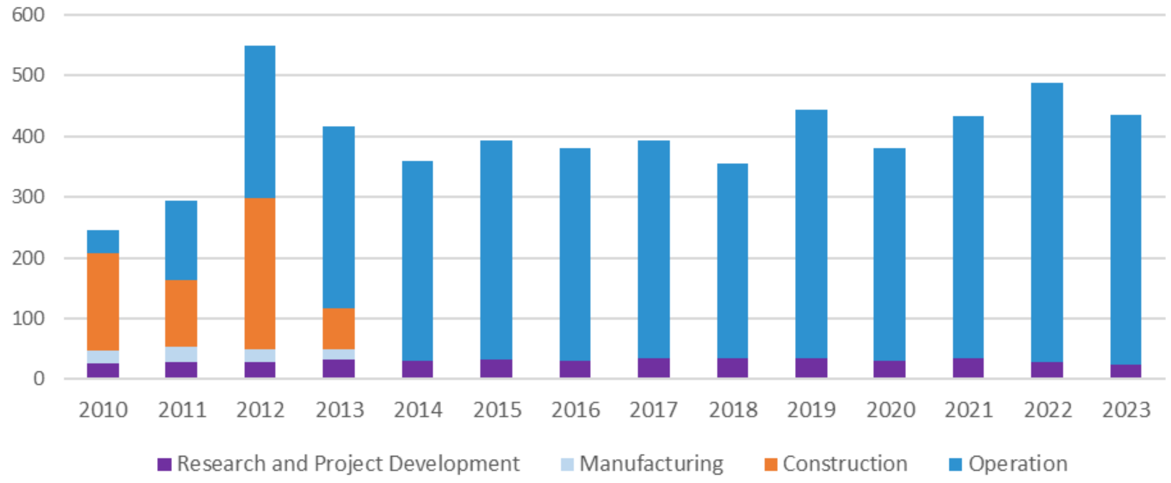


Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

[24] Eurostat (2025). Electricity production capacities for renewables and wastes [nrg_inf_epcrw]. https://ec.europa.eu/eurostat/databrowser/view/nrg_inf_epcrw__custom_17146711/default/table?lang=en.

Since 2014, gross value added has been limited entirely to research and project development activities and the operation of existing CSP plants. Until 2013, construction played a relevant role due to the expansion of new capacities. However, since no additional capacities have been added since 2012, no further economic activities have been recorded in the construction segment.

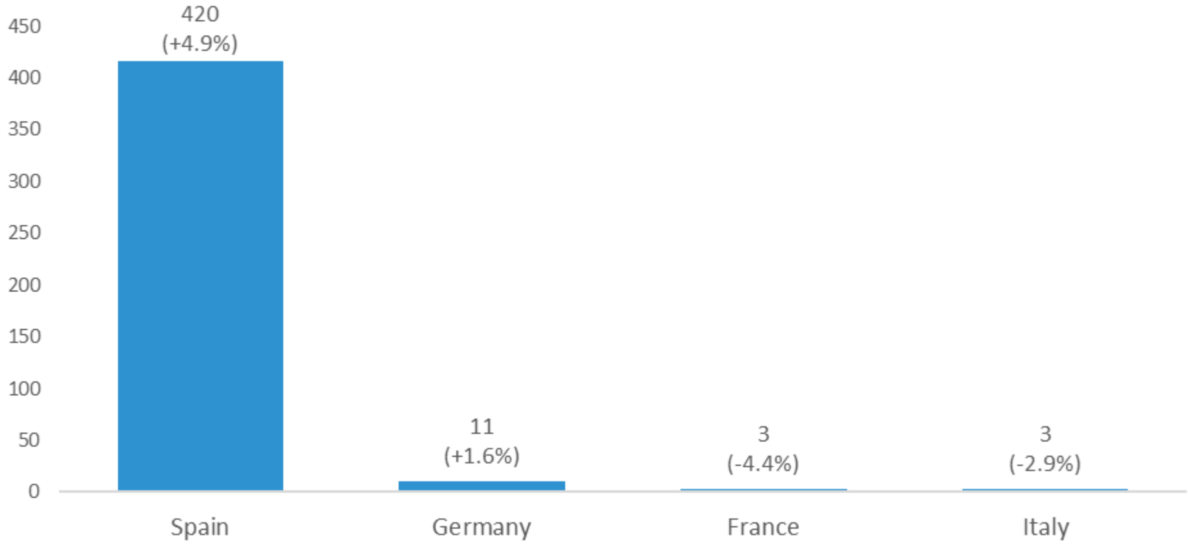
Figure 65 Gross value added by value chain segment in the EU CSP energy sector (in MEUR) over the period 2010–2023



Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Unlike all other clean energy technologies, CSP is almost entirely concentrated in Spain, with no other EU country reporting operation activities in this sector. Only a low level of gross value added is recorded in Germany, limited to research and project development activities.

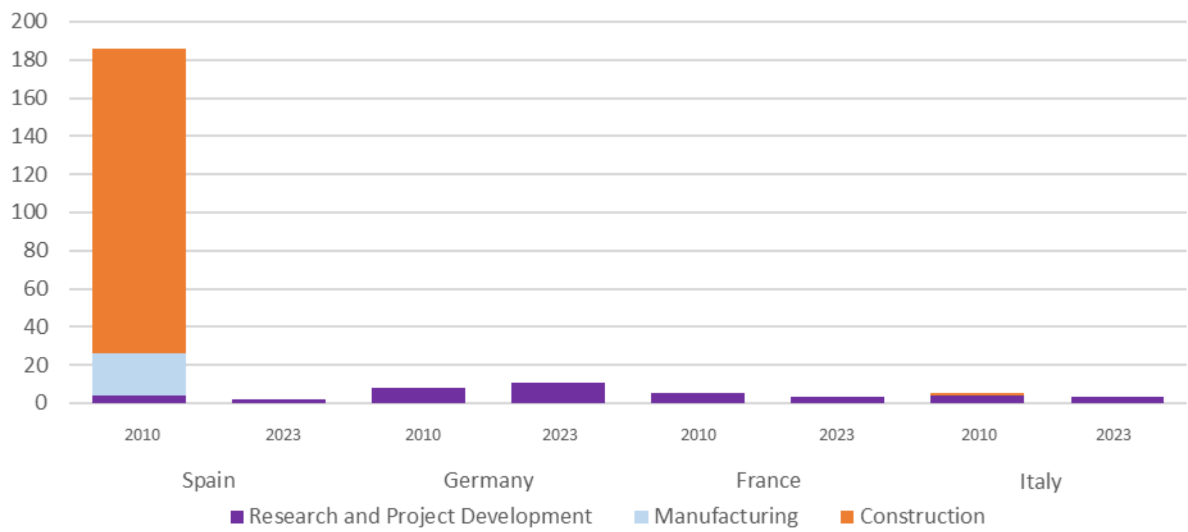
Figure 66 Gross value added of the CSP energy value chain in selected EU Member States in 2023 (in MEUR) and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The results are presented as nominal values, reflecting the respective annual price level. The graph displays only those EU Member States that report the highest result values.

By 2023, construction activities had ceased to contribute to gross value added. While the construction segment in Spain accounted for around EUR 160 million in gross value added in 2010, this figure had declined to zero by 2023. Similarly, the manufacturing segment records no gross value added at all in the analysed data.

Figure 67 Gross value added by value chain segment, excluding operation, in the top four Member States in 2010 and 2023 (in MEUR)

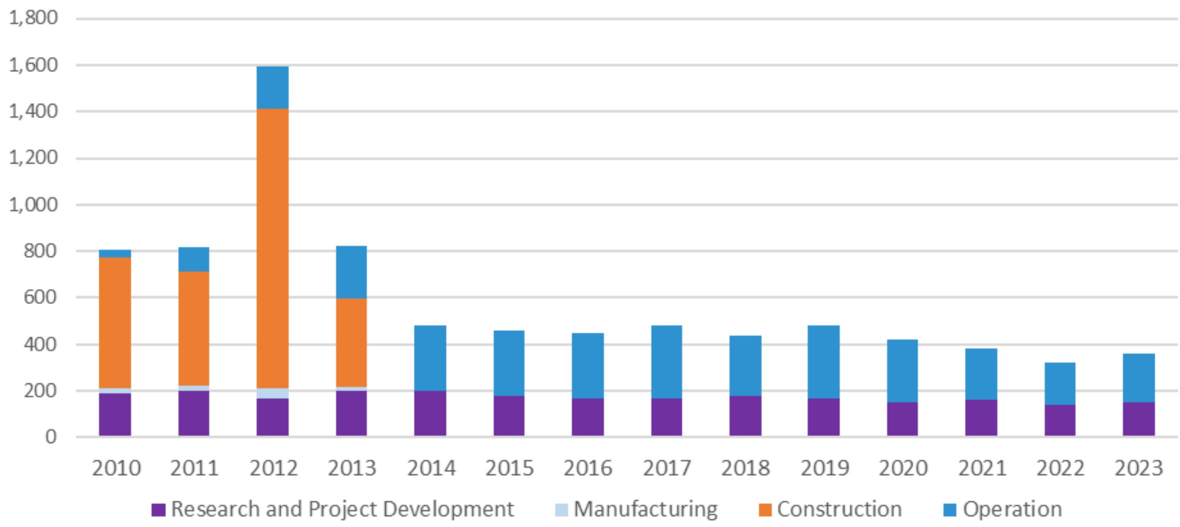


Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level.

Enterprises

From 2013 only companies involved in research and project development activities and the operation of existing plants have remained active. In 2023, around 210 enterprises were recorded in the operation segment, as well as 150 in research and project development. Until 2012, most companies in the CSP sector were concentrated in the construction segment.

Figure 68 Number of CSP energy enterprises by value chain segment in the EU over the period 2010–2023

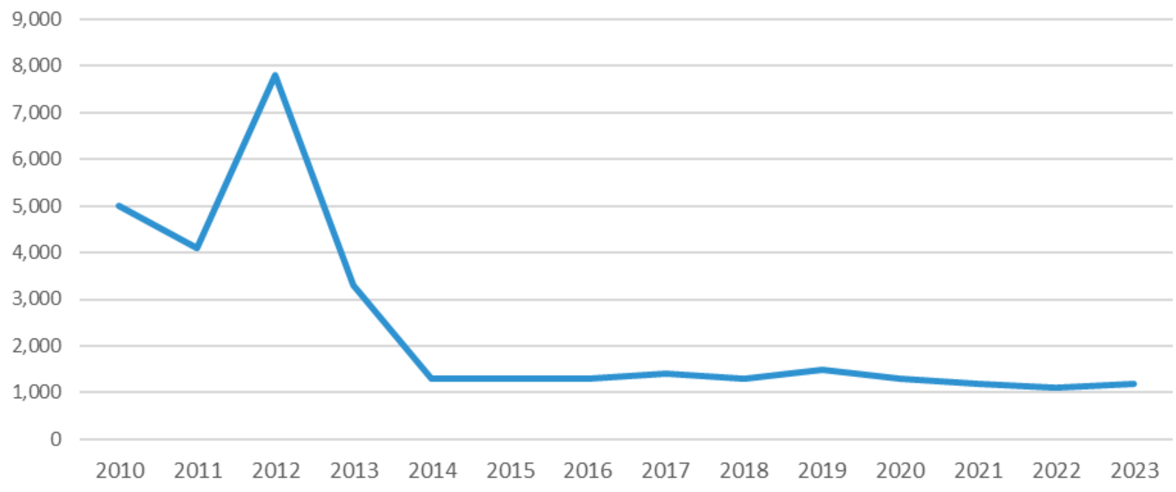


Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Employment

Since 2014, the number of persons employed has stagnated, as no more capacities have been added. After peaking in 2012, the CSP market experienced a sharp decline in employment, stabilising at around 1,300 persons employed by 2014 – a level that has remained essentially unchanged since.

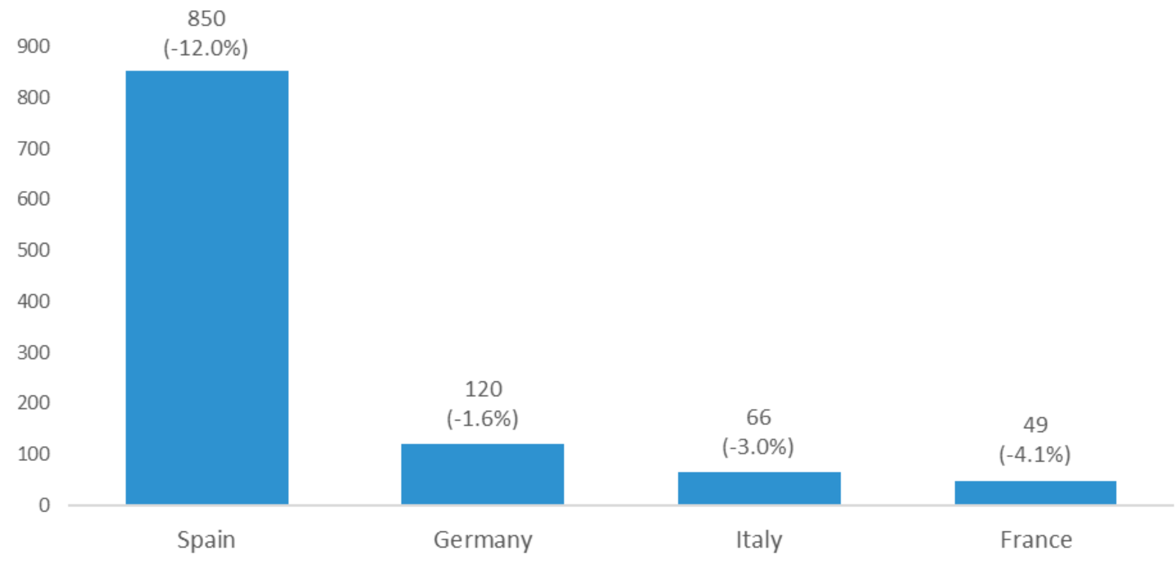
Figure 69 Employment in the EU CSP energy sector over the period 2010–2023



Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

In line with installed capacity figures, Spain is also the only EU country with a significant number of persons employed in the CSP sector. Of the approximately 1,200 persons employed, 850 are located in Spain and around 120 in Germany. However, the number is declining in both countries.

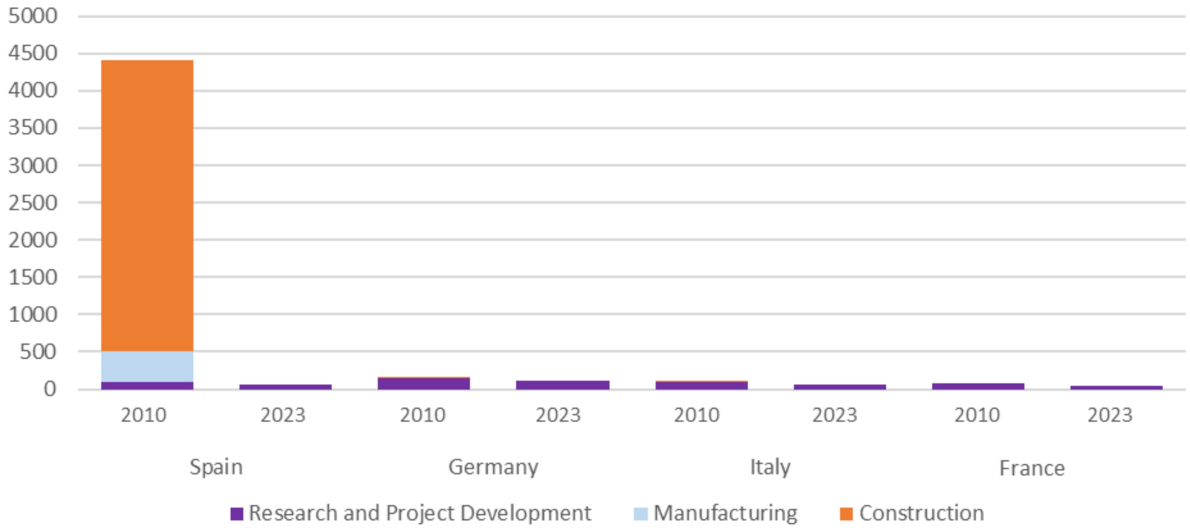
Figure 70 Employment in the CSP energy value chain in selected EU Member States in 2023 and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The graph displays only those EU Member States that report the highest result values.

The CSP market shows no significant employment once operation activities are excluded. Employment in the construction segment declined from around 3,900 persons in 2010 to zero by 2023. Similarly, the model no longer reports any employment in the manufacturing segment.

Figure 71 Employment per CSP energy value chain segment, excluding operation, in the top four Member States in 2010 and 2023



Source: Prognos 2025.

4.9. Solar thermal energy

Solar thermal energy technologies generate heat. Most of the other clean energy technologies produce electricity, making direct comparisons more challenging. Electricity-generating power plants are almost always connected to electricity grids, enabling comprehensive data collection on installed capacity and produced energy. Heat-generating systems are mostly small-scale applications for private use. While it is difficult to provide reliable and comprehensive estimates for development of the solar thermal energy market, the limited data available can reveal some relevant trends.

Between 2010 and 2023, gross heat production from solar thermal energy rose from 57 TWh to around 812 TWh, representing more than a tenfold increase.[25] The number of newly installed collectors, however, is declining. While around 3.2 million square metres of new collectors were installed in 2010, this figure had dropped to just under 1.7 million square metres by 2023.[26]

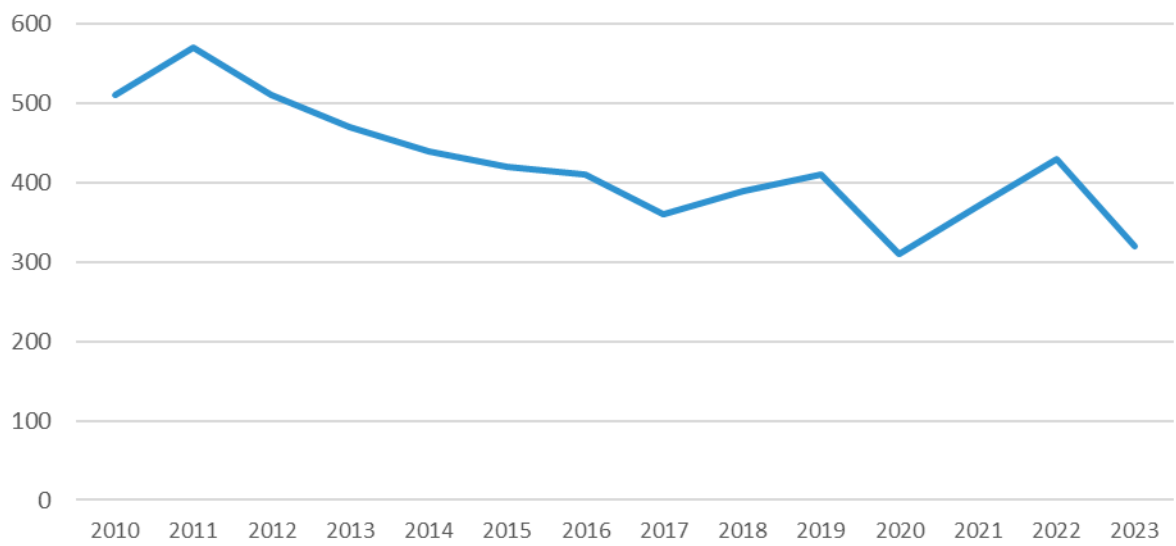
Gross value added

From 2010, gross value added decreased from around EUR 510 million to EUR 320 million in 2023.

[25] Eurostat (2025). Complete energy balance [nrg_bal_c]. https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_c/default/table?lang=en.

[26] EurObser'ER (2025). Annual installed capacity (flat plate collectors) (m2). https://www.eurobserv-er.org/online-database/.

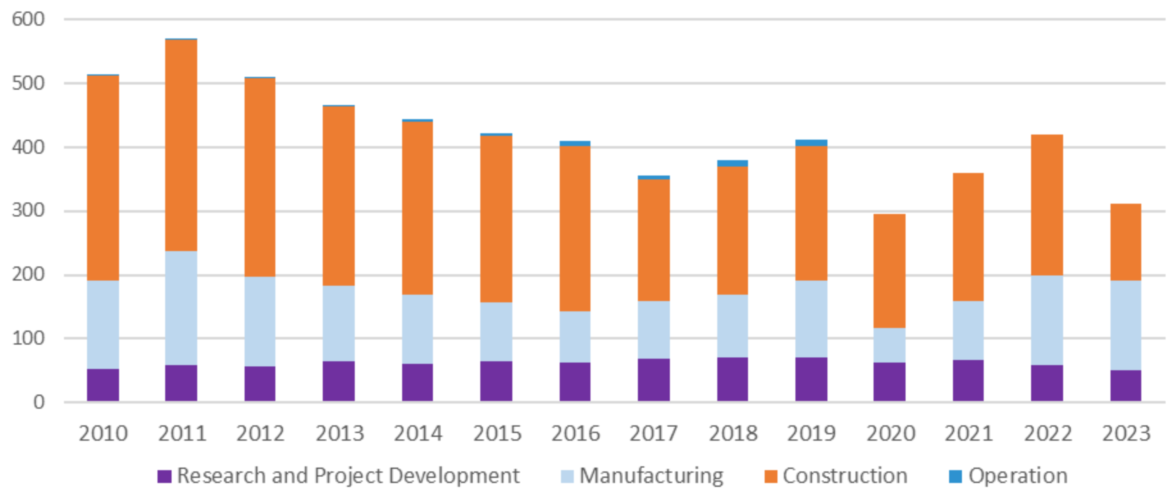
Figure 72 Gross value added of the EU solar thermal energy value chain (in MEUR) over the period 2010–2023



Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

The value creation from construction activities dominates the overall gross value added, but has declined over time, due to falling annual installations. The gross value added of construction activities decreased from EUR 320 million in 2010 to EUR 120 million in 2023. The value chain segments of research and project development, as well as manufacturing, have maintained relatively constant gross value added over time. The operation segment is of minimal significance, as solar thermal energy systems are primarily used for residential heating purposes. Private use, however, does not constitute a measured economic impact as there are no direct revenues generated through sales.

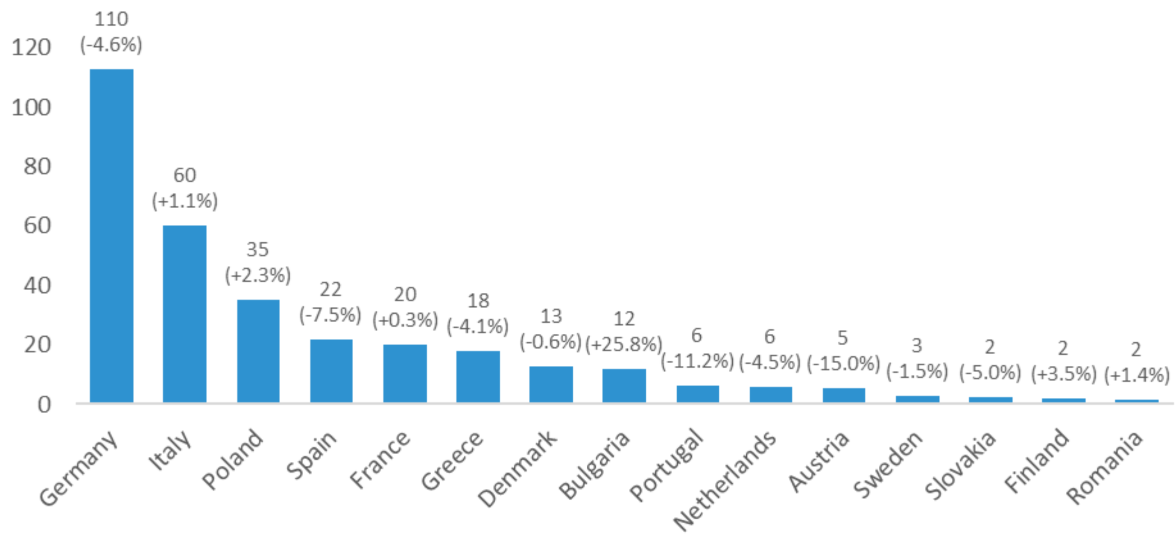
Figure 73 Gross value added by value chain segment in the EU solar thermal energy sector (in MEUR) over the period 2010–2023



Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Across EU Member States, opposing trends of growth and decline can be observed. Approximately one-third of the gross value added in the EU comes from Germany, making it the largest market. At EUR 110 million, the German market is nearly twice the size of Spain's market as the second-ranked country. However, Germany has experienced a decline in gross value added at a rate of -4.6% per year. This trend is also evident in other countries, such as Spain and Greece. In contrast, Italy and Poland show a steady growth trend.

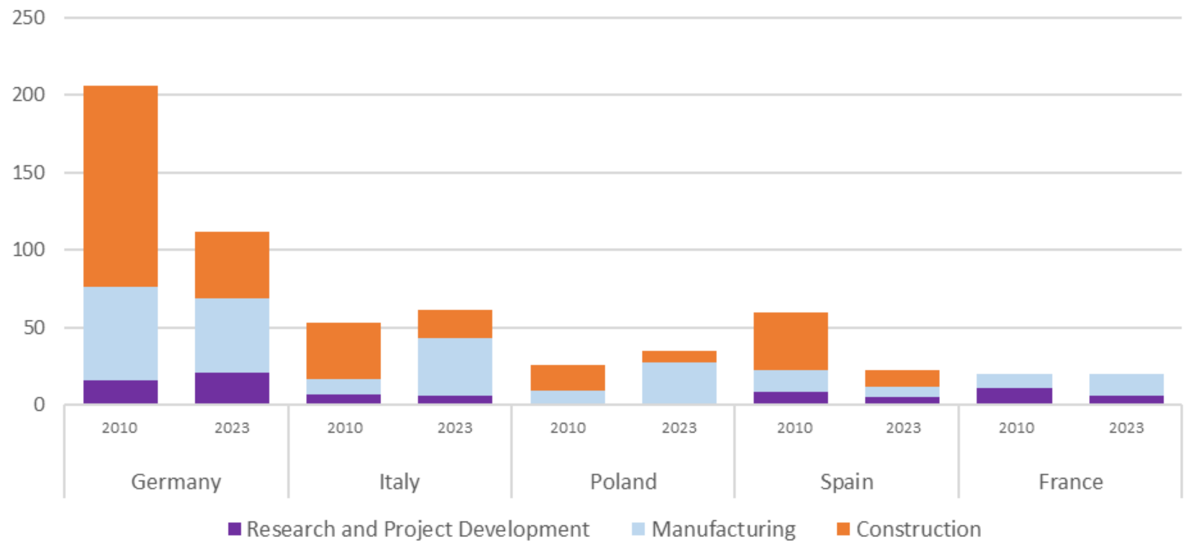
Figure 74 Gross value added of the solar thermal energy value chain in selected EU Member States in 2023 (in MEUR) and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The results are presented as nominal values, reflecting the respective annual price level. The graph displays only those EU Member States that report the highest result values.

Across the largest EU markets, gross value added from construction activities declined, particularly in Germany and Spain. For example, in Germany the gross value added of construction decreased from EUR 130 million in 2010 to around EUR 40 million in 2023. In contrast, the manufacturing segment experienced significant growth in Italy and Poland.

Figure 75 Gross value added by value chain segment, excluding operation, in the top five Member States in 2010 and 2023 (in MEUR)

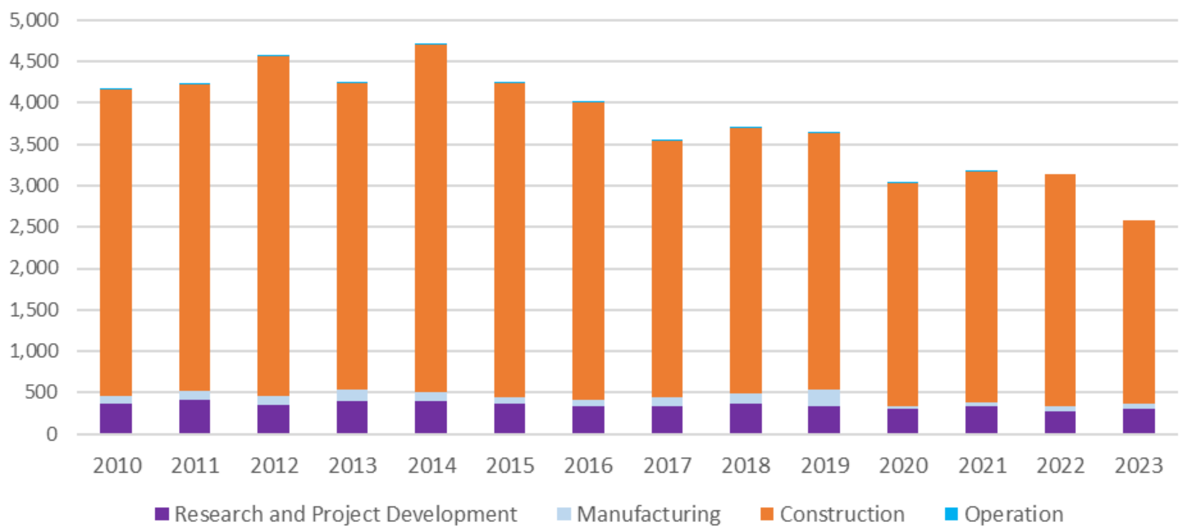


Source: Prognos 2025. The results are presented as nominal values, reflecting the respective annual price level.

Enterprises

A declining trend is also evident in the number of enterprises in the EU, with negative growth of -3.6% per year. The solar thermal energy sector has the highest number of companies in the construction segment, with many small businesses involved in the installation of domestic solar thermal energy systems. However, driven by falling annual installations of collectors, the total number of enterprises decreased from 4,200 in 2010 to 2,600 in 2023.

Figure 76 Number of solar thermal energy enterprises by value chain segment in the EU over the period 2010–2023

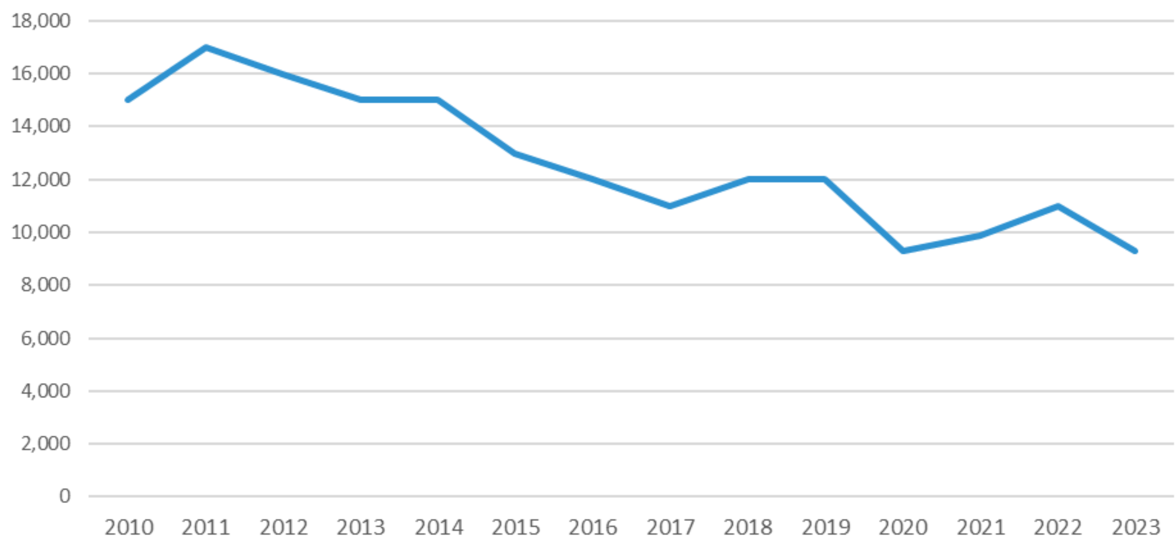


Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

Employment

Since 2011, the number of persons employed in the solar thermal energy sector has steadily declined from 16,900 in 2011 to 9,300 in 2023. This decrease is primarily due to the falling installation rates for new solar collectors.

Figure 77 Employment in the EU solar thermal energy sector over the period 2010–2023

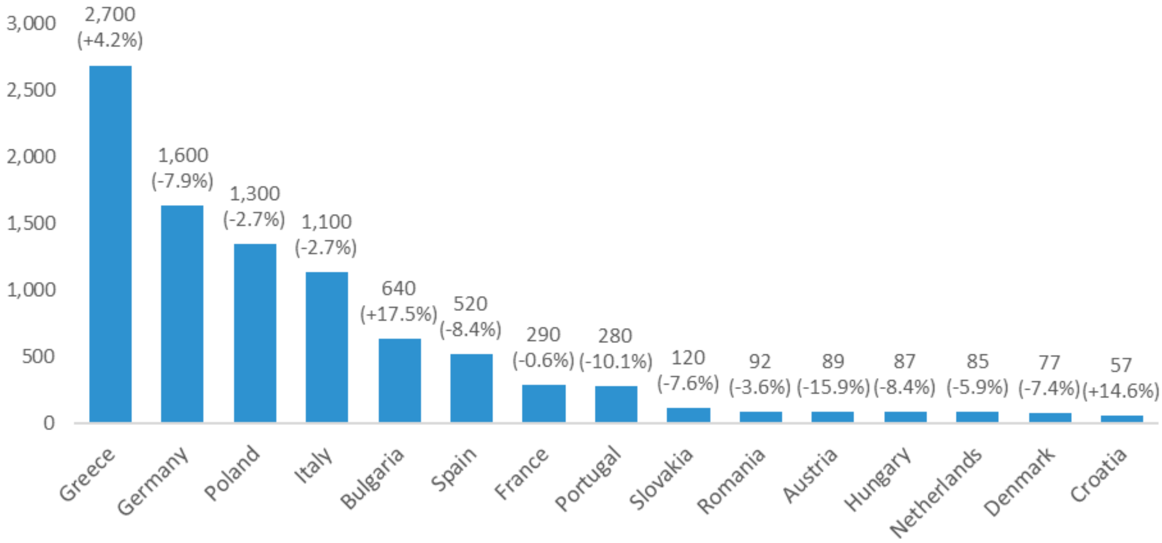


Source: Prognos 2025. The EU aggregate figures do not include Cyprus, Malta, and Luxembourg.

In terms of the number of persons employed, Greece is the largest market in the EU, driven by growth in annual installations. With nearly 2,700 persons employed, Greece even surpasses larger EU Member States like Italy and Germany. This is largely due to the rising number of annual installations, which generate significant employment.[27] The number of jobs in Greece grew by around 4.2% per year, while most other EU countries show a declining trend.

[27] EurObser'ER (2025). Annual installed capacity (flat plate collectors) (m2). https://www.eurobserv-er.org/online-database/.

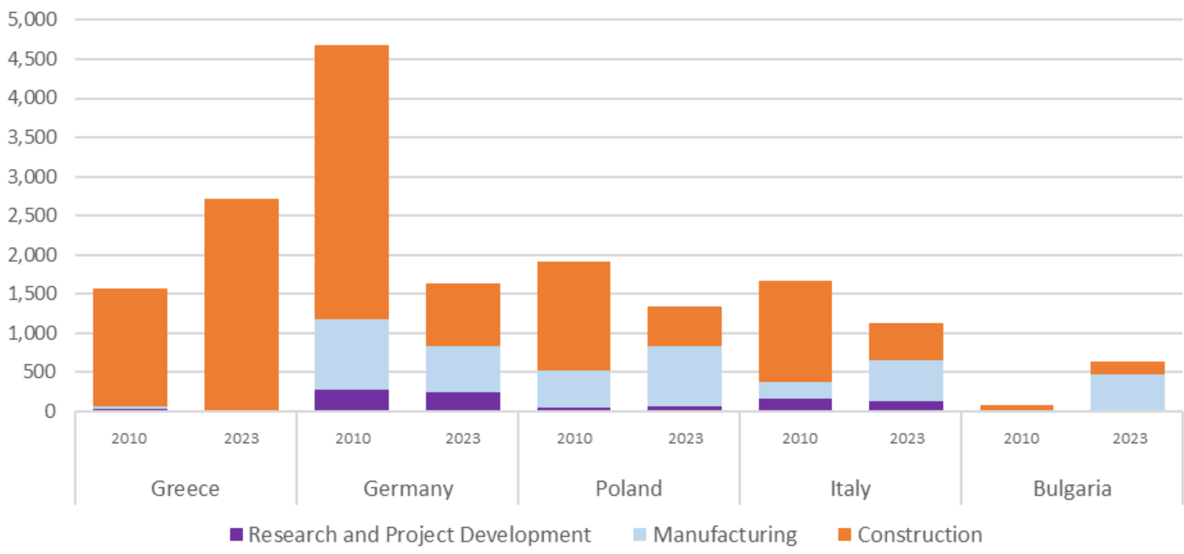
Figure 78 Employment in the solar thermal energy value chain in selected EU Member States in 2023 and annual growth over the period 2010–2023



Source: Prognos 2025. Annual growth is calculated as the compound annual growth rate (CAGR) over the period 2010–2023. The graph displays only those EU Member States that report the highest result values.

The number of persons employed in construction activities nearly doubled between 2010 and 2023 in Greece. While the analysis shows no persons employed in research and project development or manufacturing for Greece, the increasing installed capacity of solar collectors has driven new employment in the construction sector. In the same period employment declined in Germany, Poland and Italy.

Figure 79 Employment per solar thermal energy value chain segment, excluding Operation, in the top five Member States in 2010 and 2023



Source: Prognos 2025.

4.10. Other technologies

This chapter provides an overview of the main findings related to the clean energy technologies that could not be incorporated into the primary modelling exercise due to insufficient data availability. Accordingly, the analysis of these technologies is based solely on a compilation of identified immediately available literature and data. The main purpose of this part of the study was to investigate what publicly available data exists that can inform an assessment of the competitiveness of these technologies. Sources consulted include for example industry reports and publications from international agencies. However, it should be noted that many of the consulted sources are not updated on an annual or regular basis, meaning that the information they contain can quickly become outdated. It should also be noted that much of the research was done in 2023 thus relying on information that was available at the time. Latest desk research was completed by mid-2024 supplemented with some more targets updated undertaken more recently, i.e. consulting 2025 sources. This limitation affects the timeliness and precision of the findings, underscoring the need for continued data collection and regular updates to maintain the relevance of the findings. Each technology-specific sub-chapter focuses on elements where data were available to provide relevant insights for the specific technology. Where the collected data has allowed, each sub-chapter seeks to consider 4 key market dimensions: state of technology, sustainability, costs and production. However, given the novelty of some of these technologies, it is not always relevant to address all four dimensions due to data limitations.

4.10.1. Carbon capture, utilisation and storage (CCUS)

Carbon capture, utilisation and storage are the only technologies that are dual in the sense that they contribute to reducing emissions in sectors where it is difficult to reduce emissions and that they can remove CO2 thus balancing emissions that are challenging to avoid.[28] The investigation of available data undertaken in 2023 focused largely on identifying and mapping CCUS projects, and this focus is reflected in the below description.

While CCUS deployment has not yet met expectations, recent trends suggest a positive, albeit insufficient trajectory. As reported by the IEA in 2023, more than 700 projects are at various stages of development. However, even with this activity, CCUS deployment would remain well below the levels required under the IEAs Net Zero Scenario.[29] The high capital intensity and associated costs of CCUS technology pose a challenge to its uptake.[30] The IEA reports that 45 commercial facilities are currently in operation, applying the technology to industrial processes, fuel transformation and power generation. While capture capacity and storage are expected to increase, they still only deliver around 40% (capacity) and 60% (storage) of the amounts captured and stored under the Net Zero Emissions by 2050 Scenario.

The CCUS projects in the EU Member States are mainly at the development stage, with the capacity of operational projects remaining low. During the extensive data and information collection carried out in 2023, a list of 88 projects related to CCUS in EU Member States was compiled. The projects were mainly at the development stage, i.e. at a low technology readiness level). Around 60% of the projects were in development, while

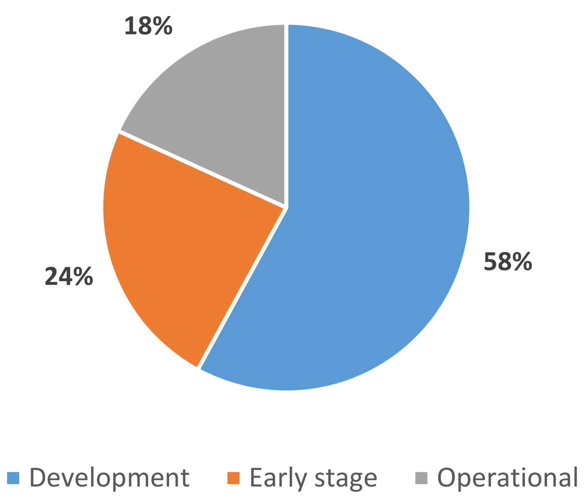
[28] IEA (2020), *CCUS in Clean Energy Transitions*, IEA, Paris https://www.iea.org/reports/ccus-in-clean-energy-transitions, Licence: CC BY 4.0 CCUS in Clean Energy Transitions – Analysis – IEA

[29] IEA homepage (last updated 2024). Carbon Capture Utilisation and Storage – Energy System – IEA.

[30] Publyon homepage (2024). Carbon capture, utilisation and storage (CCUS) in the EU.

fewer than 20% were categorised as operational. However, an upward trend has been observed in recent years.

Figure 80 Overview of projects identified in late 2023 by stage of readiness



Source: Results of the literature search conducted in late 2023 on CCUS projects. The information was drawn from project-specific websites.

Based on the 2023 data, most of the identified projects were concentrated in a few Member States. Belgium, France, Germany and the Netherlands all had more than 10 projects at various stages of development. Operational projects were also found in these four countries, as well in Croatia, Czechia, Hungary, Poland and Sweden. During the data collection stage, no CCUS projects were identified in 10 EU Member States – these were primarily, though not exclusively, smaller countries.[31] Suitable storage capacity is found especially in the North Sea, as also illustrated by recent major projects there such as Porthos and Bifrost,[32] which started in 2023 and 2021, respectively. These two projects are recent examples of relatively large-scale projects. The Porthos project aims to capture CO_2 from the port of Rotterdam, transport it and store it in empty gas fields under the North Sea.[33]

High upfront costs are a major barrier to the deployment of CCUS. The required energy consumption can also constitute a barrier, especially when energy costs are high. The development and commercialisation of CCUS in the EU is supported financially at the EU level through instruments such as the Innovation Fund and the Connecting Europe Facility. The technology is also supported at the national level, including through EU funds like the Just Transition Mechanism. In addition to financial support for deployment, further research and development is also crucial to reduce costs. For example, the Grantham Institute at LSE provides a specific example showing that the costs of CO_2 capture in power generation decreased by 35% between the first and second large-scale installations. In addition, overcoming challenges related to planning, coordination and provision of the necessary infrastructure is essential.[34]

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[31] Portugal, the Baltic States, Luxembourg, Slovakia, Slovenia, Malta, Cyprus and Romania.

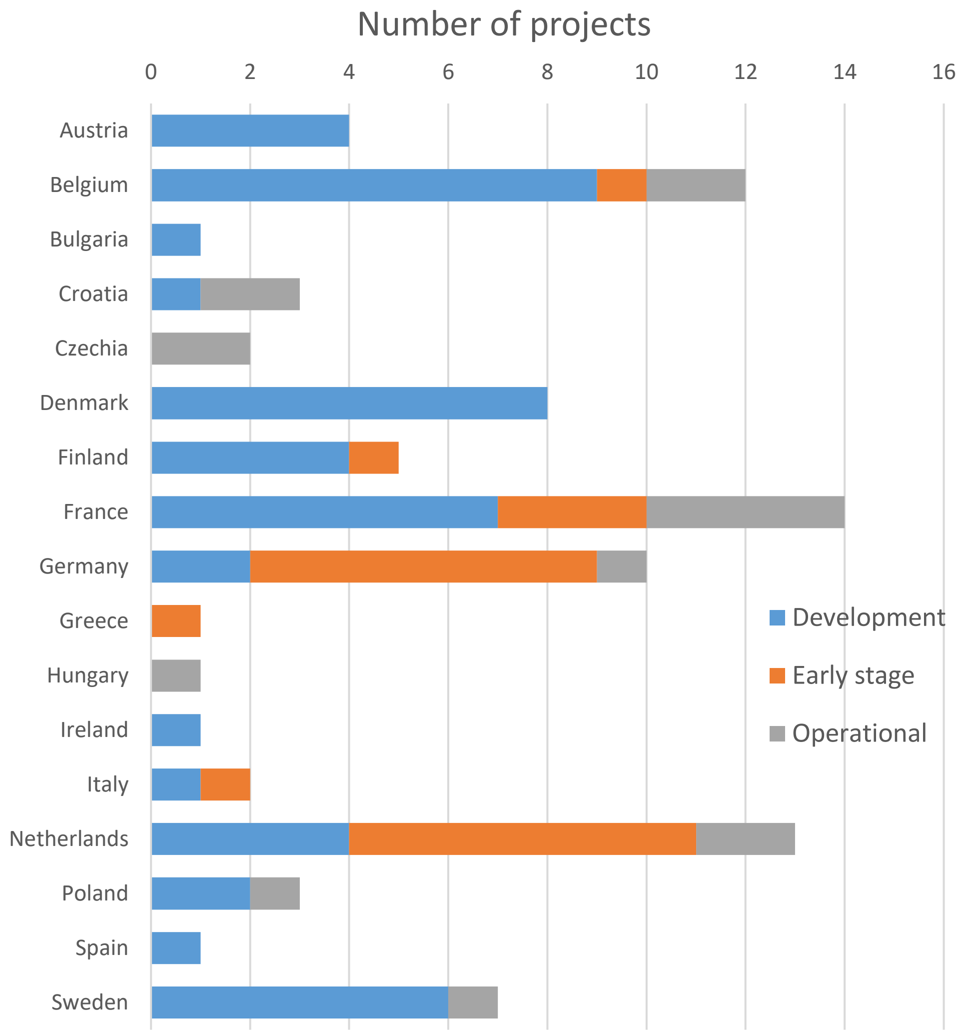
[32] Publyon homepage (2024). Carbon capture, utilisation and storage (CCUS) in the EU.

[33] Porthos homepage (2025). CO_2 reduction through storage under the North Sea – Porthos.

[34] Blog on homepage of CECO Environmental (2025). Barriers to Successfully Implementing Carbon Capture, Utilization, and Storage (CCUS) – CECO Environmental and from Explainer on LSE Grantham Research Institute homepage

CCUS technologies can play an important role in maintaining activities and jobs in energy-intensive industries and can be the least costly option for maintaining activities in such sectors. In energy-intensive industries, the alternatives to CCUS can be significantly more expensive. However, a risk associated with CCUS is the potential for leakages from CO_2 storage sites.[35]

Figure 81 Overview of CCUS projects by Member State and stage of readiness, according to data collected in 2023



Source: Results of the literature search conducted in late 2023 on CCUS projects. The information was drawn from project-specific websites.

The projects identified in 2023 span various phases and sectors, with carbon capture being the most frequently observed activity – predominantly in the cement industry. The identified projects cover a variety of sectors and many cover more than one sector. A project can include several phases, from capture to transport, storage or use. Most of the projects include carbon capture, with between one-third to one-fourth of the identified projects also involving transport, storage or use.

(2023) What is carbon capture, usage and storage (CCUS) and what role can it play in tackling climate change? – Grantham Research Institute on climate change and the environment.

[35] Explainer on LSE Grantham Research Institute homepage (2023). What is carbon capture, usage and storage (CCUS) and what role can it play in tackling climate change? – Grantham Research Institute on climate change and the environment,

Table 2 **Number of projects by sector and by stage (capture, transport, storage and use) in the EU**

	Number of projects (may include one or more phases)			
Sector	**Capture**	**Transport**	**Storage**	**Use**
Advanced bioethanol	1			1
Ammonia	2	1	1	
Biofuel	2	1	1	1
Biomass	1			1
Cement	15	3	3	2
Hydrogen	11	4	7	2
Methanol	6			4
Oil & Gas	3	2	5	
Power generation (several sources)	1			
Power-to-x	1			4
Several industries	16	16	13	1
Steel/Mining	6	4	1	2
Synthetic fuel	3			3
Waste management	6			1
Total	**74**	**31**	**31**	**22**

Source: Results of the literature search conducted in late 2023 on CCUS projects. The information was drawn from project-specific websites.

4.10.2. Novel thermal storage

Novel thermal energy storage refers to a range of technologies, with data availability largely depending on maturity. Each technology has distinct applications. This data collection exercise focused on four primary types of storage, encompassing a total of seven technologies. The availability of information varied among these technologies, largely depending on their maturity – less mature technologies had limited data accessible through open sources. As a result, data collection for these storage technologies included a diverse array of sources, such as industry reports, publications by international agencies, consultancy papers and news articles.

State of technology

The technology status of different thermal energy storage systems varies significantly, impacting their current applications and levels of adoption. As previously noted, even the more advanced technologies have specific applications that are still under development or in the experimental stage. Molten salt thermal energy storage (MSTES) currently leads in commercial adoption, particularly in conjunction with concentrated solar power (CSP) plants. Meanwhile, technologies like liquid air energy storage (LAES) have made significant progress and are nearing commercialisation. The table below summarises the discussions on Technology Readiness Levels (TRL) for the various storage systems, providing a systematic evaluation of their maturity, which typically ranges from 1 to 9, with each level representing a different stage of technological development.

Table 3 Overview of state of technology by storage technology

Technology	Status
Molten salt	Technology: Research and development (TRL 4 and above) is needed in areas such as cost reduction (e.g. single-tank storage), increased efficiency (e.g. higher temperatures) and enhanced reliability (e.g. standardisation of salt components and addressing service life issues). Application: Since 2010, this technology has been commercially used in solar thermal power plants (TRL of 9), with ongoing exploration of new applications like industrial process heat and electricity storage, including retrofitting conventional power plants.
Low-temperature phase change materials	Salt hydrates like strontium bromide have been commercialised for domestic heating, while commercial paraffin waxes are popular due to their low cost, moderate latent heat (around 200 kJ/kg) and broad melting temperature range. However, they still face several limitations, with a TRL of between 4 and 7.[36]
High-temperature phase change materials	Latent heat storage systems with integrated finned tube heat exchangers have been developed for phase change temperatures of 140 °C to 305 °C, exhibiting power outputs of 1 to 700 kW and hourly capacities. This technology has reached a TRL of 7.[37]
Reversible-based reaction storages	The TRL stands between 2 and 4 [38] Cu. Focussing on calcium looping a method has been tested for carbon capture in a cement industry. While still at the early stages of development, the technology is relevant in relation to heating as well as industrial processes. Overall, the integration of chemical looping as well as other thermochemical storage systems together with renewables can aid decarbonisation of industrial processes that require higher-temperature process heat,[39]
Sorption-based storage	Research on seasonal energy storage for low-temperature building applications is progressing in Europe, focusing on salt hydration and absorption systems.[40] Salt hydration shows promise for seasonal heat batteries but faces challenges like material corrosion and stability. Absorption systems provide higher energy storage densities and are suitable for low-grade heat use. However, ongoing challenges must be resolved for wider adoption.
Adiabatic compressed air energy storage (A-CAES)	A-CAES systems are in the demonstration phase.[41] Caves are normally used to reduce cost, creating geographical constraints.[42] Tunnel boring machine and micro-tunnel boring machine development could bring cost disruption and reduce the geological constraints.

[36] Energy Storage in association with BVES (2024). Fact sheet produced by the Energy Storage Technology Collaboration programme in collaboration with BEVIS (one of 39 Technology collaboration programmes with the IEA) (2024): FactSheet_Thermal_Latent_LT.pdf.

[37]IRENA (2020). Innovation Outlook: Thermal Energy Storage, International Renewable Energy Agency, Abu Dhabi. Innovation outlook: Thermal energy storage.

[38] Fact sheet produced by the EERA (European Energy Storage Alliance (2018). Fact Sheet (eera-energystorage.eu).

[39] IRENA (2020). Innovation Outlook: Thermal Energy Storage, International Renewable Energy Agency, Abu Dhabi. Innovation outlook: Thermal energy storage (irena.org).

[40] IRENA (2020). Innovation Outlook: Thermal Energy Storage, International Renewable Energy Agency, Abu Dhabi. Innovation outlook: Thermal energy storage (irena.org).

[41] EASE. Adiabatic Compressed air Energy Storage (EASE_TD_ACAES.pdf (ease-storage.eu).

[42] IRENA (2020). Innovation Outlook: Thermal Energy Storage, International Renewable Energy Agency, Abu Dhabi. Innovation outlook: Thermal energy storage (irena.org).

Technology	Status
Liquid air energy storage (LAES)	LAES systems may be standalone or hybrid. Overall, energy efficiency and economic performance still need improvement.[43] The TRL for this technology is estimated to be between 7 and 8.[44]

The storage technologies cater to a variety of applications, with some focused on the power sector and others serving industries and district heating and cooling, among other uses. Additionally, many of these storage systems are applicable across multiple sectors. They also vary in their readiness for market adoption. Molten salts and liquid air energy storage (LAES) are suitable for large-scale applications, while low-temperature phase change materials are better for smaller systems. Molten salts demonstrate high efficiency and durability, making them a strong option for long-term energy storage, while other technologies provide varying benefits in terms of response time and operational suitability. Ultimately, the choice of technology should align with specific energy storage needs and conditions.

Cost estimates

Cost-effectiveness and investment scalability are crucial factors in evaluating the energy storage technologies and vary across technologies. The table below compares the various energy storage technologies based on cost, investment and maintenance. Molten salts are identified as the most cost-effective option, with low expenses and manageable maintenance requirements. In contrast, low- and high-temperature phase change materials are significantly more expensive, accompanied by high maintenance costs, particularly for low-temperature options. A-CAES and LAES call for substantial investments and have higher maintenance costs, which could hinder their adoption. Reversible-based reaction storages and sorption-based storage exhibit more variability in costs, with sorption options showing a wide range. Overall, while molten salts emerge as

[43] Beline, Emiliano, PV magazine (2024). Standalone liquid air energy storage system for power, heating, cooling supply. Standalone liquid air energy storage system for power, heating, cooling supply – pv magazine International.

[44] IRENA (2020). Innovation Outlook: Thermal Energy Storage, International Renewable Energy Agency, Abu Dhabi. Innovation outlook: Thermal energy storage (irena.org).

the most financially attractive technology, A-CAES and LAES provide scalability benefits at a higher cost, highlighting the potential of such technologies for large scale applications.

Table 4 Cost estimations of different storage technologies[45]

Technology	Investment cost per kW (EUR)	Investment cost per kWh (EUR)	Operating and maintenance cost
Molten salts		20-70	1% of overall investment per year
Low-temperature phase change materials	200-400	20-100	EUR 2,500/y
High-temperature phase change materials	50-100	40-80	<1% of overall investment
Reversible-based reaction storages			
Sorption-based storage	500	30-130	
Adiabatic compressed air energy storage (A-CAES)	1,200-2,000[46]	12-18	2-3% of overall investment per year
Liquid air energy storage (LAES)	1,100-3,000	50-200	1-2% of overall investment per year

Source: IEA ES, 2024.

Production[47]

MSTES has well-developed commercial applications, particularly in relation to concentrated solar power (CSP) deployment. By the end of 2021, it was estimated that approximately 23 GWh of thermal energy storage, primarily utilising molten salts, was functioning alongside CSP plants.[48] Notably, only two of the 25 CSP plants completed worldwide since late 2014 do not feature thermal energy storage (TES). TTES capacity, predominantly installed in conjunction with CSP, accounts for nearly 40% of the global energy storage capacity outside of pumped hydropower.

In reversible-based reaction storages, calcium looping is being investigated as a viable energy storage technology for concentrated solar power (CSP) systems and may also have applications in other high-temperature sectors, such as industry and the broader power sector. In Taiwan, high-efficiency calcium looping has been tested as a carbon capture method in the cement industry; however, its application for integrating renewable energy in industrial processes is still in development. Additionally, solar energy captured through CSP could potentially be stored as chemical energy via an endothermic

[45] Homepage of the Technology Programme by IEA (2025): Energy Storage Technologies – IEA ES TCP; note that according to the source, the investment cost per kW is based on the output-specific parts of the storage, while the investment cost per kWh is based on the capacity-specific parts. To calculate the overall investment for a system, both must be added together.

[46] EASE. Adiabatic Compressed air Energy Storage. EASE_TD_ACAES.pdf.

[47] No data were collected relating to production or deployment for low-temperature phase change materials, high-temperature phase change materials or liquid air energy storage.

[48] REN21 – Renewables now (2022). Renewables 2022 Global Status Report. GSR2022_Full_Report.pdf (ren21.net).

oxidation reaction in a chemical looping system, enabling solar energy to be stored and later released through a chemical reaction, a concept currently under research.

Small-scale demonstrators for adiabatic compressed air energy storage (A-CAES) are planned, with the smallest units expected to have capacity of close to 100 MW (to reap benefits from economies of scale).[49] In Germany, over 30 GW of potential A-CAES output has been identified, corresponding to four times the capacity of installed pumped hydro power.[50] A demonstration project for next-generation A-CAES is being developed in Switzerland. A Swiss company ALACAES has focused on advanced adiabatic compressed air energy storage technology, successfully building and testing a 1 MWh pilot plant in the Swiss Alps in 2016.[51] Hydrostor, a Canadian company, specialises in energy storage solutions and has deployed multiple A-CAES projects in Canada and Australia. Its portfolio includes over 6 GW of large-scale A-CAES projects under development across the USA, Canada, Chile and Australia.[52] In total, Hydrostor has A-CAES projects with planned capacity of 7 GW.

4.10.3. Renewable fuels of non-biological origin (RFNBO)

Renewable fuels of non-biological origin (RFNBOs) are still at an early stage of development, but efforts are being made to promote their development and uptake. However, due to their currently limited commercial role, data on RFNBOs are limited. RFNBOs use renewable hydrogen as a feedstock for e-fuels. The hydrogen is then combined with other elements (such as nitrogen or carbon) to produce synthetic liquid, such as ammonia, e-methanol, e-kerosene, e-diesel, e-gasoline, or synthetic gases like e-methane.[53] The benefit of RFNBOs lies in their capacity to reduce greenhouse gas emissions in hard-to-abate sectors like industry, maritime transport and aviation. Accordingly, there is a legislative push to accelerate the development and uptake of RFNBOs, but the commercial use of RFNBOs remains limited at present. For that reason, the desk-based economic and market analysis drew on several data sources, including industry databases and information concerning companies/projects, focusing on the RFNBOs with the most substantial amounts of readily accessible data. These include e-methanol, particularly in the maritime sector; e-ammonia, which is relevant to industry and agriculture; e-kerosene, which is used in aviation; and e-methane, which was examined for its applications in industry, heating and the maritime sector.

State of technology

The technology for producing RFNBOs is largely commercially available, although some processes for adapting and integrating renewable hydrogen are still under development. E-fuel synthesis largely mirrors existing commercial processes using non-renewable sources. The main barriers to RFNBO uptake lie upstream: scaling green hydrogen production via electrolysis and improving carbon capture, especially direct air capture. Notably, integrating water electrolysis with e-ammonia production and simultaneous hydrogen-nitrogen separation remains at the pre-commercial or early development stage. Similarly, small-scale Fischer-Tropsch and distillation processes for e-

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[49] EASE. Adiabatic Compressed air Energy Storage (EASE_TD_ACAES.pdf (ease-storage.eu) .

[50] EASE. Adiabatic Compressed air Energy Storage (EASE_TD_ACAES.pdf (ease-storage.eu)

[51] Information extracted from homepage of ALACAES (extracted mid 2025). ALACAES

[52] Information extracted from homepage of Hydrostor (extracted mid 2025). Home – Hydrostor

[53] For RFNBOs to qualify towards the EU's renewable energy targets, they must achieve greenhouse gas emissions savings of over 70% compared to fossil fuels.

kerosene are still in demonstration phases. The table below shows the Technology Readiness Levels (TRL), with a scale from 1 to 9 used to assess technology maturity.

Table 5 Technology readiness of processes for selected RFNBOs

Fuel	State of technology
e-Methanol[54]	The technology used in the production of the product has a TRL of 9. The cleanest form of e-methanol uses direct air capture, which has a TRL ranging from 4 to 7.
e-Ammonia[55]	The Haber-Bosch synthesis method is a well-known process in the production of ammonia and is widely used on a commercial scale, having a TRL of 9. Production of e-ammonia via integration of water electrolysis for hydrogen production has a TRL of 7. Technology enabling simultaneous hydrogen production and nitrogen separation currently has a TRL of 4 to 5.
e-Kerosene[56]	The FT process is widely used on an industrial scale today, with a TRL of 9. However, smaller-scale deployment of FT, suitable for the current electrolysis capacity, is still in the demonstration phase, with a TRL of 6. In the case of the methanol-to-jet pathway, the methanol-to-olefin step has reached commercial readiness, with a TRL of 9. However, the olefin-to-distillate step is still in the demonstration phase, with a TRL of 6.
e-Methane[57]	Technology solutions for the production, transportation, storage and use of e-methane are available.

Sustainability

RFNBOs have high potential for emission savings. The cradle-to-grave greenhouse gas emission intensity of RFNBOs is around 90% lower than for fossil fuels (REDII stipulates a 94 gCO_2eq/MJ fossil fuel comparator for RFNBOs).[58] One important aspect, however, is the need to source CO_2 to synthesise these fuels. Some RFNBOs require a large amount of CO_2, resulting in potentially high demand for carbon. This could lead to a rebound effect on the projected GHG emissions for some of the RFNBOs. The figures below present current and projected total estimated greenhouse gas emissions generated throughout the entire lifecycle of the fuels (cradle-to-grave emissions).[59]

[54] IRENA AND METHANOL INSTITUTE (2021). Innovation Outlook : Renewable Methanol, International Renewable Energy Agency, Abu Dhabi Innovation Outlook: Renewable Methanol.

[55] Danish Innovation Fund, Innomission Roadmap Leveraging Danish strengths to mature and scale up e-fuels for transport. Proposal for Innomission Roadmap 2: green Fuels for Transport and Industry.Appendix 4 _ 1112-00012A – Innomission Roadmap Leveraging Danish strengths to mature and scale up e-fuels for transport.pdf (innovationsfonden.dk).

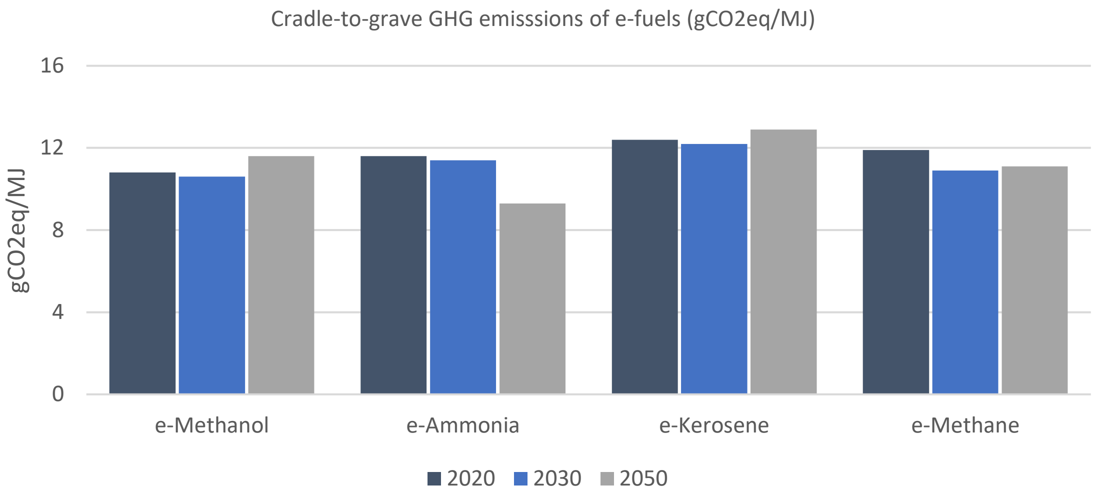
[56] Danish Innovation Fund. Innomission Roadmap Leveraging Danish strengths to mature and scale up e-fuels for transport. Proposal for Innomission Roadmap 2: green Fuels for Transport and Industry. Appendix 4 _ 1112-00012A – Innomission Roadmap Leveraging Danish strengths to mature and scale up e-fuels for transport.pdf (innovationsfonden.dk).

[57] Form the Fuel Pathway Maturity Map developed by Mærsk Mc-Kinney Møller Center for Zero Carbon Shippping. e-methane | Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping.

[58] EU, Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy for renewable sources (recast) (2018) Directive – 2018/2001 – EN – EUR-Lex.

[59] Concawe and aramco, Soler, Alba, Gordillo, Victor, Liliey, William, Schmidt, Patric,Werner, Weindorf, Bolkow, (2022) A techno-economic assessment of European domestic production and imports towards 2050, Report no. 17/22 E-Fuels. E-Fuels (concawe.eu).

Figure 82 Cradle-to-grave GHG emissions of the selected RFNBOs[60]



Source: Concawe, 2022

Cost estimates

High production costs constitute the main barrier to scaling up the uptake of RFNBOs. It is still costly to produce renewable hydrogen and to capture carbon. Combined with the limited possibilities for economies of scale, this results in e-fuels not being commercially competitive compared to other alternatives.[61] Besides technological and process-related advancements that drive costs down, policies have been put in place to promote a level playing field for RFNBOs[62] in the market. The figure below shows the estimated production cost ranges for different fuels, comparing e-fuels with alternatives such as advanced biofuels and fossil fuels. The production cost of RFNBOs varies depending on the availability of renewable power supply. Accordingly, a range has been provided based on conditions reflecting the production of RFNBOs in Central Europe in 2020.[63]

Production

The production of RFNBOs is still under development, but an increasing number of projects have been announced. Project-specific data availability and data types vary from fuel to fuel. Some projects are more mature than others, with data more readily available via open sources, while others are at an earlier stage of development, with only limited information available through announced projects and company information. Nonetheless, several projects have been announced on the production of various e-fuels. The producers

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[60] Values for e-fuel cradle-to-grave GHG emissions were calculated based on parameters for e-fuel production in Central Europe. Furthermore, these estimates may vary according to factors depending on different scenarios, both regional and technical. For comparison purposes, REDII stipulates an emission level of 94 gCO_2eq/MJ for fossil fuels.

[61] IEA Bioenergy Summary Series, Task 41 (2020). Technology Collaboration Programme (2020). Advanced biofuels – Potential for Cost Reduction, summary Series IEA Bioenergy: Task 41: 01 2020 Microsoft Word – IEABioenergy-2pSummary-CostAdvancedBiofuels.docx.

[62] Such as to internalise the cost of other fuels and make e-fuels more competitive, e.g. expanding the sectors covered by the ETS. Furthermore, the EU has set mandatory requirements for RFNBO shares in transport and industry.

[63] Concawe and aramco, Soler, Alba, Gordillo, Victor, Liliey, William, Schmidt, Patric,Werner, Weindorf, Bolkow, (2022) A techno-economic assessment of European domestic production and imports towards 2050, Report no. 17/22 E-Fuels. E-Fuels (concawe.eu).

are often large energy companies, typically operating in a consortium with partners along the e-fuel value chain under a flagship project.

According to the Methanol Institute,[64] there were 58 e-methanol projects in 2023 around the world, including established and upcoming projects, of which about half are European. Among those, 30 have been announced in Europe. All the projects are expected to be completed by 2035, reaching total production of 5,125,270 tonnes per year globally, of which 34% is projected to be produced in Europe. Accordingly, while more projects (30 out of 58) are expected to be developed in Europe, non-European projects expect a higher production capacity (66% of the total). Recently, the company European Energy produced the first batch of industry-grade e-methanol fulfilling the ISCC-EU RFNBO criteria. Kassø Power-to-X is the world's first commercial-scale e-methanol facility, with annual capacity of 42,000 tonnes.[65] On the demand side, companies such as LEGO and Novo Nordisk have already taken steps to secure e-methanol for their operations[66] and through agreements with the mentioned supplier which owns the Kassø facility[67]. LEGO intends to use e-methanol as a low-carbon solution to substitute conventional plastic ingredients. Novo Nordisk will use the low-carbon chemical in the production of medical devices. The Danish shipping company Maersk has been a proactive first mover on the demand side. The company has ordered 19 dual-engine methanol vessels, which can operate on green methanol and will be delivered by 2025.[68] These vessels will require around 750,000 tonnes of e-methanol.

Little information exists on global or European production of renewable ammonia reflecting its low penetration. However, a blog published in 2024 suggests that 10 million tons of global capacity was announced in 2023[69], while another report indicates that global ammonia production in 2023 was about 182 metric tonnes of which green ammonia accounted for only just under 0.2%[70]. The largest ammonia companies in the world CF Industries and Yara have announced projects to upgrade their existing production facilities to substitute their ammonia production fully or partially with e-ammonia, as well as to build new production facilities for the green chemical.[71] The largest of the European projects is HØST PtX Esbjerg,[72] to be developed in Esbjerg, Denmark. This project is being developed by Copenhagen Infrastructure Partners, Maersk and DFDS and is expected to have a production capacity of 600,000 tonnes per year. The ammonia is intended for use as both maritime fuel and fertiliser.

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[64] Homepage of the Methanol Institute (extracted mid 2025). Renewable Methanol | METHANOL INSTITUTE.

[65] Press release from European Energy (2020). E-methanol from Kassø gets first ever EU certification on green fuels - European Energy.

[66] Reuters Daily Briefing Letter (2023). LEGO, Novo Nordisk agree to buy green methanol for plastic production | Reuters.

[67] Article in Sustainability Magazine (2025). Why LEGO, Maersk & Novo Nordisk Are Investing in e-Methanol. https://sustainabilitymag.com/articles/why-lego-maersk-novo-nordisk-are-investing-in-e-methanol.

[68] Press Release from Maersk Darly, James , A.P. Moller – Maersk continues green transformation with six additional large container vessels (2022). A.P. Moller – Maersk continues green transformation with six additional large container vessels | Maersk.

[69] McCallum Tristan, Blogs on the homepage of FGE Nexant ECA (2024). Global Green Ammonia Market Snapshot. Global Green Ammonia Market Snapshot.

[70] MG Market Growth Reports (last updated 2025). Summary of Green Ammonia market Size, Share, Growth, and Industry Analysis, By Type(Exceptional Purity, Low Putity) By Application (Power Generation, Transportation, Industrial Feedstock, Others), Regional Insights and Forecast to 2033. Green Ammonia Manufacturing Market Market Size & Growth [2033].

[71] IRENA and AEA (2022). Innovation Outlook: Renewable Ammonia, International Renewable Energy Agency, Abu Dhabi, Ammonia Energy Association, Brooklyn. Innovation Outlook: Renewable Ammonia (irena.org).

[72] Homepage of Høst PTX Esbjerg About the plant » HØST PtX Esbjerg (hoestptxesbjerg.dk).

At present, there are not yet any e-kerosene projects operational in the EU. A 2024 study by the European NGO Transport and Environment identified a total of 45 e-kerosene projects announced in the EEA, 25 of which are industrial projects and 20 are pilot projects. However, none of these projects had reached the stage of a final investment decision.[73] The identified projects would together result in production capacity of 1.7 Mt of e-kerosene by 2030, exceeding the ReFuelEU target.

E-methane production in Europe is expanding rapidly and continuous growth of the sector is expected. The European Biogas Association (EBA) published a white paper in 2024, which identified 35 operational plants in Europe, 33 of which are fully renewable; in addition, 20 new plants are either planned or under construction.[74] According to the association, e-methane production capacity in Europe has increased from 20 GWh per year to 449 GWh per year in the past eight years. It is projected that production capacity in 2027 will reach nearly 3,000 GWh per year, equivalent to 0.27 billion cubic meters (bcm). In the maritime sector, the French company Engie, has entered into a partnership with the shipping company CMA CGM to develop synthetic methane production and distribution for the shipping sector.[75] The shipping company invests significantly in dual-fuel engines vessels running on LNG that are 'e-methane ready' as seen in the recent order of 12 LNG dua fuel ships in South Korea[76]. In the gas sector, the Japanese company, Mitsubishi Corporation, is developing a project in conjunction with Tokyo Gas, Osaka Gas and Togo Gas, to build a complete supply chain, from hydrogen production and carbon capture, in order to produce e-methane.[77] The project plans to locate its production facility in the US, aiming to produce 130,000 tonnes of e-methane per year, all which would be then exported to Japan, using existing gas infrastructure for transport and storage. In Europe, the Belgian company Tree Energy Solutions is developing a green energy hub by the German port of Wilhelmshaven, with a view to later producing and importing e-methane made from green hydrogen.[78] [79]

4.10.4. Advanced biofuels

Advanced biofuels are defined as biofuels that are produced from feedstock with no direct or indirect land use change. This EU definition of advanced biofuels by specific feedstock categories differs from the definition used in other regions, where advanced biofuels are defined by applied technology. The use of different definitions of advanced biofuels could lead to inconsistencies in data.[80] Advanced biofuels are at the development stage, which

[73] Press Release from T&E (2024). E-fuels for planes: with 45 projects, is the EU on track to meet its targets? E-fuels for planes: with 45 projects, is the EU on track to… | T&E.

[74] News announcement on the homepage of EBA European Biogas Association, (2024). First Assessment of European e-methane roll-out released today. First assessment of European e-methane roll-out released today | European Biogas Association.

[75] Homepage of engie (2021). CMA CGM and ENGIE:a strategic and industrial partnership to decarbonise shipping. CMA CGM and ENGIE: a strategic and industrial partnership to decarbonize shipping | ENGIE.

[76] News Article published by Ship & Bunker (2025). CMA CGM Adds Methanol-Fuelled Boxship to its Fleet. https://shipandbunker.com/news/world/718666-cma-cgm-adds-methanol-fuelled-boxship-to-its-fleet.

[77] Description on the homepage of Mitsubishi Corporation. E-methane Development Project Utilizing the Cameron LNG Terminal in the US, project https://www.mitsubishicorp.com/jp/en/bg/next-generation-energy-business-group/project/e-methane/.

[78] Collins, Leigh, Article published on the homepage of Recharge (0222). The cheapest way to ship green hydrogen is via e-methane – we will help wean Germany of Russian Gas. 'The cheapest way to ship green hydrogen is via e-methane – we will help wean Germany off Russian gas' | Recharge (rechargenews.com).

[79] Article published on the homepage of Hydrogen insights: Parks, Rachel (2024). Hydrogen derived e- methane import terminal moves a step closer to fid after exemption. https://www.hydrogeninsight.com/policy/hydrogen-derived-e-methane-import-terminal-moves-a-step-closer-to-fid-after-exemption/2-1-1618530

[80] EC Knowledge for policy (2025). Advanced biofuels, Glossary Item, Advanced biofuels | Knowledge for policy.

means that only limited data are available. While there is ample information on biofuels in general, data specific to advanced biofuels are limited to preliminary findings emerging from dedicated reports, which cover projects, production and potential costs, but lack extensive historical data.

State of technology

Numerous advanced biofuels are under development, with diverse pathways and at varying levels of technology readiness. These include cellulosic ethanol, biomethanol, DMF, Bio-DME, Fischer-Tropsch diesel, mixed alcohols and wood diesel.[81] Some fuels, such as algal biofuels and hydrogen derived from biomass, are still in the early stages of development. IEA Bioenergy offers an overview of these advanced biofuels pathways along with the technology readiness levels (TRL) for the main fuel types, as described below.[82]

- **Bioethanol:**
  Cellulosic ethanol is at a very early stage of commercialisation, whereas ethanol produced from sugar and starch crops has reached commercial maturity.

- **Diesel-type biofuels:**
  Fischer–Tropsch liquids are in the very early stage of commercialisation, while biodiesel (FAME) and hydrotreated vegetable oil (HVO) are commercially established.

- **Biomethane:**
  Biomethane derived from gasification is in the early stage of commercialisation, while biomethane produced through anaerobic digestion is more advanced and commercially available.

- **Other advanced biofuels:**
  Fuels based on pyrolysis and hydrothermal liquefaction (HTL) are currently in the demonstration phase.

Cost estimates

Production costs for biofuels are heavily influenced by feedstock prices and conversion efficiencies. Generally, ethanol from cellulosic sources is more expensive than ethanol derived from corn fibre, which benefits from lower costs and integration with existing plants. Biofuels produced from waste materials are notably cheaper than those from biomass. Although capital costs for production facilities remain similar across different feedstocks, the negative costs associated with waste feedstocks help reduce overall expenses. In contrast, production of Fischer-Tropsch products or gasoline hydrocarbons incurs higher costs due to their complexity. There is also considerable uncertainty surrounding bio-oil production costs, while established technologies like hydrotreated vegetable oils (HVO) and anaerobic digestion have more consistent and lower cost ranges. Medium-term cost reductions for advanced biofuels are anticipated as more commercial plants are built, allowing for learning from early deployments, ongoing R&D, process optimisation and improved integration with other operations. Long-term cost reductions are

[81] IEA Bioenergy (2025). Technology Collaboration Programme by IEA, Definitions, Task 39: Biofuels to decarbonize transport, Definitions | Task 39.

[82] IEA Bioenergy (2024). Sonnleitner, Andrea and Bacovsky, Dina (2024). Development and Deployment of advanced biofuel demonstration facilities,IEA Bioenergy Technology Collaboration Programme Task 39. IEA-Report-T39-T4-Development-and-Deployment-of-advanced-biofuel-demonstration-facilities-2024.pdf.

expected through extensive technology deployment and experiential learning. However, these are harder to estimate and are likely to occur beyond a 15-year timeline[83].

Production

Several biomass conversion facilities have been identified, with the high number of upcoming projects indicating growing interest in advanced liquid and gaseous biofuels for transport. The IEA Bioenergy database lists a total of 258 facilities, of which 134 are operational, while 85 are planned or under construction.[84] The remaining 39 entries represent projects that are non-operational, on hold, idle or cancelled.

4.10.5. Water electrolysis

Water electrolysis is the primary method for producing green hydrogen. Green hydrogen can replace grey hydrogen and provide a fuel for end uses that may be technically difficult to decarbonise through other means. It is used, for example, in heavy industry, shipping and long-term energy storage. Accordingly, water electrolysis and green hydrogen play a key role in the EU's green transition There are four main technologies in water electrolysis: alkaline water electrolysis (AWE), proton exchange membrane (PEM), solid oxide electrolysis cells (SOEC) and anion exchange membrane (AEM).

State of technology

Water electrolysis projects aimed at technological improvements and preparations for production scale-up were identified. The study compiled a list of companies that have applied for patents in hydrogen production based on water electrolysis and provided examples of the projects associated with the patent applications. Key insights are presented below.

[83] IEA Bioenergy Technology Cooperation Programme (2020). Advanced Biofuels – Potential for Cost Reduction. https://task39.ieabioenergy.com/wp-content/uploads/sites/37/2020/02/Advanced-Biofuels-Potential-for-Cost-Reduction-Final-Draft.pdf.

[84] Technology Collaboration Programme by IEA (2025). Facilities. https://www.ieabioenergy.com/installations/.

Table 6 Examples of water electrolysis projects (based on data collected in 2023)

Project example	Aim or content of the project	Further information
Cost-effective high-pressure technology for water electrolysis coordinated by the Consiglio Nazionale Delle Richerche in Italy	This project aims to (i) reduce the energy needs associated with hydrogen and (ii) reduce capital costs of large-scale application of water electrolysis.	February 2023 to January 2026. Budget: EUR 1.6 million[85]
The REFHYNE 2 project at the Shell Rheinland Energy and Chemicals Plant in Germany[86]	This is an expansion of the REFHYNE 1 project, which produces approximately 1,300 tonnes of hydrogen each year and has a peak capacity of 10 MW. The REHYNE 2 project increases the size by a factor of 10, aiming to install capacity of 100 MW.	Received financial support from Horizon 2020. EUR 149 million (of which the EU contribution is EUR 32 million), coordinated by SINTEF A/S (Norway). October 2021 to September 2026[87]
Seawater electrolysis, China	In June 2023, researchers in China announced that they have achieved water electrolysis using seawater without the need for prior desalination. To avoid corrosion of equipment, they kept the electrolyser separate from the seawater with a waterproof, breathable membrane. The prototype – a floating offshore platform – has demonstrated it can withstand strong winds, high waves, storms and operate consistently for over 133 days without deterioration.[88]	This technology would allow for the offshore production of green hydrogen using nearby wind or ocean energy technologies.
European offshore electrolysis	Germany has set aside an area of the North Sea for a wind farm connected to a 1 GW hydrogen project using water electrolysis by 2030.[89] The resulting hydrogen is to be pumped onshore through pipes. Success of the project will hinge on fast-track permitting for the 30 GW wind farm required. The Dutch government also plans to issue a tender for a 500 MW offshore-powered electrolyser, which	

[85] CORDIS, EU research results, Advanced High pressure and Cost-Effective PEM Water Electrolysis Technology, Project description Project ADVANCEPEM, signed December 2022. Advanced High Pressure and Cost-Effective PEM Water Electrolysis Technology | ADVANCEPEM | Project | Fact sheet | HORIZON | CORDIS | European Commission (europa.eu)

[86] Project overview provided on the homepage of REFHYNE (2025). https://www.refhyne.eu/refhyne-2/.

[87] CORDIS, EU research results, Clean Refinery Hydrogen for Europe II, project description provided of REPHYNE II signed in September 2021 provided on the homepage of CORDIS, EC. Clean Refinery Hydrogen for Europe II | REFHYNE II | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu).

[88] homepage Hydroinsight news, Collins, Leigh (2024). Chinese scientists produce green hydrogen directly from seawater at floating offshore pilot project Chinese scientists produce green hydrogen directly from seawater at floating offshore pilot project | Hydrogen Insight/ / homepage of Offshore Energy, Habibic Ajsa (2023). China tests hydrogen production through direct seawater electrolysis at Xinghua Bay OWF. China tests hydrogen production through direct seawater electrolysis at Xinghua Bay OWF - Offshore Energy (offshore-energy.biz) .

[89] Homepage of Hydrogeninsight, Collins, Leigh (2023). Offshore hydrogen Germany plans 1GW of wind-powered green H2 production at sea, with pipeline to share. Offshore hydrogen | Germany plans 1GW of wind-powered green H2 production at sea, with pipeline to shore | Hydrogen news and intelligence (hydrogeninsight.com).

Project example	Aim or content of the project	Further information
	would pump renewable hydrogen onshore via a pipeline.[90]	
Sinopec (China) Inner Mongolia Erdos wind-solar green hydrogen project	This project aims to produce 30,000 tonnes of green hydrogen annually using wind and solar to power water electrolysis and hydrogen storage and transport. 450 MW of wind and 270 MW of solar are to be installed to power this plant.[91]	Budget: USD 828 million

Sustainability

There is significant potential for GHG emission reductions in shifting from grey hydrogen production to green hydrogen, which alone could reduce the EU's total emissions by 8%.[92] Furthermore, the use of green hydrogen is particularly relevant in hard-to-abate sectors, such as the steel industry, which currently accounts for 7% of the total EU emissions.

Cost estimates

It is necessary to reduce the costs of electrolyser systems, with technological innovation playing a crucial role in achieving this goal. According to IRENA,[93] the investment costs for electrolyser plants can be decreased by 40% in the short term and 80% in the long term by implementing a range of strategies. These include improving the design and construction of electrolyser systems, taking advantage of economies of scale, using abundant metals instead of scarce materials and enhancing operational efficiency and flexibility. Data on current cost levels and the expected level by 2030 are presented below.

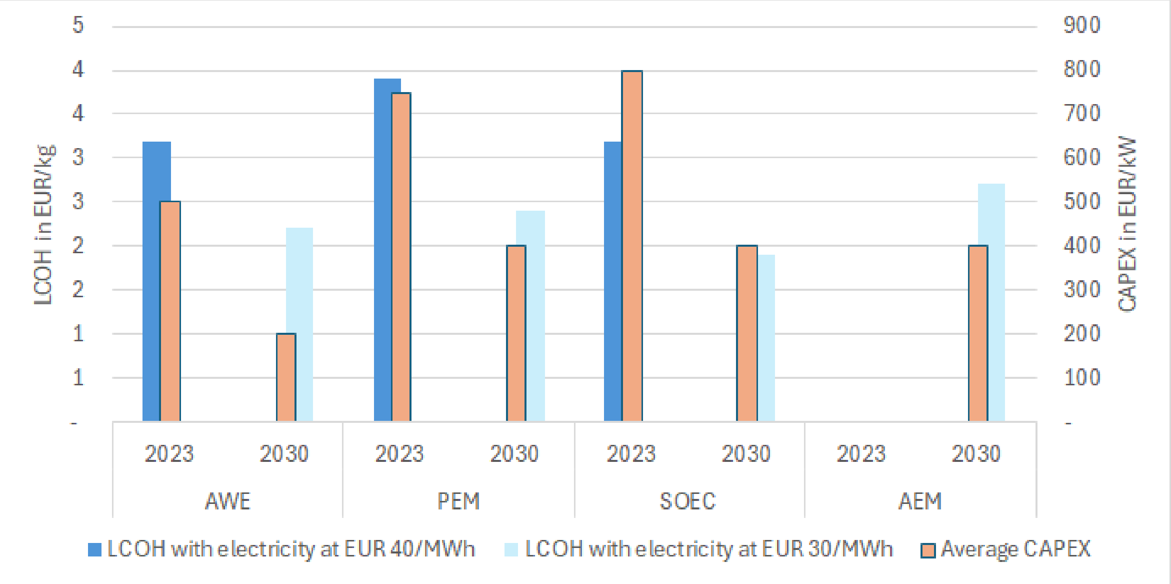
[90] Homepage of Hydrogeninsight, Lee, Andrew (2023). Tender for 500MW offshore green hydrogen project in North Sea announced by Dutch government. Tender for 500MW offshore green hydrogen project in North Sea announced by Dutch government | Hydrogen news and intelligence (hydrogeninsight.com).

[91] MERCOM, Hazarika, Gautamee, (2023). China's Sinopec Launches $828 million Green Hydrogen Projects. China's Sinopec Launches $828 million Green Hydrogen Project (mercomindia.com).

[92] Homepage of Hydrogen Tech World, Bernuy-Lopez, Carlos (2023). Electrolysis technologies and LCOH: current state and prospects for 2030. Electrolysis technologies and LCOH: current state and prospects for 2030.

[93] EPO and IRENA (2022). Patent insight report. Innovation trends in electrolysers for hydrogen production, EPO, Vienna. Innovation trends in electrolysers for hydrogen production: Patent insight report (irena.org).

Figure 83 Costs of water electrolysis technologies



Source: [Electrolysis technologies and LCOH: current state and prospects for 2030 (hydrogentechworld.com)]

Production

Significant investment in water electrolysis capacity is needed. According to the IEA, in 2023, global manufacturing capacity reached 25 GW per year[94], considerably lower than the projected need in 2030. Data on planned and announced projects are uncertain. The majority do not yet have a signed FID and 30% of the announced projects do not have a target year for commencement of operations. Still, 2023 data suggests that the global capacity in 2030 can deliver 70% of the capacity needed in 2030[95]. China, the US and the EU account for the biggest capacity shares (in the said order), but many investments require government support for financial viability.

4.10.6. Ocean energy

The ocean represents a largely untapped energy source with significant potential, with only a few technologies having reached commercial maturity to harness the benefits. Altogether, ocean energy is estimated to be able to potentially provide between 45,000 and 135,000 TWh of electricity.[96] Among the technologies currently being explored, ocean thermal energy conversion has the highest energy potential at 44,000 TWh.[97] After OTEC, wave energy has the second highest potential at 29500 TWh. The global potential of tidal energy is estimated at around 1200 TWh. Accordingly, the potential generation capacity estimated for wave energy is nearly 25 times higher than for tidal energy. The ocean energy market

[94] IEA homepage on low-emission fuels on electrolysers. https://www.iea.org/energy-system/low-emission-fuels/electrolysers.

[95] IEA, Paris, Overview of report: IEA (2023). Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach, https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach/making-the-net-zero-scenario-a-reality.

[96] IRENA (2020). Innovation outlook: Ocean energy technologies, International Renewable Energy Agency, Abu Dhabi. Innovation outlook: Ocean energy technologies (irena.org).

[97] IRENA and OEE (2023). Scaling up investments in ocean energy technologies, International Renewable Energy Agency, Abu Dhabi. https://www.oceanenergy-europe.eu/wp-content/uploads/2023/03/IRENA_OEE_Scaling_up_investment_ocean_energy_2023.pdf.

is projected to face significant challenges in meeting capacity goals, with current estimates falling far short of the potential outlined in climate scenarios. According to Astute Analytica, total installed capacity by 2030 is currently projected to reach around 2.2 GW (based on the current project pipeline).[98] The European offshore energy strategy, aligned with the European Green Deal, has set high targets for the deployment of ocean energy, with the goals of 1.3 GW of tidal and wave energy deployed by 2030 and 60 GW deployed by 2050. These targets not only align with the energy transition objectives, but also with the European strategy of remaining a leader in renewable energy technologies.[99] EuroObserv'ER projects that the ocean energy net capacity in the EU will be around 1 GW by 2030.[100]

State of technology

Ocean energy technologies are at varying stages of readiness and deployment, with significant implications for future developments. Tidal barrage is the most developed ocean energy technology with a TRL of 9.[101] However, given the physical constraints to tidal barrage, attention has shifted towards a growing number of technologies with higher generation and deployment potential. Therefore, although the most well-established technology is tidal barrage, most projects today focus on tidal stream and wave energy technologies. This is due to their immense energy potential and technology readiness. Several technologies within wave and tidal stream are in the scale-up process. Tidal stream is more advanced and closer to commercialisation. Despite their very high potential, OTEC and salinity gradient are technologies still at the research and early development stages, with small-scale projects being conducted and most activities occurring in research centres and universities.[102]

[98] Press release published by Astute Analytica India Pvt. Ltd. (2023) published on yahoo!finance (2023). Global Wave and Tidal Energy Market set to soar to reach US¤ 10,064 million by 2031: Astute Analytica. Global Wave and Tidal Energy Market Set to Soar to Reach US$ 10,064 Million by 2031: Astute Analytica: ccording to their studies, the market value of ocean energy in 2022 is estimated to be close to USD 500 million for installed capacity of 535 MW. Based on their estimation of 2.2 GW, a market value of USD 10 billion is expected by 2031 for wave and tidal energies, representing a compound annual growth rate (CAGR) of 43%. IRENA, however, expects the market for ocean energy to reach 10 GW by 2030 (see footnote 100).

[99] IRENA (2020). Innovation outlook: Ocean energy technologies, International Renewable Energy Agency, Abu Dhabi. Innovation outlook: Ocean energy technologies (irena.org).

[100] Ocean Energy Barometer, EurObserv'er (2022). Ocean Energy Barometer 2022 - EurObserv'ER (eurobserv-er.org).

[101] IRENA (2020). Innovation outlook: Ocean energy technologies, International Renewable Energy Agency, Abu Dhabi. Innovation outlook: Ocean energy technologies (irena.org).

[102] IRENA (2020). Innovation outlook: Ocean energy technologies, International Renewable Energy Agency, Abu Dhabi. Innovation outlook: Ocean energy technologies (irena.org).

Table 7 Status of ocean technologies

Technology	Status
Tidal energy[103]	Tidal energy – beyond tidal barrage – is moving towards a convergence in technology, with most projects today focusing on horizontal-axis turbines. Large-scale tidal farms with this technology are currently under construction, bringing this energy technology closer to the commercialisation stage. Horizontal-axis turbines have a TRL of 8. Over two-thirds of the companies working with a tidal technology of above TRL 6 are employing this technology.
Wave energy[104]	Three wave technologies have been identified by IRENA as most promising for commercialisation: oscillating water column (OWC), oscillating water surge converter (OWSC) and point absorbers (a type of oscillating body technology).

Production/deployment

By 2020, 97% (521.5 MW) of deployed ocean energy is based on tidal barrage technology. This form of energy generation is largely distributed between two countries: South Korea, which has the highest generating capacity (254 MW), and France, which ranks second (240 MW). Beyond tidal barrage, tidal stream capacity accounts for the largest share of alternative technologies, with total installed capacity of 10.6 MW in 2020. According to Ocean Energy Europe, installed tidal production capacity in Europe reached 11.75 MW in 2023[105] with the main countries leading the way being France and UK, in 2020. Electricity production based on tidal energy has been steadily increasing in Europe over the last more than 20 years reaching more than 90 GWh in 2023[106]. Among the active tidal devices, 13 of the 16 are horizontal-axis turbines. In contrast, despite its greater potential, wave energy has significantly less deployed capacity, amounting to just 2.31 MW[107] Wave energy is especially found in Southern Europe. with installations in 2023 spanning over 4 nations (Portugal, Italy, Spain and France) and expected additional deployments over the coming years in the region[108].

A project pipeline of 2.83 GW comprising tidal stream and wave projects was identified in 2020, with Europe leading 55% of the projected capacity and maintaining its position as a frontrunner in the ocean energy market through numerous projects and developers. Tidal stream (2.4 GW) represents the bulk of these projects, with wave energy accounting for just under 500 MW. A further 5.5 GW of tidal barrage is also planned, with the main projects in the pipeline located in South Korea and the UK. Over 40 tidal stream projects are underway across 15 countries. Of the 31 countries planning to deploy ocean energy technologies, by 2020 55% of the projected energy capacity lies in Europe, making it a clear leader in this emerging sector. However, whilst Europe is the market leader in tidal energy, the US is stepping up accounting for all tidal additions outside Europe in

[103] IRENA (2020). Innovation outlook: Ocean energy technologies, International Renewable Energy Agency, Abu Dhabi. Innovation outlook: Ocean energy technologies (irena.org).

[104] IRENA (2020). Innovation outlook: Ocean energy technologies, International Renewable Energy Agency, Abu Dhabi. Innovation outlook: Ocean energy technologies (irena.org).

[105] Ocean Energy Stats & Trends 2023, Ocean Energy (2024). Ocean-Energy-Stats-and-Trends-2023.pdf.

[106] Ocean Energy Stats & Trends 2023, Ocean Energy (2024). Ocean-Energy-Stats-and-Trends-2023.pdf.

[107] IRENA (2020). Innovation outlook: Ocean energy technologies, International Renewable Energy Agency, Abu Dhabi. Innovation outlook: Ocean energy technologies (irena.org).

[108] Ocean Energy Stats & Trends 2023, Ocean Energy (2024). Ocean-Energy-Stats-and-Trends-2023.pdf.

2023[109]. The ocean energy market has been dominated by European countries – including Finland, France, Ireland, Italy, Portugal, Spain, Sweden and the UK – as well as Australia, Canada, South Korea and the United States. These countries together with China are at the forefront in terms of testing, deploying and planning the largest number of ocean energy projects. They are also home to the highest numbers of project developers and device manufacturers.[110] Intensified funding and support programmes in the US and China supports technological progress and unlocks new developments. In 2023, installed capacity in China and the US peaked at 1 MW reaching a total installed wave energy capacity in these two countries of 13.1 MW. By comparison, the total installed capacity in Europe reached 13.3 MW in 2023.[111].

[109] Ocean Energy Stats & Trends 2023, Ocean Energy (2024). Ocean-Energy-Stats-and-Trends-2023.pdf.

[110] IRENA (2020). Innovation outlook: Ocean energy technologies, International Renewable Energy Agency, Abu Dhabi Innovation outlook: Ocean energy technologies (irena.org).

[111] Ocean Energy Stats & Trends 2023, Ocean Energy (2024). Ocean-Energy-Stats-and-Trends-2023.pdf.

5. Conclusions

Timely and high-quality competitiveness indicators are essential for pursuing the objectives of the Clean Industrial Deal. The clean energy industry plays a vital role in Europe. It is a cornerstone of the future competitiveness of European industry, a key contributor to the green transition and an important generator of economic growth and employment. The Competitiveness Compass and the Clean Industrial Deal aim to ensure that policies are in place that properly support competitiveness. In this context, timely and high-quality indicators play a critical role by providing evidence-based feedback to assess the effectiveness of policies and policy needs. This study contributes to the goal of delivering high-quality economic indicators of clean energy technology value chains through a statistical delineation model for analysing economic competitiveness and comparing clean energy technologies at a more detailed level. Below, we highlight the main findings and key lessons learned.

The critical role of wind energy and photovoltaic energy in decarbonising the energy system is reflected in the sharply increasing economic value added of economic activities in these sectors. Given the EU's ambitious targets, this pronounced upward trend is expected to persist. Bioenergy and hydropower also play an important role, though their development is less dynamic due to limited expansion potential. For bioenergy, this is due to land-use competition with other activities, such as food production. In the case of hydropower, most suitable locations in EU countries, such as rivers with sufficient gradient and waterflow, have already been extensively developed. The markets for heat pumps and batteries are still relatively small compared to sectors such as wind energy but have experienced highly dynamic growth in recent years. In contrast, solar thermal energy, concentrated solar power (CSP) and geothermal energy exhibit comparatively low economic significance and are growing at below-average rates.

The comparison between EU countries reveals several geographical specialisations in different clean energy technologies, with certain countries standing out for their competitiveness. Among the EU Member States, Germany is the leading market for clean energy technologies, accounting for 36% of the total EU gross value added from all clean energy technologies. This outcome is primarily driven by the country's size and continuous deployment of new clean energy capacities, generating substantial economic activity. In addition, strong manufacturing capacities, particularly in the fields of wind energy, heat pumps and batteries have been established in Germany. In the field of wind energy, Denmark exhibits a comparatively high level of specialisation in manufacturing, with a significant increase since 2010. Between 2010 and 2023, Swedish companies established substantial manufacturing capacities in the heat pump sector, positioning the country as the leading producer within the EU. In Hungary, the government has provided extensive support to establish the country as a key hub for battery production – these efforts resulted in a substantial value-added contribution in 2023, the highest among all EU Member States in this clean energy technology. Further specialisations can be identified across EU Member States.

The more granular analysis at the value chain segment levels and their economic activities offered by this study allows policymakers critical insights into the economic impact of emerging technologies. The results of this study allow identifying where the greatest economic value is created within and between the clean energy technologies in EU Member States. The robust data foundation contributes to the monitoring of sectoral developments and the identification of specific areas of competitive strength across EU Member States at the value chain segment level. Placing these findings in a global context—using complementary data on international trade and innovation, allows to identify trends and developments related to the EU's competitiveness in clean energy technologies. The results highlight that, despite intense and heightened global competition in the manufacturing of clean technologies, the European manufacturing value chain segment remains robust across a range of technologies, offering innovative and competitive solutions. However, some clean energy technologies have been more affected by global market pressures already. These insights can help to inform strategic decisions on investment, regulation, and international collaboration.

The value chain segment analysis, building upon the model approach of the study, allows a holistic understanding of the economic activities by revealing the size and trends of each segment of the clean energy technology value chain. In addition to portraying the economic importance of each clean energy technology, monitoring each value chain segment allows for pinpointing the specific composition, and drivers and constraints of each clean energy technology's development. The applied model allows to trace these developments and can support a more nuanced analysis on the importance of relations between different value chain segments. The results, for example, can also be read in terms of the different economic geographical scales of competitiveness. Economic actors in downstream activities, such as construction, installation, and operation, are more exposed to regional competition from other such service providers and to regional demand drivers, including the strengthening and waning of regional or national support schemes or for other employment opportunities. The manufacturing segment, in contrast, is exposed to European and global competition, as goods travel more readily across borders, as well as global, national and regional deployment dynamics and demand. To sustain global competitiveness, innovation, economies of scale, and/or specialisation remain important for delivering cost-effective and innovative solutions. Equally important is proximity to markets, which enables businesses to respond to, shape, and be informed by local demand and circumstances. Examples include Denmark’s relatively high concentration in wind energy, Greece’s in solar thermal, and Sweden’s in heat pumps, alongside the decline of PV manufacturing in Germany. The indicator value added makes these patterns of economic concentration and their trends particularly clear.

The present analysis highlights that, in terms of economic value generated, downstream activities contribute the most along the value chain segments, while upstream manufacturing activities face intense international competition. The Draghi report and the Clean Industrial Deal emphasise the strategic importance of strengthening technological capabilities and manufacturing within the EU to ensure competitiveness and resilience. This analysis shows that the economic impact across value chain segments is largely driven by downstream activities – such as construction and installation, as well as operation – reflecting the continued expansion of generation capacities. The operation segment is a key driver behind the economic performance of the clean energy technology industry, due to low electricity and heat generation costs combined with high market revenues. This underscores the strong cost-competitiveness of clean energy technologies. The manufacturing segment exhibits divergent trends, facing growing international competition. The production of heat pumps and batteries is experiencing very dynamic growth, suggesting that EU companies keep pace with international competition, and can offer cost-effective technological solutions to meet the European demand generated by the energy transition ambition. The wind energy sector shows positive trends as regards manufacturing in Germany and Denmark; however, there are signs that international competition is increasing. The manufacturing segment in the photovoltaic (PV) sector has lost significant market shares to China.

This report contributes to building a robust evidence base by collecting data on the economic footprints of clean energy technologies, differentiated by value chain segments. Ongoing assessment of the EU's competitiveness in clean energy technologies and the development of corresponding policy measures require a comprehensive and robust data foundation that provides detailed insights, disaggregated by country, technology and value chain segment. As part of this project, a complex evidence-based statistical modelling approach was developed to generate additional data for assessing European competitiveness. The analysis underscored especially the central importance of downstream activities, such as the operation of clean energy technologies.

The main strength of the analysis is that it is based on the most detailed and coherent economic data available at the European level. The Structural Business Statistics and PRODCOM datasets are derived from surveys of European enterprises and reported by EU Member States, providing a valid and empirically robust data foundation. In addition, the use of official statistics, aligned with standardised classification systems, provides a detailed and methodologically consistent basis for generating differentiated insights – both thematic and geographical – across various clean energy technologies.

The main limitation of the analysis is that not all relevant activities related to clean energy technologies can be directly identified due to the varying levels of detail in economic classification systems. Some must be inferred from broader, heterogeneous categories of goods and services, requiring estimation methods that differ in approach and robustness. This limitation is expected to diminish over time, as classification systems continue to evolve, not least to reflect goods and services that increasingly gain greater economic relevance – particularly in the field of clean energy technologies. Three EU Member States, Cyprus, Luxembourg, and Malta, could not be robustly covered by the model and analysis, as data availability was limited.

Future efforts could focus on further developing the model, particularly in estimating heterogeneous activity shares, and incorporating additional quantitative approaches to address limitations of the model. As demonstrated in Chapter 2, the collected data exhibit methodological constraints that need to be addressed in future work. In particular, the calculation of shares for heterogeneous product groups can be continuously improved, including through the use of newly available secondary statistics. Additionally, some technologies – such as hydrogen production via electrolysis or CCUS – could not be captured by the model and were instead addressed through market analysis. As the economic footprint of currently unmodelled clean energy technologies increases, future efforts could aim to incorporate them into the analysis. To enable an evidence-based assessment that also encompasses these areas, a quantitative evaluation of the European start-up landscape could be undertaken in the future. Such data on the start-up landscape could provide further insights into the development and progress of the emerging clean energy technologies. Efforts should continue to align official statistics with policymakers' need for reliable, current data on evolving trends.

Appendix 1: Overview of the implementation process and deliverables

This appendix provides an overview of the implementation process, focusing on changes made in comparison to the processes envisaged in the Tender Specifications.

Project timetable

The implementation of the contract was intended to align with the timeline for preparing the annual Progress Report on Competitiveness of Clean Energy Technologies (henceforth: CPR) and the related reports prepared by the Clean Energy Technology Observatory (CETO) on specific energy technologies (henceforth: CETO reports). The CPR and the CETO reports were typically published in the autumn (October) of the respective years. For each of the two full calendar years covered, the workflow under this contract was tentatively designed to follow this cycle. However, changes to the timing of the second year also resulted in changes to the timeline for this contract.

The timeline for publication of the 2024/2025 CPR changed, resulting in delays to the production of fact sheets and policy briefs (Task 4). The 2023 CPR was published in October of that year, causing only a slight delay in the production of fact sheets and policy briefs. However, no CPR was published in 2024;[112] instead it was published on 26 February 2025.

The actual timetable for Tasks 1 and 2 deviated from the initially foreseen schedule to ensure the use of the latest available data and to provide results in a timely manner. The updated timeline ensured both timely data delivery and improved alignment with the reporting needs of the respective CETO authors.

Contract management

The contract was novated through an amendment, reflecting the transfer of COWI's EU service line to Viegand Maagøe. The proposal was submitted by a consortium consisting of COWI (as lead) and Prognos, with COWI signing the contract on the consortium's behalf. In November 2024, COWI transferred its EU activities to Viegand Maagøe, prompting a request to CINEA to novate the contract, i.e. transfer it to Viegand Maagøe. The contract was subsequently novated through an amendment, with a second amendment extending the duration of the contract until 7 July 2025.

Contract management. The contract was formally managed by the European Climate, Infrastructure and Environment Executive Agency (CINEA) as the Contracting Authority and by Viegand Maagøe representing the Contractor. Coordination and planning also involved the Directorate-General for Energy and the Joint Research Centre as the main anchor points for the CPR and the CETO reports respectively. Within the consortium, Prognos acted as the lead for Tasks 1 and 2.

[112] Instead, the reporting on competitiveness was '*done through the ninth State of the Energy Union Report and the Clean Energy Technology Observatory reports.*' (see: Clean energy competitiveness).

Project organisation and coordination

Regular and ad-hoc meetings facilitated coordination, further supported by informal exchanges of draft documents where relevant. Aside from the coordination tools set out in the Tender Specifications (flash reports, progress reports, status meetings and inception/interim report meetings), coordination was also facilitated by the flexible approach of all involved parties. This included ad-hoc meetings as needed and exchanging and discussing pilot versions of fact sheets and policy briefs. Ad-hoc meetings were typically agreed and organised by the relevant parties, such as by Prognos and CETO[113] in relation to Task 1 issues, with participation in such meetings typically open to all involved parties. This flexible approach played a key role in effective and efficient project implementation.

A shared platform for exchange of documents facilitated overview of the project. At the start of the project, a platform was established for storing and sharing all official and final submissions. Given the long duration of the contract and its numerous deliverables, this allowed for a consistent and transparent overview of project outputs.

Project deliverables

The foreseen deliverables were produced, albeit with modifications. The tables below provide an overview of the relevant changes by deliverable, followed by an overview of planned and actual deliverables. Compared to the Tender Specifications there were two major modifications to the list of deliverables: one in relation to Task 3 (review support) and another in relation to Task 1 (indicator data). These are further elaborated on below.

The review support foreseen under Task 3 was not requested to the extent anticipated. The limited resource budget set aside for Task 3 was therefore used to support other elements of the contract, in particular Task 4,[114] and to produce a new deliverable under the contract. The new deliverable was scoped and agreed on in March 2025 and delivered in April 2025. It comprised three main components: a) mapping of applied dimensions of competitiveness applied in key EU documents, b) mapping of indicators available for assessing the identified dimensions and of the extent to which the relevant indicators are covered in the CETO reports and c) considerations for future approaches, such as for systematically accessing updated indicator values.

To address a request for in-depth discussion of the applied models, including to enhance transparency regarding their workings, specific workshops were organised to support Task 1. Three deep-dive workshops were held in April and May 2024 to align the model methodology, jointly explore identified focus points and investigate any remaining comments. These technical workshops were not specially foreseen in the Tender Specifications but served the important purpose of addressing reservations and questions raised during the first contract progress meeting. The workshops were primarily targeted at technology-focused staff at the Joint Research Centre (JRC)/CETO. The themes for the three workshops were: 1) Overall value chain modelling approach illustrated by the solar value chain, 2) Focus on geothermal, heat pumps, solar thermal and wind energy, and 3) Focus on batteries.

[113] Or by the lead on the contractor's side at the request of the relevant parties.

[114] Resources were used to ensure that the fact sheets and policy briefs complied with EU accessibility requirements. These requirements did not exist at the time of preparing the proposal. Resources were also redirected towards Task 4, where the production of fact sheets and policy briefs was found to require more resources and turnarounds than foreseen.

Table 8 Overview of the foreseen main deliverables and of major agreed modifications, including in relation to the tentative timeline set out in the Tender Specifications

Task	Deliverables produced		Modifications (if any)
Inception report			The final inception report was delivered in M2, one and half months later than stipulated under the Tender Specifications. The kick-off meeting was held just before the Christmas break and it was agreed to organise an inception meeting to discuss the draft inception report, which was then completed on the basis of the outcomes of that meeting.
Progress reports			Two progress reports were delivered. Draft versions were discussed at progress meetings. The reports were consequently revised accordingly. The first progress report was delivered on time. The second report was delayed by two months. The delay was partly caused by changes to the timing of the CPR (see below under Task 4) and by the timing of the rescoping of Task 3 (see below under Task 3).
Final report			This draft final report was delivered with a delay of two months, partly due to the delays described above under 'Progress reports'.
Task 1	**D1**	Evidence-based methodology and data sets	Following a detailed description of the methodological approach and an initial assessment of relevant publicly available data for clean energy technologies, the definitions and scope of the clean energy technologies were aligned with the CETO reports and with JRC, CINEA and DG ENER. In response to the expressed need for greater transparency on the robustness of the estimation of the clean technology activities, the supplied data were supplemented to include greater detail on the estimation procedure, robustness checks and sensitivity. Based on this, three deep-dive workshops were held in April and May 2024 with JRC staff to address questions on the methodological approach, support interpretation of the results, align the model methodology and jointly explore identified focus points. All feedback received on Interim results was incorporated into the modelling approach, which was implemented during the last data update cycle.
	D2	Data management plan	Completed and updated with each data cycle.
Task 2	**D3**	In-depth analysis	Completed and updated with each data cycle. The structure of the latest D3 report was revised for improved alignment with the CETO and CPR reports.
	D4	Power point presentations	PowerPoint presentations were produced to support the methodological deep-dive workshops held with the JRC.
	D5	Workshop for the EC services	Originally tentatively planned for autumn 2023 and autumn 2024, technical workshops were instead organised in spring 2024 as a follow-up to agreements made at the first progress meeting. The purpose of the workshops was to align the model methodology, jointly explore the identified focus points and investigate any remaining comments. A final workshop was held in July 2025 to introduce and discuss the present report to relevant Commission services, CINEA and JRC.
Task 3	**NEW**	Indicators for competitiveness	No specific deliverables were planned for Task 3. The task was originally intended to provide review support. Task 3 resources were allocated to support other tasks, in particular Task 4 (e.g. costs of complying with accessibility requirements, which did not exist at the time of contract signature) and to a deliverable conceptualised jointly by DG ENER, JRC and the contractor in early spring 2025. The draft version of the deliverable was submitted in early May 2025.
Task 4	**D6**	Communication and dissemination plan	The first version was delivered after six months, i.e. with a two-month delay compared to the tentative timetable under the Tender Specifications.
	D7	Policy briefs	First round policy briefs delivered with a slight delay compared to the tentative timetable under the Tender Specifications. Second round delivered in February 2025, reflecting the change in timing of the CPR report.
	D8	Fact sheets	First-round fact sheets delivered with a slight delay compared to the tentative timetable under the Tender Specifications. Process to produce the second round of technology fact sheets commenced in December 2024/January 2025.

Appendix 2: Goods and services covered in the statistical analysis

Table 9 Overview of goods and services considered in the wind energy value chain

NACE Rev.2 Code	NACE Rev.2 Description	Prodcom 2019 Code	Prodcom 2019 Description	Value Chain Segment	Applied Share
2511	Manufacture of metal structures and parts of structures	251122	Towers and lattice masts of iron or steel	Manufacturing	Partly considered Prodcom
2711	Manufacture of electric motors, generators and transformers	271161	Parts suitable for electrical motors and generators	Manufacturing	Partly considered Prodcom
2811	Manufacture of engines and turbines, except aircraft, vehicle and cycle engines	281124	Wind turbines	Manufacturing	Fully considered Prodcom
2812	Manufacture of fluid power equipment	281220	Parts of fluid power equipment	Manufacturing	Partly considered Prodcom
2815	Manufacture of bearings, gears, gearing and driving elements	281524	Gears and gearing; ball or roller screws; gear boxes and other speed changers	Manufacturing	Partly considered Prodcom
3011	Building of ships and floating structures	-	-	Manufacturing	Partly considered Prodcom
3320	Installation of industrial machinery and equipment	33202910	Installation of engines and turbines (excluding aircraft, vehicle and cycle engines)	Construction	Partly considered Prodcom
3320	Installation of industrial machinery and equipment	33202910	Installation of engines and turbines (excluding aircraft, vehicle and cycle engines)	Construction	Partly considered Prodcom
3510	Electric power generation, transmission and distribution	-	-	Operation	Partly considered NACE
4200	Civil engineering	-	-	Construction	Partly considered NACE
5222	Service activities incidental to water transportation	-	-	Construction	Partly considered NACE
7100	Architectural and engineering activities; technical testing and analysis	-	-	Research and project development	Partly considered NACE

7200	Scientific research and development	-	-	Research and project development	Partly considered NACE
7490	Other professional, scientific and technical activities n.e.c.	-	-	Research and project development	Partly considered NACE

Table 10 Overview of goods and services considered in the photovoltaic energy value chain

NACE Rev.2 Code	NACE Rev.2 Description	Prodcom 2019 Code	Prodcom 2019 Description	Value Chain Segment	Applied Share
2511	Manufacture of metal structures and parts of structures	25112360 (code applies for the years 2010-2011)	Weirs, sluices, lock-gates, landing stages, fixed docks and other maritime and waterway structures, of iron or steel, Structures and parts of structures of iron or steel, n.e.s. [...]	Manufacturing	Partly considered Prodcom
2511	Manufacture of metal structures and parts of structures	25112355 (code applies for the years 2012-2023)	Weirs, sluices, lock-gates, landing stages, fixed docks and other maritime and waterway structures, of iron or steel, Structures and parts of structures of iron or steel, n.e.s. [...]	Manufacturing	Partly considered Prodcom
2611	Manufacture of electronic components	26112240	Photosensitive semiconductor devices; solar cells, photo-diodes, photo-transistors, etc.	Manufacturing	Partly considered Prodcom
2611	Manufacture of electronic components	26114070	Parts of diodes, transistors and similar semiconductor devices, photosensitive semiconductor devices and photovoltaic cells, light-emitting diodes and mounted piezo-electric crystals	Manufacturing	Partly considered Prodcom
2711	Manufacture of electric motors, generators and transformers	2711505	Inverters having a power handling capacity ≤ 7,5 kVA	Manufacturing	Partly considered Prodcom
2790	Manufacture of other electrical equipment	2790415	Inverters having a power handling capacity > 7,5 kVA	Manufacturing	Partly considered Prodcom
3510	Electric power generation, transmission and distribution	-	-	Operation	Partly considered NACE

4200	Civil engineering	-	-	Construction	Partly considered NACE
4300	Specialised construction activities	-	-	Construction	Partly considered NACE
7100	Architectural and engineering activities; technical testing and analysis	-	-	Research and project development	Partly considered NACE
7200	Scientific research and development	-	-	Research and project development	Partly considered NACE
7490	Other professional, scientific and technical activities n.e.c.	-	-	Research and project development	Partly considered NACE

Table 11 Overview of goods and services considered in the bioenergy value chain

NACE Rev.2 Code	NACE Rev.2 Description	Prodcom 2019 Code	Prodcom 2019 Description	Value Chain Segment	Applied Share
0100	Crop and animal production, hunting and related service activities	-	-	Resource sourcing	Partly considered NACE
0210	Silviculture and other forestry activities	-	-	Resource sourcing	Partly considered NACE
0220	Logging	-	-	Resource sourcing	Partly considered NACE
1629	Manufacture of other products of wood; manufacture of articles of cork, straw and plaiting materials	16291500	Pellets and briquettes of pressed and agglomerated wood and of wood waste and scrap	Operation	Fully considered Prodcom
2014	Manufacture of other organic basic chemicals	20147200	Wood charcoal whether or not agglomerated (including shell or nut charcoal)	Operation	Fully considered Prodcom
2059	Manufacture of other chemical products n.e.c.	20595800	Biodiesel and mixtures thereof [...]	Operation	Fully considered Prodcom
2059	Manufacture of other chemical products n.e.c.	20595997	Biofuels (diesel substitute)	Operation	Fully considered Prodcom
2059	Manufacture of other chemical products n.e.c.	20595990	Biofuels (diesel substitute), other chemical products, n.e.c.	Operation	Fully considered Prodcom
2420	Manufacture of tubes, pipes, hollow profiles and related fittings, of steel	242011	Line pipe of a kind used for oil or gas pipelines, seamless, of steel	Manufacturing	Partly considered Prodcom
2521	Manufacture of central heating radiators and boilers	25211200	Boilers for central heating other than those of HS 8402	Manufacturing	Partly considered Prodcom
2529	Manufacture of other tanks, reservoirs and containers of metal	252911	Reservoirs, tanks, vats and similar containers (other than for compressed or liquefied gas), of iron, steel or	Manufacturing	Partly considered Prodcom

			aluminium, of a capacity > 300 litres, not fitted with mechanical or thermal equipment)		
2530	Manufacture of steam generators, except central heating hot water boilers	25301150	Vapour generating boilers (including hybrid boilers) (excluding central heating hot water boilers capable of producing low pressure steam, watertube boilers)	Manufacturing	Partly considered Prodcom
2711	Manufacture of electric motors, generators and transformers	27113250	Generating sets (excluding wind-powered and powered by spark-ignition internal combustion piston engine)	Manufacturing	Partly considered Prodcom
2811	Manufacture of engines and turbines, except aircraft, vehicle and cycle engines	28112160	Steam turbines and other vapour turbines	Manufacturing	Partly considered Prodcom
2811	Manufacture of engines and turbines, except aircraft, vehicle and cycle engines	28112300	Gas turbines (excluding turbojets and turboprops)	Manufacturing	Partly considered Prodcom
2821	Manufacture of ovens, furnaces and furnace burners	28211150	Furnace burners for solid fuel or gas (including combination burners)	Manufacturing	Partly considered Prodcom
2825	Manufacture of non-domestic cooling and ventilation equipment	28251410	Machinery and apparatus for filtering or purifying air (excluding intake filters for internal combustion engines)	Manufacturing	Partly considered Prodcom
2825	Manufacture of non-domestic cooling and ventilation equipment	28251410	Machinery and apparatus for filtering or purifying air (excluding intake filters for internal combustion engines)	Manufacturing	Partly considered Prodcom
2829	Manufacture of other general-purpose machinery n.e.c.	28296090	Machinery, plant or laboratory equipment, whether or not electrically heated, for the treatment of materials by a process involving a change of temperature, n.e.c.	Manufacturing	Partly considered Prodcom
2830	Manufacture of agricultural and forestry machinery	2830	Manufacture of agricultural and forestry machinery	Manufacturing	Partly considered NACE
2893	Manufacture of machinery for food, beverage and tobacco processing	289320	Machines for cleaning, sorting or grading seed, grain or dried leguminous vegetables	Manufacturing	Partly considered Prodcom
2899	Manufacture of other special-purpose machinery n.e.c.	28993130	Dryers for wood, paper pulp, paper or paperboard	Manufacturing	Partly considered Prodcom
3510	Electric power generation, transmission and distribution	-	-	Operation	Partly considered NACE
3521	Manufacture of gas	-	-	Operation	Partly considered NACE
3522	Distribution of gaseous fuels through mains	-	-	Operation	Partly considered NACE

3523	Trade of gas through mains	-	-	Operation	Partly considered NACE
3530	Steam and air conditioning supply	-	-	Operation	Partly considered NACE
4200	Civil engineering	-	-	Construction	Partly considered NACE
4300	Specialised construction activities	-	-	Construction	Partly considered NACE
7100	Architectural and engineering activities; technical testing and analysis	-	-	Research and project development	Partly considered NACE
7100	Architectural and engineering activities; technical testing and analysis	-	-	Research and project development	Partly considered NACE
7200	Scientific research and development	-	-	Research and project development	Partly considered NACE
7200	Scientific research and development	-	-	Research and project development	Partly considered NACE
7490	Other professional, scientific and technical activities n.e.c.	-	-	Research and project development	Partly considered NACE
7490	Other professional, scientific and technical activities n.e.c.	-	-	Research and project development	Partly considered NACE

Table 12 Overview of goods and services considered in the hydropower value chain

NACE Rev.2 Code	NACE Rev.2 Description	Prodcom 2019 Code	Prodcom 2019 Description	Value Chain Segment	Applied Share
2711	Manufacture of electric motors, generators and transformers	27113250	Generating sets (excluding wind-powered and powered by spark-ignition internal combustion piston engine)	Manufacturing	Partly considered Prodcom
2811	Manufacture of engines and turbines, except aircraft, vehicle and cycle engines	281122	Hydraulic turbines and water wheels	Manufacturing	Fully considered Prodcom
2811	Manufacture of engines and turbines, except aircraft, vehicle and cycle engines	281132	Parts of hydraulic turbines, water wheels including regulators	Manufacturing	Fully considered Prodcom

2812	Manufacture of fluid power equipment	28121200	Rotating hydraulic and pneumatic motors	Manufacturing	Partly considered Prodcom
2812	Manufacture of fluid power equipment	28122000	Parts of fluid power equipment	Manufacturing	Partly considered Prodcom
2813	Manufacture of other pumps and compressors	28133100	Parts of pumps for liquids and for liquid elevators	Manufacturing	Partly considered Prodcom
3510	Electric power generation, transmission and distribution	-	-	Operation	Partly considered NACE
4200	Civil engineering	-	-	Construction	Partly considered NACE
7100	Architectural and engineering activities; technical testing and analysis	-	-	Research and project development	Partly considered NACE
7200	Scientific research and development	-	-	Research and project development	Partly considered NACE
7490	Other professional, scientific and technical activities n.e.c.	-	-	Research and project development	Partly considered NACE

Table 13 Overview of goods and services considered in the heat pumps value chain

NACE Rev.2 Code	NACE Rev.2 Description	Prodcom 2019 Code	Prodcom 2019 Description	Value Chain Segment	Applied Share
2825	Manufacture of non-domestic cooling and ventilation equipment	28251130	Heat exchange units	Manufacturing	Partly considered Prodcom
2825	Manufacture of non-domestic cooling and ventilation equipment	28251130	Heat exchange units	Manufacturing	Partly considered Prodcom
2825	Manufacture of non-domestic cooling and ventilation equipment	28251380	Heat pumps other than air conditioning machines of HS 8415	Manufacturing	Fully considered Prodcom
2825	Manufacture of non-domestic cooling and ventilation equipment	28251380	Heat pumps other than air conditioning machines of HS 8415	Manufacturing	Fully considered Prodcom
2825	Manufacture of non-domestic cooling and ventilation equipment	28251390	Other refrigerating or freezing equipment	Manufacturing	Partly considered Prodcom
3530	Steam and air conditioning supply	-	-	Operation	Partly considered NACE
4100	Construction of buildings	-	-	Construction	Partly considered NACE
7100	Architectural and engineering activities; technical testing and analysis	-	-	Research and project development	Partly considered NACE
7200	Scientific research and development	-	-	Research and project development	Partly considered NACE
7490	Other professional, scientific and technical activities n.e.c.	-	-	Research and project development	Partly considered NACE

Table 14 Overview of goods and services considered in the batteries value chain

NACE Rev.2 Code	NACE Rev.2 Description	Prodcom 2019 Code	Prodcom 2019 Description	Value Chain Segment	Applied Share
2720	Manufacture of batteries and accumulators	272023	Nickel-cadmium, nickel metal hydride, lithium-ion, lithium polymer, nickel-iron and other electric accumulators	Manufacturing	Partly considered Prodcom
2720	Manufacture of batteries and accumulators	27202410	Parts of electric accumulators. Separators.	Manufacturing	Fully considered Prodcom
2720	Manufacture of batteries and accumulators	27202420	Parts of electric accumulators. Other than separators.	Manufacturing	Fully considered Prodcom
3830	Materials recovery	-	-	Recycling	Partly considered NACE
7100	Architectural and engineering activities; technical testing and analysis	-	-	Research and project development	Partly considered NACE
7200	Scientific research and development	-	-	Research and project development	Partly considered NACE
7490	Other professional, scientific and technical activities n.e.c.	-	-	Research and project development	Partly considered NACE

Table 15 Overview of goods and services considered in the geothermal energy value chain

NACE Rev.2 Code	NACE Rev.2 Description	Prodcom 2019 Code	Prodcom 2019 Description	Value Chain Segment	Applied Share
2711	Manufacture of electric motors, generators and transformers	27113250	Generating sets (excluding wind-powered and powered by spark-ignition internal combustion piston engine)	Manufacturing	Partly considered Prodcom
3510	Electric power generation, transmission and distribution	-	-	Operation	Partly considered NACE
3530	Steam and air conditioning supply	-	-	Operation	Partly considered NACE
4300	Specialised construction activities	-	-	Construction	Partly considered NACE
7100	Architectural and engineering activities; technical testing and analysis	-	-	Research and project development	Partly considered NACE
7200	Scientific research and development	-	-	Research and project development	Partly considered NACE
7490	Other professional, scientific and technical activities n.e.c.	-	-	Research and project development	Partly considered NACE

Table 16 Overview of goods and services considered in the concentrated solar power value chain

NACE Rev.2 Code	NACE Rev.2 Description	Prodcom 2019 Code	Prodcom 2019 Description	Value Chain Segment	Applied Share
2511	Manufacture of metal structures and parts of structures	25112200	Iron or steel towers and lattice masts	Manufacturing	Partly considered Prodcom
2511	Manufacture of metal structures and parts of structures	25112360 (code applies for the years 2010-2011)	Weirs, sluices, lock-gates, landing stages, fixed docks and other maritime and waterway structures, of iron or steel, Structures and parts of structures of iron or steel, n.e.s. [...]	Manufacturing	Partly considered Prodcom
2511	Manufacture of metal structures and parts of structures	25112355 (code applies for the years 2012-2023)	Weirs, sluices, lock-gates, landing stages, fixed docks and other maritime and waterway structures, of iron or steel, Structures and parts of structures of iron or steel, n.e.s. [...]	Manufacturing	Partly considered Prodcom
2530	Manufacture of steam generators, except central heating hot water boilers	25301170	Super-heated water boilers (excluding central heating hot water boilers capable of producing low pressure steam)	Manufacturing	Partly considered Prodcom
2752	Manufacture of non-electric domestic appliances	27521400	Non-electric instantaneous or storage water heaters	Manufacturing	Partly considered Prodcom
2811	Manufacture of engines and turbines, except aircraft, vehicle and cycle engines	28112160	Steam turbines and other vapour turbines	Manufacturing	Partly considered Prodcom
3510	Electric power generation, transmission and distribution	-	-	Operation	Partly considered NACE
3530	Steam and air conditioning supply	-	-	Operation	Partly considered NACE
4200	Civil engineering	-	-	Construction	Partly considered NACE
4300	Specialised construction activities	-	-	Construction	Partly considered NACE
7100	Architectural and engineering activities; technical testing and analysis	-	-	Research and project development	Partly considered NACE

7200	Scientific research and development	-	-	Research and project development	Partly considered NACE
7490	Other professional, scientific and technical activities n.e.c.	-	-	Research and project development	Partly considered NACE

Table 17 Overview of goods and services considered in the solar thermal value chain

NACE Rev.2 Code	NACE Rev.2 Description	Prodcom 2019 Code	Prodcom 2019 Description	Value Chain Segment	Applied Share
2511	Manufacture of metal structures and parts of structures	25112360 (code applies for the years 2010-2011)	Weirs, sluices, lock-gates, landing stages, fixed docks and other maritime and waterway structures, of iron or steel, Structures and parts of structures of iron or steel, n.e.s. [...]	Manufacturing	Partly considered Prodcom
2511	Manufacture of metal structures and parts of structures	25112355 (code applies for the years 2012-2023)	Weirs, sluices, lock-gates, landing stages, fixed docks and other maritime and waterway structures, of iron or steel, Structures and parts of structures of iron or steel, n.e.s. [...]	Manufacturing	Partly considered Prodcom
2530	Manufacture of steam generators, except central heating hot water boilers	25301170	Super-heated water boilers (excluding central heating hot water boilers capable of producing low pressure steam)	Manufacturing	Partly considered Prodcom
2752	Manufacture of non-electric domestic appliances	27521400	Non-electric instantaneous or storage water heaters	Manufacturing	Partly considered Prodcom
2825	Manufacture of non-domestic cooling and ventilation equipment	28251130	Heat exchange units	Manufacturing	Partly considered Prodcom
3530	Steam and air conditioning supply	-	-	Operation	Partly considered NACE
4300	Specialised construction activities	-	-	Construction	Partly considered NACE
7100	Architectural and engineering activities; technical testing and analysis	-	-	Research and project development	Partly considered NACE

7200	Scientific research and development	-	-	Research and project development	Partly considered NACE
7490	Other professional, scientific and technical activities n.e.c.	-	-	Research and project development	Partly considered NACE

Appendix 3: Robustness and sensitivity of the statistical analysis

The following table presents a summary of the robustness and sensitivity checks performed for each of the clean energy technologies of the statistical delineation model.

The number of activities lists the number of economic activities mapped to the economic classification system.

Robustness: For each of the mapped economic activities, the robustness of the estimated economic value of the clean energy technology's economic activities was assessed and categorised as high, medium or low by considering:

- Representativeness of selected code (clarity of matching of economic activity to the economic classification, heterogeneity of code).
- Data quality for estimation (reliability of sources, availability of data per MS, per year, data gaps).
- Assumptions in calculations (directness/complexity of share derivation, strength of assumptions).
- Data quality of SBS indicator data (based on the share of imputed data of used NACE codes).

The Top 3 economic activities of the clean energy technology value chain are listed in terms of the share in the total clean energy technology value chain to express the sensitivity of the overall result of the clean energy technology to these economic activities vis-à-vis how robust the estimate is.

The table shows that most economic activities of the clean energy technology value chains are based on estimation methods of high or medium robustness, especially amongst those economic activities which have a high influence on the overall results.

Table 18 Robustness and Sensitivity of the statistical analysis on clean energy technologies

	Wind	Solar PV	Solar CSP	Solar Thermal	Bioenergy	Hydropower	Geothermal Energy	Heat Pumps	Batteries
Number of activities	14	12	13	10	35	11	7	10	7
No. Robustness high	3	4	3	2	18	5	3	4	5
No. Robustness medium	10	8	10	8	13	6	4	6	2
No. Robustness low	1	0	0	0	4	0	0	0	0
Top 3 activities									
Top 1 as % of Total	77%	48%	62%	60%	52%	96%	35%	65%	85%
Robustness	High	High	High	Medium	High	High	High	Medium	High
Top 2 as % of Total	8%	27%	26%	30%	16%	1%	31%	17%	6%
Robustness	High	Medium	Medium	Medium	High	High	High	High	High
Top 3 as % of Total	4%	12%	5%	7%	8%	1%	25%	9%	3%
Robustness	Medium	Medium	Medium	Medium	High	Medium	Medium	High	Medium
Sum of Top 3 in Total	89%	86%	93%	97%	76%	98%	91%	91%	95%

Appendix 4: Fact sheets and policy briefs

Policy briefs

Policy briefs are concise fact sheets that summarise key policy-relevant points related to the competitiveness of clean energy technologies. Each brief consists of two pages.

Two sets of policy briefs were delivered in the scope of the project:

- One set associated with the publication of the 2023 CPR report
- One set associated with the publication of the 2025 CPR report

For the 2025 CPR report, it was decided to produce two policy briefs. The scope of the two briefs was as follows:

- A horizontal policy brief covering issues that characterise the status of deployment and competitiveness of clean energy technologies
- A technology policy brief presenting key findings for each of the technologies

The policy briefs were therefore aligned with the executive summary of the CPR report, covering, first, horizontal issues and, second, technology-specific issues. The technology brief includes two key bullet points for each technology. The horizontal policy brief features the following headings: the growing role of clean energy in the EU, challenges to EU competitiveness and EU actions to stay competitive in clean energy. Compared to the 2023 policy briefs, the 2025 briefs are richer in content, covering findings and messages in comparable detail and also including figures such as pie charts or highlighted numbers to illustrate relevant key facts. This, together with the change of approach (described here), contributed to a stronger visual impact. The two policy briefs are presented below.

The 2025 policy briefs are available here: 2025 Competitiveness Progress Report: Opportunities to boost EU clean tech

For the 2023 CPR report, the focus of the policy brief was to present key findings on the competitive situation of each technology. It was decided to prepare a policy brief for a selection of technologies. The policy briefs had three headings: headline findings, key competitiveness challenges and key policy recommendations. The section on headline findings included statements on the overall level of implementation/deployment of the technology, the level and nature of competition within the specific industry and, finally, statements on the costs or profitability of the technology. Depending on the technological maturity and the level of deployment, the content varied across the policy briefs. The content under key challenges depended on the maturity of the technology, with further development support or assistance in upscaling of the deployment being key challenges. The recommendations primarily addressed key barriers to the further development and deployment of each technology. A total of 11 policy briefs were produced, covering the following technologies: renewable hydrogen, wind, high voltage direct current systems (HVDC), bioenergy, batteries, carbon capture, utilisation and storage (CCUS), solar thermal, geothermal, heat pumps, ocean and photovoltaics.

The 2023 policy briefs are available here: DG Energy Documents – Library

Technology fact sheets

Technology fact sheets are based on the CETO reports and summarise key points on each of the clean energy technologies, focusing on aspects of their competitive situation. Each fact sheet consists of two pages.

Two sets of technology fact sheets were delivered in the scope of the project:

- One set associated with the CETO 2023 reports
- One set associated with the CETO 2024 reports

The 2025 technology fact sheets are fully based on and linked to the 2024 CETO reports. Compared to the 2023 fact sheets, they are richer in content. Each 2025 fact sheet communicates the essential messages and findings of the corresponding CETO report, with one fact sheet produced for each of the technologies. It was decided to provide more information on each of the fact sheets than in the previous round. Two technologies were used as pilots. Pilot fact sheets were prepared and discussed in depth, with the aim of the final versions serving as structural templates for the subsequent fact sheets. However, several iterations proved necessary, reflecting the need to ensure consistency across fact sheets and account for differences in the technologies that impact the extent to which similar structures can be applied. In addition, expert comments needed to be included to enhance the quality of the fact sheets, and it was necessary to perform alignment and proofreading across the fact sheets. The principal structure applied includes the following elements: a) Introduction (where necessary to contextualise the technology for the reader), b) Capacity data and c) Monetary data where available (such as on exports/imports and turnover). The data available on both those aspects differ, as reflected in the CETO reports. That is also mirrored in the fact sheets. The following fact sheets were produced:

- Advanced biofuels
- Battery technology
- Bioenergy
- Carbon capture, utilisation and storage (CCUS)
- Fuel cells
- Geothermal energy
- Heat pumps
- Water electrolysis and hydrogen
- Hydropower and pumped-storage hydropower
- Novel energy storage
- Ocean energy
- Renewable fuels of non-biological origin (RFNBO)
- Smart grids

- Smart thermal networks
- Solar photovoltaics
- Solar thermal energy
- Wind energy

The 2025 fact sheets are available here: Technology fact sheets – Clean Energy Technology Observatory – European Commission

The 2023 technology fact sheets were simpler in content and structured according to three headings: key technologies, key value chain figures and key facts. Under each of these headings, two to three facts or findings were presented. Under the heading 'key technologies', specific technologies and their level of technology readiness were presented. In the case of technologies with many specific 'variants', each variant was described with respect to its technology readiness level. Under the second heading of 'key value chain figures', data for sector turnover and employment were set out. Finally, under the heading 'key facts', various other data points were presented, reflecting the types of data available and relevant to the specific technology. The technologies covered in the fact 2023 sheets largely resemble those in 2025, with the exception that smart grids and smart thermal networks were not included.

The 2023 technology fact sheets are available here: DG Energy Documents – Library

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