



OECD Science, Technology and Industry Working Papers
2024/11

A comprehensive overview
of the renewable energy
industrial ecosystem

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<https://dx.doi.org/10.1787/94dce592-en>

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A comprehensive overview of the Renewable Energy Industrial Ecosystem

Antoine Dechezleprêtre¹, Hélène Dernis¹, Luis Diaz¹, Guy Lalanne¹, Francesco Losma¹, Sara Romaniega Sancho¹, Lea Samek¹

While renewable energy adoption has accelerated globally, significant challenges remain in meeting ambitious deployment targets. This paper analyses bottlenecks in the renewable energy ecosystem and explores potential policy solutions by examining data on trade, innovation, M&A, jobs, and skills. The analysis reveals three key findings: First, the renewable energy ecosystem spans multiple sectors beyond electricity production, with machinery, computer and electronics and scientific and technical activities playing central roles in innovation activity and job creation. Second, supply chain concentration is increasing for both capital goods and critical raw materials, creating dependencies on key supplier countries. Third, while innovation offers a pathway to address these dependencies through developing leading-edge manufacturing capabilities and material substitutes, patenting activity in renewable technologies is declining. Additionally, the sector faces potential skills shortages in crucial areas like engineering and technical trades. The findings suggest that successful renewable energy deployment requires coordinated policy approaches addressing innovation support, supply chain resilience, and workforce development.

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Keywords: Industrial ecosystems; Renewable energy; Net-zero transition; Industrial policy

JEL Code: L64, L52, O25, O38, Q42

Acknowledgements

The authors thank Anca Dumitrescu Goranov and Roman Arjona (DG GROW) for their support throughout this project and for their insightful feedback. They are grateful to Sara Calligaris, Edoardo Falchi, Antton Haramboure, Andrea Greppi, Daniel Nachtigall and Alzbeta Vitkova for their help with several data sources, and to William Connell Garcia, Maria Garrone, Jacopo Tattini and Jacek Truszczyński for their comments.



**Funded by
the European Union**

Table of contents

Acknowledgements	4
Executive summary	8
1 Introduction	10
Scope of this analysis	11
2 The international supply chain	13
Capital goods used for renewable energy	13
Critical raw materials for renewable energy technologies	17
3 Technological leadership in renewable energy	24
A recent decline in patenting activity for most renewable technologies	25
At the country level, technology leadership and export performance are linked	28
Who innovates in renewable energy?	30
Innovation to develop alternatives to and improve recovery and recycling of critical raw materials	34
M&As have increased in the renewable energy ecosystem and are mainly focused on solar and smart grid	36
4 Skills demand for the development and the deployment of renewable energy	38
Data and methodology	39
The share of online vacancies linked to renewable technologies remains modest	40
Renewable energy jobs span a large number of sectors, reflecting the complexity of the value chain	42
Engineering and managerial professions are the most sought-after in the renewable energy ecosystem	44
Main distinct skill bundles: Business acumen, technical expertise and sales	45
5 Policies for the renewable energy ecosystem	49
Indirect support to renewable energy production has increased in recent years	49
Support to businesses in the renewable energy ecosystem mainly focuses on electricity production	51
Support to renewable energy has also been an important part of COVID recovery packages	53
Countries are increasingly supporting new renewable energy technologies through R&D and demonstration schemes	54

Endnotes	56
References	59
Annex A. Setting the scene: Scoping the renewable energy ecosystem and its value chain	65
Annex B. Technological leadership in renewable energy	74
Annex C. Skills demand for the development and the deployment of renewable energy	82
Annex D. Policies for the renewable energy ecosystem	93

FIGURES

Figure 1.1. Scope of this paper	12
Figure 2.1. Exports of capital goods used in renewable technologies, 2012 and 2021	15
Figure 2.2. Concentration in the global market	16
Figure 2.3. Number of trade dependencies for OECD Member countries, by product	17
Figure 2.4. Export value of raw materials used in solar photovoltaics and wind power	19
Figure 2.5. Export concentration of critical raw materials	19
Figure 2.6. The most concentrated critical raw materials (weighted by their import contribution) for wind power and solar photovoltaics differ across importing economies	20
Figure 2.7. The most concentrated critical raw materials for wind power and solar PV tend to have less substitutes	21
Figure 3.1. Patents in technologies related to renewable energy	25
Figure 3.2. Renewable energy technologies developed by economies, 2007-11 and 2017-21	26
Figure 3.3. Revealed technology advantage (RTA) of economies in renewable energy, 2007-11 and 2017-21	27
Figure 3.4. Technology leadership correlates with a better export performance 10 years later	29
Figure 3.5. Renewable energy patents developed by public research organisations, 2017-21	30
Figure 3.6. Links between renewable energy technologies, public research organisations and science, 2010-21	31
Figure 3.7. Renewable energy technologies developed by industries, 2017-21	32
Figure 3.8. Age of companies developing renewable energy technologies, 2017-21	33
Figure 3.9. Patents in renewable energy technologies owned by young firms	33
Figure 3.10. Concentration of patents in renewable energy fields, 2017-21	34
Figure 3.11. Patents in recycling or substitution of critical raw materials, 2017-21	35
Figure 3.12. Value of deals involving at least one firm from the renewable energy sector, by year and by type of deal partners.	36
Figure 3.13. Distribution of firms by main patent technology, 2017-21	37
Figure 4.1. Technology contributions to renewable energy vacancies	41
Figure 4.2. Sectoral distribution of renewable energy vacancies, 2022	43
Figure 4.3. Top five over-demanded occupations in the renewable energy ecosystem	44
Figure 4.4. Over-demanded skills in renewable energy vacancies	46
Figure 4.5. Skill network, United States	47
Figure 4.6. Skill network, France	48
Figure 5.1. IPAC countries have increased their carbon pricing in the last decade, mainly driven by European countries	50
Figure 5.2. Regulation measures such as bans on the construction of new coal power plants have importantly increased in recent years	50
Figure 5.3. Direct support to businesses linked to renewable energy mainly focuses on energy production	52
Figure 5.4. Support to renewable energy represents the majority of green industrial policies	52
Figure 5.5. Support to renewable energy has also been a crucial part of COVID recovery packages	53

Figure 5.6. Countries are increasing their R&D and demonstration support towards the ecosystem driven by new technologies such as green hydrogen and smart grid	55
Figure 5.7. Public RD&D vs deployment support in renewable energy, 2018 (bn USD)	55
Figure A A.1. Revealed comparative advantage for wind power and solar PV associated goods.	66
Figure A A.2. Revealed comparative advantage for solar thermal and hydropower associated goods.	66
Figure A A.3. Number of trade dependencies across countries and goods (2012-2014)	67
Figure A A.4. Number of trade dependencies across countries and goods (2019-2021)	67
Figure A A.5. Extra-EU exports for photovoltaic semiconductor devices, photovoltaic cells, and LEDs	68
Figure A A.6. Bilateral trade dependencies across countries	71
Figure A B.1. Revealed technology advantage and relative comparative advantage, by technology	76
Figure A B.2. Age of companies developing renewable energy technologies, 2017-21	76
Figure A B.3. Specialisation in recycling or substitute of critical raw materials, 2017-21	77
Figure A B.4. Distribution of target firms by main patent technology and by acquiring economy, 2017-2021	77
Figure A B.5. Share of economies in renewable energy technologies, 2007-11 and 2017-21	78
Figure A C.1. Comparison of target texts and lemmatisation approaches	84
Figure A C.2. Sectoral distribution of renewable energy vacancies in European countries, 2022	87
Figure A C.3. Top ten skills by technology group	89
Figure A C.4. Correlation of top 20 skills and their pairs in renewable energy vacancies in European countries, 2022	90
Figure A D.1. Support mainly channels through grants	94

TABLES

Table A A.1. List of goods used for the production of the different renewable technologies.	65
Table A A.2. Export value of raw materials used in solar photovoltaics and wind power	69
Table A A.3. Critical raw materials for renewable energy technologies	71
Table A B.1. Search strategies for patents in technologies related to renewable energy	75
Table A B.2. Search strategies for patents for recycling or substitution of critical raw materials: semiconductors and rare earths	80
Table A B.3. Search strategies for patents for recycling or substitution of critical raw materials: metals, noble materials, batteries	81
Table A C.1. English keyword list and associated technology group	82

Executive summary

The net-zero transition relies to a large extent on the large-scale deployment of reliable and affordable renewable electricity, fuels, and heat. The pace of adoption of renewable energy has dramatically accelerated globally, but faster change is now needed. For instance, the share of renewable energy in total energy consumption reached 23% in 2022 in the European Union but needs to reach a minimum of 42.5% by 2030 according to the revised Renewable Energy Directive.

The deployment of renewable energy faces many challenges beyond the high cost of capital and the length of permitting procedures, flagged as important hindrances in several countries. Renewable energy production relies on a long and complex value chain. Key capital goods (e.g. hydro turbines, solar panels, electrolyzers but also batteries) also rely on geographically concentrated critical raw materials. Additionally, several steps of this supply chain depend on specific skills that might be in short supply and on technologies that are still being developed or improved. Alleviating these bottlenecks is key, not only to enable the deployment of renewable energy, but also to ensure that its cost keeps decreasing, thereby limiting as much as possible the cost of the clean energy transition.

This paper characterises and delineates the renewable energy ecosystem using data on trade, innovation, mergers and acquisitions, jobs and skills, and sheds light on the aforementioned bottlenecks and potential policy solutions. The main findings of the paper are as follows.

First, the renewable energy industrial ecosystem spans a wide variety of sectors beyond renewable electricity production, reflecting the variety of renewable energy value chains and the complexity of the underlying technologies. Within manufacturing, several sectors play an important role, including chemicals, basic metals, machinery, computer and electronics, and electrical equipment. Most patents protecting renewable technologies are developed by the manufacturing sector. Manufacturing is also the sector where the most renewable energy online vacancies are. Additionally, the strong role of R&D, innovation and engineering in renewable energy means the professional and scientific activities sectors also represent a significant share of renewable energy patents and job demand.

Second, several segments of the renewable energy value chain are increasingly concentrated. For capital goods relevant for renewable energy production, as well as for magnets, the market is increasingly concentrated in a few supplying countries, with a Herfindahl-Hirschman (HHI) index above 0.25. This has led to a growing number of dependencies of OECD Member countries vis-à-vis partner economies, especially the People's Republic of China (hereafter, 'China'). Concentration of some critical raw materials necessary to produce those goods (semiconductors, rare earths and metals) is also very high, including for niobium, chromium, boron and rare earths. This may affect the ability of some countries to sustain their leadership position in the medium run. For instance, Japan's production of wind turbines relies on imports of rare earths from Vietnam. The most concentrated critical raw materials for wind turbines and solar panels also tend to be the least substitutable. This is the case of rare earths, boron and niobium for wind, and boron and nickel for solar.

Third, innovation is a key lever to address these dependencies. OECD Member countries can use innovation to develop leading-edge manufacturing capacities to produce renewable energy goods,

reducing dependencies vis-à-vis partner economies. Innovation – for example in automated production processes – can also help limiting the cost of reshoring production units currently located in low-wage economies. OECD Members still have a strong position in the innovation landscape for most renewable energy technologies, and patent data shows that countries that were most innovative 10 years ago have since enjoyed solid positions in export markets, highlighting the crucial role of innovation for competitiveness. Renewable energy technologies are still subject to R&D-led technological progress: even for solar technologies, which are sometimes thought of as mature, innovation activity is still significant, including in OECD Members who represent over two-thirds of global patenting activity, notably within public research organisations and young start-ups, where new types of semiconductor materials are being experimented with. Companies developing new solar technologies are also over-represented as targets of merger and acquisition operations.

Innovation may also play a role in reducing dependencies thanks to the development of alternative materials or recycling, in solar photovoltaics (PV) or in other technologies. Efforts to develop substitutes to critical raw materials identified in the patent data collected for this analysis mainly focus on silicon, a key input for solar cells. Nonetheless, more efforts are needed to develop substitutes for materials used in wind turbines, such as boron and rare earths, given their low substitutability and high export concentration. Regarding recycling, recent efforts have focused on batteries, silicon and nickel, but recycling processes for metals and rare earths are also accelerating.

Yet, this paper documents a decreasing trend in patenting in most renewable energy technologies, which may be driven by several factors. The contribution of young firms to innovation has decreased – potentially as a symptom of increased mergers and acquisitions in the sector, and likely difficulties in accessing the relevant skills. Public support has focused on deployment and production of energy, rather than on public and private R&D, and on the energy sector rather than manufacturing and professional services, which contribute significantly to innovation in renewables.

Finally, some of the most sought-after skills and occupations for renewable energy jobs are already in high demand in the economy. Without significant investment in training (both initial and lifelong), skills shortages might appear and eventually jeopardise the ability of OECD Member countries to invent, manufacture and deploy renewable energy technologies. Business and administration professionals and science and engineering professionals are the most sought-after occupations in the renewable energy ecosystem, with respectively around 30% and 25% of job ads, followed by administrative and commercial managers and electrical trade workers. While there is no shortage of business administration degrees in universities, science and engineering-related skills are in short supply. Socio-emotional skills, computer literacy, business acumen, sales and technical expertise form essential components of the human capital necessary to work in this ecosystem. In European countries, foreign language proficiency also matters. Policies to enhance the supply of these skills should thus constitute a key component of renewable energy deployment policies.

1 Introduction

The share of renewable energy in total energy use reached 21.8% in 2021 in the European Union (Eurostat, 2023^[1]) and, although lower, has more than doubled over the last decade in Korea (3.7%), Japan (8.8%) and the United Kingdom (12.5%), with the world share being 12.5% (International Energy Agency (IEA), 2024^[2]). According to the recent renewable energy report of the IEA (2024^[3]), global additions of renewable capacity in 2023 have been the fastest in the last two decades (increasing by almost 50% to 510 gigawatts (GW) in 2023), driven by the deployment of solar photovoltaics (PV) in China. This fast global deployment rate will continue over the next five years, induced by supportive policies worldwide, and with solar PV and wind power accounting for 95% of this growth. China is expected to account for almost 60% of new renewable capacity additions.

While deployment of renewable energy in Europe and North America have set records in recent years¹, continued deployment at fast pace still faces challenges such as i) delayed policy response to the new macroeconomic environment characterised by higher interest rates; ii) insufficient investment in grid infrastructure necessary for renewables expansion; iii) cumbersome administrative barriers and permitting procedures and iv) supply chain disruptions (IEA, 2024^[3]).

The renewable energy expansion also requires significant growth of enabling technologies such as smart grid, long-duration energy storage (LDES) and green hydrogen (IRENA, 2023^[4]); whose investment levels have been lagging behind (IEA, 2024^[3]). In addition, the necessary deployment of renewable energy technologies requires substantial amounts of mineral resources, which face concerns regarding their future availability due to geopolitical and geological factors (Pommeret, Ricci and Schubert, 2022^[5]).

The renewable energy ecosystem has considerably increased its economic weight recently. For example, in the European Union, its value added and employment grew 13% and 12%, respectively, from 2020 to 2021, outperforming the overall economy (European Commission, 2023^[6]). However, most of the renewable energy technologies display a trade deficit in 2022, in particular solar PVs (EUR 22 billion), with China being the main exporter. In addition, the manufacturing segment of the ecosystem has faced recent supply chain disruptions and employment shortages in Europe, creating concerns among policy makers given its role in providing the necessary components for deployment while safeguarding strategic autonomy.

In this context, resilient supply chains and competitive domestic industries are required to ensure continued deployment. Several countries, some of which have been supporting demand and production of renewable energy for a long time, have recently launched more comprehensive industrial strategies to develop local manufacturing capacities, secure the supply of raw materials and improve the resilience of supply chains. For instance, the EU launched the Industrial Green Deal Plan made up of three different branches : the Net-Zero Industry Act (NZIA) intended to promote investments for development and manufacturing of net-zero technologies² (see Box A D.1 in the Appendix); the EU Critical Raw Materials Act aimed at ensuring a secure supply of critical raw materials for the industrial base of renewable energies and other key sectors³ (European Commission, 2023^[7]) (see Box.2.1); and the revised EU Electricity Market Design oriented to make electricity bills less dependent on fossil fuel prices and to boost investment in renewables through stable long-term contracts⁴ (European Commission, 2023^[8]).

Relying on a variety of sources (on trade, innovation, mergers and acquisitions, jobs and skills, and policies), this paper both contributes to delineating the ecosystem and shedding light on the challenges linked to the aforementioned bottlenecks, as well as on potential policy solutions.

The renewable energy ecosystem covers not only the production of energy out of renewable sources, but also the production of complex and highly technological goods that allow this transformation, as well as the labour-intensive deployment of these technologies. Building on several data sources such as the UN Comtrade database, the US geological survey, patent data, mergers and acquisitions (M&A) transactions and Lightcast data on skills, this paper identifies the boundaries of the industrial ecosystem surrounding renewable energies, including related innovations and underlying skills. It then maps the existing policies supporting the ecosystem and provides recommendations to help policymakers better articulate renewable energy strategies.

Several studies jointly analyse the dynamics of the different actors of the renewable energy ecosystem and their policy consequences. For instance, the EU Clean Energy Technology Observatory (2023^[6]) provided an integrated analysis of clean energy technologies in the EU by considering the innovation, value chain and skills dimensions; the study concluded that the EU renewable energy ecosystem has increased its economic weight, employment and patenting activity but has developed a trade deficit in most technologies while facing skill shortages. Another EU report, the Climate Neutral Industry Competitiveness Scoreboard (2022^[9]), focuses on the manufacturing segment of clean energy technologies and shows more detailed innovation trends together with information about its overall competitiveness. Taking a more global perspective, recent flagship reports of IRENA (2023^[4]) and the IEA (IEA, 2024^[3]), also show the recent deployment trends in the ecosystem, along with some information about the manufacturing segment.

This paper differs from previous studies in the use of the industrial ecosystem concept and the mobilisation of a wider range of data sources, allowing a more exhaustive mapping of the ecosystem and the identification of new results, trends and policy recommendations.

The remainder of the introduction focuses on defining the scope of technologies and economic activities considered in this paper. Section 2 then identifies the main capital goods used for renewable energy technologies along with the corresponding critical raw materials used in their production and analyses the trade patterns and dependencies for those goods. Section 3 focuses on the development of the technologies underpinning these capital goods, while Section 4 explores the skills demanded by the ecosystem. Section 5 provides a landscaping of existing policies supporting the ecosystem (market-based measures, direct support to businesses, R&D support and COVID-19 recovery packages) and identifies potential gaps.

Scope of this analysis

Following the definition of the European Commission (2021^[10]), the 'Renewable energy' ecosystem encompasses the following economic activities (Figure 1.1):

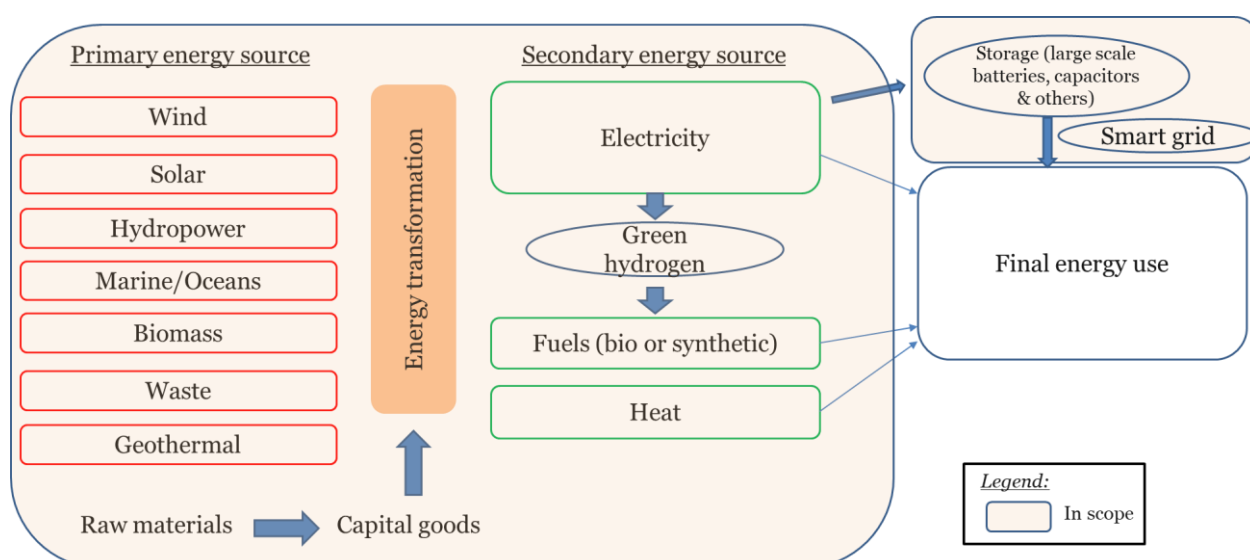
- The transformation of primary renewable energy sources (IEA, 2022^[11]) into a secondary energy source such as electricity, fuels or heat.
- The operation of electrolyzers to produce hydrogen out of water and renewable electricity (green hydrogen).
- LDES and adaptation of electricity grids to the specificities of renewable electricity, notably due to its intermittency.

- The production of capital goods and specific intermediary products that are required for these activities (e.g. hydro and wind turbines, solar panels, permanent magnets, large-scale batteries and capacitors, electrolyzers).
- The extraction and refining of raw materials required to produce the capital goods listed above.

Final energy use is not considered in the scope of the ecosystem and is not discussed in this paper. For instance, activities related to energy efficiency, carbon capture or new industrial equipment (e.g. hydrogen boilers) are not covered in this paper, but will be included in the forthcoming analysis on the ‘Energy-Intensive Industries’ ecosystem.

Due to data limitations, the sections below will not always be able to cover all the relevant activities and technologies. In practice, however, wind, solar and hydro powers represent more than 97% of the renewable electricity installed capacity (IEA, 2022^[11]). Furthermore, as outlined by the IEA (IEA, 2024^[3]), in the next five years renewable power capacity additions will be driven by wind and solar PV technologies, which together will account for 96% of the new capacity additions.

Figure 1.1. Scope of this paper



Source: Authors.

The critical raw materials identified in this study are grouped in three main categories: **semiconductors**, **rare earths and metals**. These were considered as critical based on the categorisation of the European Commission (2023^[12]), Kowalski and Legendre (2023^[13]) and the IEA (2021^[14]).

2 The international supply chain

This section describes the global value chain of goods required to produce renewable energy. After focusing on the main capital goods (e.g. wind and hydro turbines, solar PVs) and some of their parts (notably magnets), this section also describes international trade in the critical raw materials that are needed to produce those goods and, ultimately, renewable energy.

It shows that China is the first exporter of goods used to produce renewable energy, but several EU countries exhibit a comparative advantage in the production of wind energy and hydro power capital goods. Furthermore, concentration has risen significantly for the exports of these goods over the last decade, leading to increases in bilateral dependencies, in particular with respect to China.

Goods used to produce renewable energy depends on several critical raw materials: semiconductor materials, rare earths and metals. In terms of value, the more deployed renewable energies - solar PV and wind energy - rely mostly on metals that, to some extent, have potential substitutes and are not concentrated. Nevertheless, the supply of boron, chromium, manganese, nickel and niobium are highly concentrated and cannot be easily substituted for the production of goods used for wind power and solar PVs.

Capital goods used for renewable energy

This subsection focuses on trade in capital goods that are used for energy transformation. It first lists the relevant goods that can be identified in trade statistics. For each of these goods, the main exporting countries, concentration of supply and bilateral trade dependencies are then described.

Identifying the main goods required for the production of renewable energy.

A number of capital goods necessary to produce renewable energy can be identified in the Harmonised System 6-digit classification (Capital goods used for renewable energy

Table A A.1), which is the most granular level for which information on trade is available at the global level⁵. It covers the main capital goods used to produce solar, wind and hydro energy, as well as some of the parts (including magnets). Magnets, although not used only in renewable energy production, are also included given their importance in wind turbines, and their reliance on critical raw materials, in particular rare earths (see the next subsection).

According to the European Commission (2021^[15]), wind, solar PV or hydropower are among the 18 highly strategic supply chains across the EU energy sector. Additionally, based on the high-level assessment of vulnerabilities, wind and solar PV are among the nine supply chains with important vulnerabilities. Whereas for wind the vulnerabilities are riskier in the raw materials stage of the supply chain, for solar PV vulnerabilities are critical both in the raw materials and in the manufacturing and assembly stages of the supply chain. Permanent magnets and PV cells and modules were identified as vulnerable elements for the EU.

For some technologies such as biomass, waste or green hydrogen, the HS6 taxonomy is not granular enough to identify the relevant goods. For instance, electrolyzers, which are used to produce green

hydrogen out of renewable electricity and water, are included in the code '854330 - Machines and apparatus for electroplating, electrolysis or electrophoresis', along with other types of machines that are used e.g. for plating, and are therefore not linked to renewable energy.

China is the first exporter of goods used for the production of renewable energy

This subsection describes the exports and comparative advantage for the goods listed in Capital goods used for renewable energy

Table A A.1. While exports (Figure 2.1) are the most straightforward way to describe countries' position, they also reflect to a large extent their size and overall competitiveness. To account for these factors that are not specific to renewable energy goods, the current analysis is supplemented by a description of the Revealed Comparative Advantage (RCA, see Figure A A.1 and Figure A A.2). The RCA compares a country's share of exports in a particular segment to the share of global exports in this segment in global exports in all goods. Therefore, the metric is useful for assessing and understanding a country's competitive position in each renewable technology within the global market. The expression of the RCA is as follows:

$$RCA_{Ai} = \frac{\frac{X_{Ai}}{\sum_{j \in P} X_{Aj}}}{\frac{X_{wi}}{\sum_{j \in P} X_{wj}}} \quad \text{Equation 1}$$

Where X_{Ai} represents the exports of country A in segment i , $\sum_{j \in P} X_{Aj}$ represents the total exports of country A⁶. X_{wi} is the worlds' exports of segment i , $\sum_{j \in P} X_{wj}$ accounts for the world's total exports of all goods. Therefore, a value of the RCA above 1 would indicate comparative advantage.

Exports of photosensitive semiconductor devices have increased by 33% from 2012 to 2021 and the market is largely dominated by Asian producers. China maintained its dominant position as the primary exporter, contributing to 44% of total exports in 2021, see Figure 2.1. Malaysia and China are the countries with the highest RCA scores, followed by Thailand, Japan and Cambodia. For Malaysia, China and Japan, the RCA indicator has remained broadly stable since 2012 but for Thailand and Cambodia it has increased significantly.

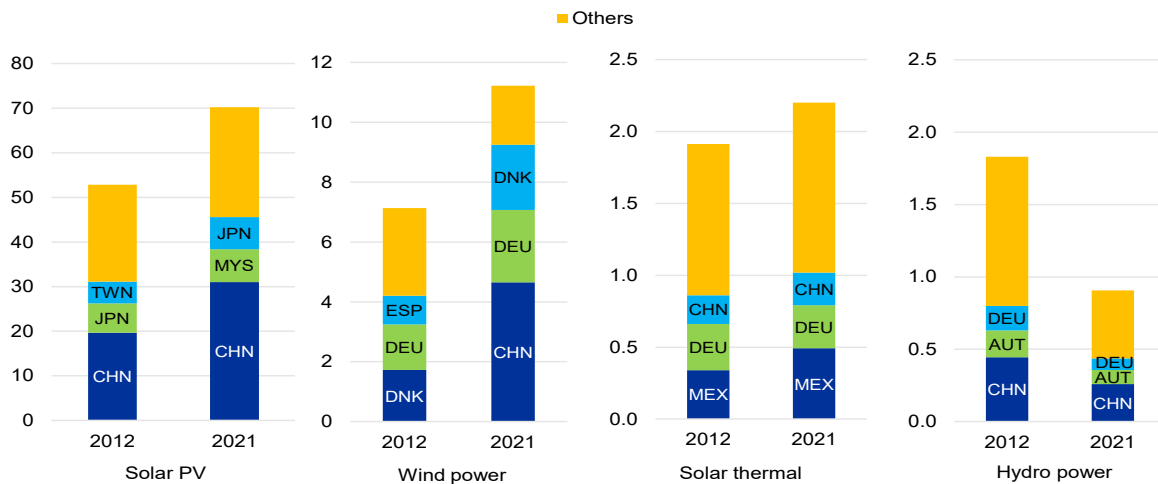
Exports of wind-associated goods have increased by 57% from 2012 to 2021. In 2012, Denmark held the position as the largest exporter, followed by Germany and Spain. However, over the years, China's role has grown significantly, now holding the primary position in total export value, with a significant difference over Denmark, Germany and Spain. Exports of wind-related goods are particularly concentrated: in 2021, the top 3 exporters accounted for 82% of total exports. This high concentration can pose challenges for the development of new capacity additions if there are disruptions in the supply of capital goods. Outside China, Europe and North America have recently experienced challenges to increase wind capacity that were partly due to supply bottlenecks (other factors include increases in costs and long permitting timelines) (IEA, 2024^[3]). For wind power associated goods, Denmark stands out with an RCA score of 40 in 2021⁷. Nonetheless, the RCA score has decreased by approximately ten points compared to its value in 2012. The RCA has also decreased in Spain (by six points) and has remained broadly stable in Germany and India. The specialisation has increased markedly in China, whose market share has risen from 13.4% in 2012 to 41.5% in 2021.

From 2012 to 2021, the contribution of the three main exporters to the total exports of solar thermal associated goods remained broadly stable. Exports of non-electric instantaneous/storage water heaters, increased by 15% from 2012 to 2021, which is much lower than the growth rate of solar PV and wind power goods, which increased by 33% and 57%, respectively. With a market share of 22%, Mexico⁸ led global exports in 2021, surpassing Germany and China which had market shares of 13% and 10%, respectively.

In 2021, Greece and Mexico exhibited the highest specialisation in exports of solar thermal goods. Greece's⁹ comparative advantage has increased since 2012, while Mexico's has remained stable.

Unlike the rest of renewable technologies, exports of hydro power associated goods decreased from 2012 to 2021. China is currently the largest exporter, followed by Austria and Germany. Over the past two decades, renewable energy policies have focused on advancing solar photovoltaic and wind power technologies, relegating hydropower to a secondary position (IEA, 2023^[16]). Hydropower projects face prolonged development timelines and significant investment requirements, making this technology a more uncertain and long-term alternative. Additionally, the impact of climate change on water availability has jeopardised the generation of electricity from hydropower sources (IEA, 2024^[3]). For hydropower technology, several central European countries present a notable specialisation. Austria, with a 10.8% share over global exports in 2021, stood out as the country with the highest comparative advantage, followed by Croatia and Slovenia. However, from 2021 to 2012 the RCA indicator has decreased by 15 points for Slovenia.

Figure 2.1. Exports of capital goods used in renewable technologies, 2012 and 2021
(Current USD, billions)



Source: Own calculations based on UN Comtrade database.

Notes: The economies selected are the three largest exporters.

Concentration and bilateral trade dependencies are rising

The existence of few countries supplying certain goods can induce trade dependencies that may ultimately result in supply bottlenecks, shortages, and higher prices.

The Herfindahl-Hirschman (HHI) Index, which is calculated as the sum of the squared market shares of each country for a certain good, is used to measure the level of concentration in each market. To smooth out annual variations, a three-year average of trade flows is used throughout this subsection. The index would equal one in the case of a monopoly and converge to zero with a large number of atomistic suppliers. Thus, the closer to zero, the lower the concentration.

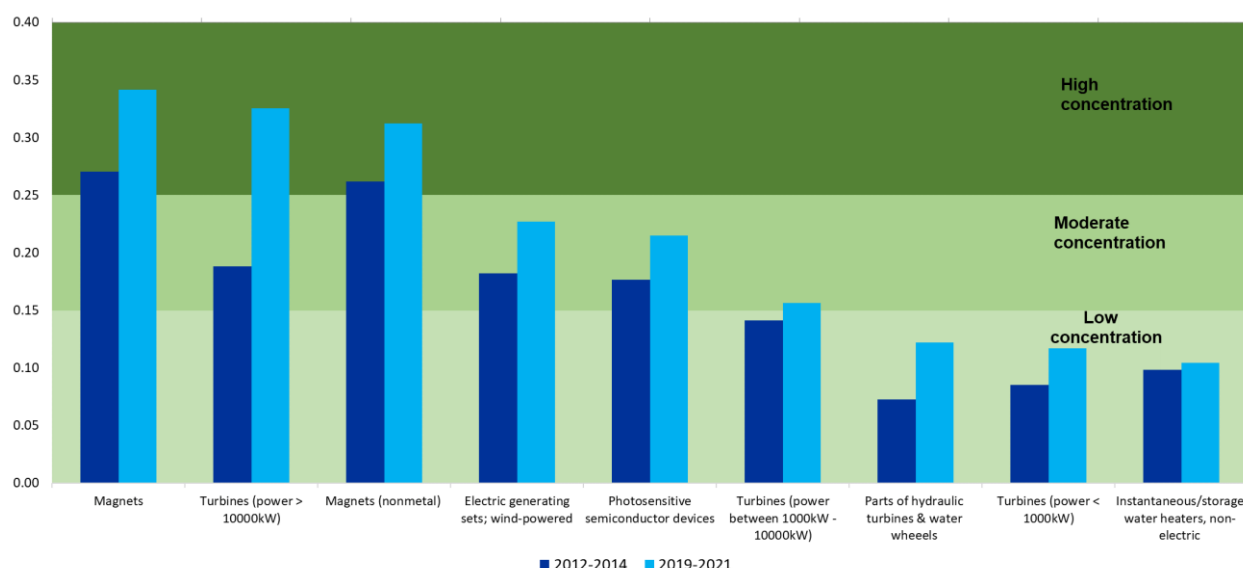
The interpretation of the index may vary depending on the context. Vicard and Wibaux, 2023^[4] and Bonnet and Ciani, 2023^[5] deem a product to be concentrated when the index is above 0.4. Following the US Department of Justice, 2010^[6] and Kowalski and Legendre, 2023^[6], this paper considers that markets with a HHI between 0.15 and 0.25 are moderately concentrated, while markets with HHI greater than 0.25 are highly concentrated.

When examining the global market and referring to the items listed in Capital goods used for renewable energy

Table A A.1, in the latest period the index surpasses the 0.25 threshold for three goods, and the 0.15 threshold for six goods. Among these, the concentration is of the highest for magnets of metal but is also high for non-metallic magnets. The concentration is also very high in the market of high-power hydro turbines. For these three goods, China's exports account for more than 50% of global exports. This contrasts with the market for turbines of lower power, where the three largest exporters together account for 52% of the global exports, with the United States, Germany, and China contributing with 25%, 14% and 13%, respectively.

Moreover, the concentration has increased for all the goods between 2012-2014 and 2019-2021. The largest increase is for high-power hydro turbines and have been driven by China and France, whose market share increased from 39% to 53% and from 1% to 15%, respectively. For metallic magnets, the increase has been mainly driven by China, whose share has increased from 47% to 56% over this period.

Figure 2.2. Concentration in the global market
(Herfindahl-Hirschman Index)



Source: Own calculations based on UN Comtrade database.

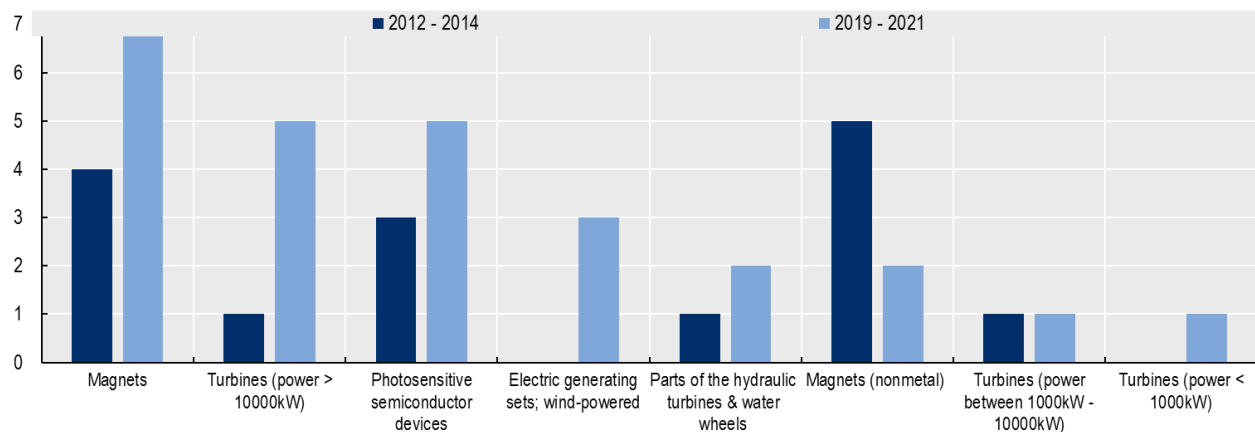
To identify dependencies, the HHI Index can also be computed for each importer country and each commodity. This analysis allows determining whether a country's imports of a specific product are concentrated in a limited number of countries. The subsequent analysis is restricted to the imports of OECD Member countries.

Additional criteria are used to determine bilateral trade dependencies of a country for a specific product, following the methodology developed by Kowalski and Legendre, 2023^[6]. Three conditions need to be met to consider that country *i* is dependent for its supply of good *k*. First, gross imports of good *k* by country *i* need to be overall highly concentrated ($HHI > 0.4^{10}$). Second, the largest non-OECD partner needs to account for a high share ($> 10\%$) of country *i*'s imports of good *k*. Finally, other OECD Member countries' import share for good *k* in country *i* needs to be smaller than 20%. Additionally, to avoid deeming as dependent a country with a high domestic production, two additional conditions were included. The ratio

of exports to imports of the good k in country i must be lower than the 90th percentile of the distribution and the imports from country i of good k need to amount to 1 USD million or more.

Following this approach, in the latest period (2019-2021), 26 dependencies are identified, among which 23 correspond to trade flows with China. Australia, with four dependencies, is the economy with the highest number of dependencies (see Figure A A.6). Compared to the earlier period (2012-2014), trade dependencies have increased by 73% while the share of trade dependencies to China over total dependencies has risen by 15 percentage points, from 73% to 88%. Across goods, dependencies are most prominent in the imports of metallic magnets and of turbines of a power exceeding 10 000 kW, see Figure 2.3.

Figure 2.3. Number of trade dependencies for OECD Member countries, by product



Source: Own calculations based on UN Comtrade database.

Critical raw materials for renewable energy technologies

The capital goods necessary to produce renewable energy are manufactured using a set of raw materials. The supply chain for some of these raw materials has recently been disrupted by events such as the COVID-19 crisis and the Russian Federation's (hereafter, 'Russia') war of aggression against Ukraine, while is further threatened by the increase in geopolitical tensions, causing concern among policymakers.

Policies aiming at ensuring healthy supply chains in the renewable energy ecosystem need to consider those critical raw materials, the magnitude of the dependencies and their origin. This section has two goals: to identify the critical raw materials used in the renewable energy ecosystem and to characterise the dependencies using trade and production data.

Renewable energy technologies depend on semiconductor materials, rare earths and metals

The critical raw materials identified in this study are grouped into three main categories: **semiconductors**, **rare earths and metals**. These were considered as critical based on the categorisation of the European Commission (2023^[12]), Kowalski and Legendre (2023^[13]) and the IEA (2021^[14]), which define criticality based on the economic importance of the raw material for the manufacturing of renewable technologies and its supply risk.^{11,12}

Semiconductor materials are key inputs for solar panels. **Silicon, gallium, indium, germanium and boron** are considered as critical. These raw materials have low substitutability, while their production is

more concentrated than their exports. **Rare earths** are **neodymium, dysprosium, praseodymium and terbium**. These materials are primarily used to produce permanent magnets, such as the ones employed in wind turbines. Like semiconductors, these minerals have low substitutability and production is more concentrated than exports. **Metals** are used for alloys with special characteristics, including heat and corrosion resistance, as well as for frames, cables, and wires. These are **aluminium, chromium, copper, nickel, niobium and zinc**. Compared to semiconductors and rare earths, these materials are used in a wider spectrum of renewable energy technologies such as solar PV, concentrated solar power (CSP), wind, geothermal, biomass and hydro energy. Metals are more substitutable than semiconductors and rare earths, and their production is less concentrated.

The list of critical raw materials for the renewable energy technologies considered in this study along with their concentration in terms of production and exports, their substitution index, as defined by the European Commission (2023^[12]), and their potential substitutes are listed in Table A A.3. Production and trade data are consistent and correspond to the same level of aggregation and processing of the good, which is defined by the US geological survey, unless otherwise indicated. Depending on the raw material and based on availability, production data may cover three different scopes: 'primary', 'processed' and 'primary and processed'.

The critical materials in **the semiconductor category** are **silicon, gallium, indium, germanium and boron**¹³; the first four are used as semiconductors in solar PV technologies, while boron is used as dopant for solar cells and in the manufacturing of magnets used in wind turbines. These minerals have low substitutability (average substitution index of 0.05), while their production is more concentrated than their exports. China is the main producer of almost all of them, except boron, which is mainly produced by Türkiye. For silicon, indium and germanium (semiconductor materials with the same level of aggregation for available production and export data), China represents on average 65% of production but only 29% of exports, indicating that most of its supply of semiconductors might be used by its domestic industry of solar cells (but also of chips). Indeed, China is a major exporter of solar cells, as shown in Figure 2.1.

China announced export restrictions on gallium and germanium starting from August 1st, 2023 based on national security considerations, and according to the press, in response to recent export restrictions on chips and chip-making equipment implemented by some countries like the United States¹⁴ and the Netherlands¹⁵. After the enactment of the policy, exports of gallium and germanium were zero in August and September¹⁶. Since those minerals are available as by products in bauxite and zinc ores (US Geological Survey, 2023^[17]), it is likely that countries with high reserves of them would start refining gallium and germanium as a response to the export controls of China.

Rare earths that are critical for the renewable energy ecosystem include **neodymium, dysprosium, praseodymium and terbium**. These materials are primarily used to produce permanent magnets, such as the ones employed in wind turbines. Neodymium is the base of neodymium permanent magnets while dysprosium, terbium and praseodymium are used to reduce demagnetisation¹⁷. Like semiconductors, these minerals have low substitutability (average substitution index of 0.06) and production is more concentrated than exports. The top producer is China, which represents 70% of global production but only 27% of global exports since it mostly supplies rare earths for its domestic industry of permanent magnets, being also an important exporter of them (see Figure 2.1). China recently announced export restrictions on rare earths processing technologies on December 2023, creating additional difficulties for the national efforts of OECD Member countries in developing national processing capacities.¹⁸

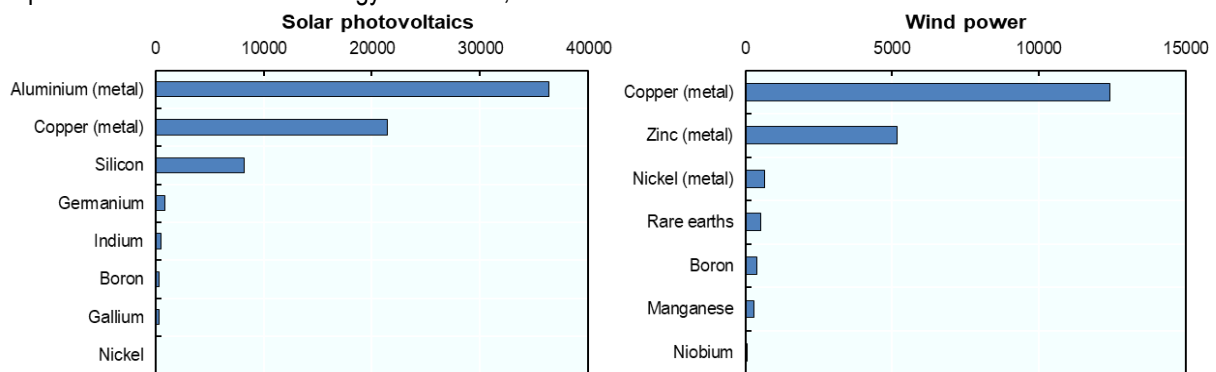
Critical raw materials in the metal category serve as materials for alloys with special characteristics, including heat and corrosion resistance, as well as for frames, cables, and wires. These are **aluminium, chromium, copper, nickel, niobium and zinc**. Compared to semiconductors and rare earths, these materials are used in a wider spectrum of renewable energy technologies such as solar PV, solar CSP, wind, geothermal, biomass and hydro energy¹⁹. Metals are more substitutable than semiconductors and rare earths, having an average substitution index of 0.17 (vs 0.04 of semiconductors and 0.06 of rare

earths); and their production is less concentrated (top producer accounts for 49% of global production on average vs ~70% in semiconductors and rare earths).

In terms of export value embodied in renewable technology, solar cells and wind turbines rely mostly on metals²⁰. Total exports of aluminium and copper used in solar PV components are USD 36.3 billion and USD 21.4 billion, respectively. Much behind are the semiconductor materials such as silicon, germanium and indium, whose exports used in solar PV components are USD 8.2 billion, USD 0.8 billion and USD 0.5 billion, respectively. With respect to wind power, total exports of copper, zinc and nickel represent USD 12.4 billion, USD 5.1 billion and USD 6.7 billion, respectively; above the export value of rare earths associated with wind power (USD 0.5 billion).

Figure 2.4. Export value of raw materials used in solar photovoltaics and wind power

Export value used in the technology 2012-2021, million USD

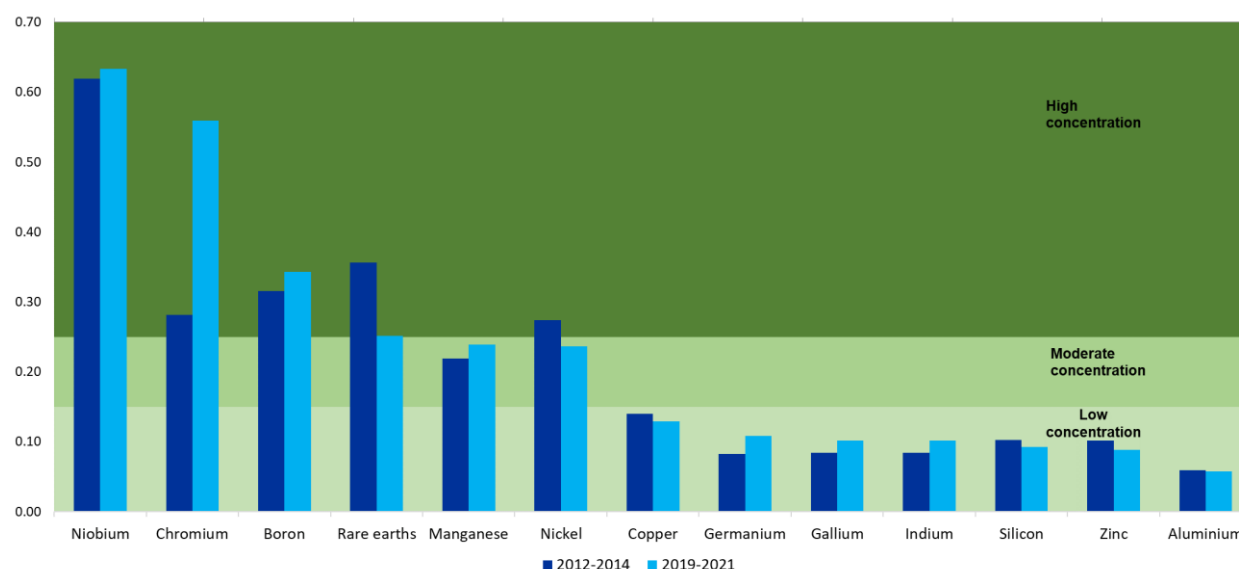


Note: The two technologies analysed in this section were selected based on the availability of data to compute the value-added share of the critical raw material used in the respective technology. The value-added share is time invariant and is calculated based on information of the period with best data availability.

Source: Own elaboration based on UN Comtrade database, EU table of material use shares (European Commission, 2023^[12]), mineral's demand information from IEA data explorer and mineral's supply information from US geological survey. Underlying data available in Table A A.2

Exports of some critical raw materials are highly concentrated**Figure 2.5. Export concentration of critical raw materials**

Herfindahl-Hirschman Index of exports of critical raw materials



Source: Own elaboration based on UN Comtrade database.

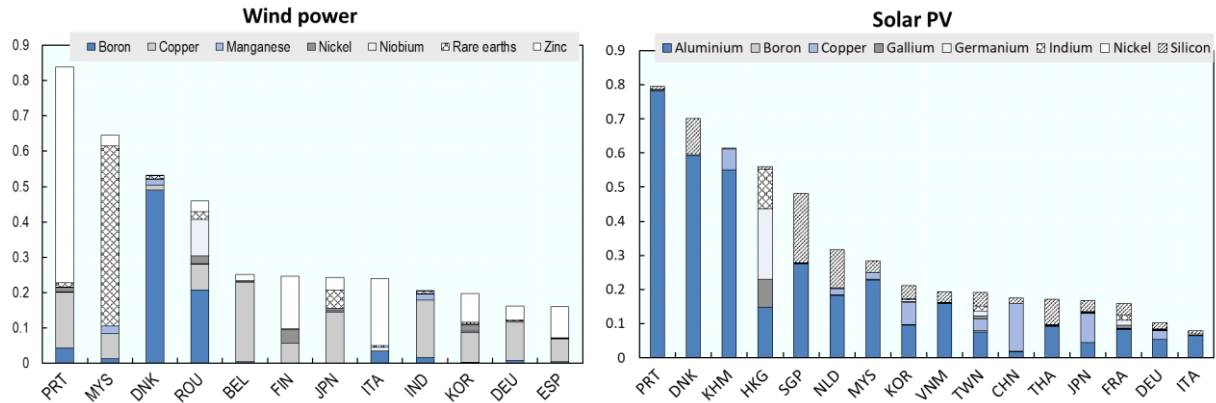
Notes: See methodology in the annex.

Global exports of some critical raw materials used in renewable energy technologies are highly concentrated among exporting countries (Figure 2.5). This is particularly the case for niobium (critical for wind), chromium (critical for CSP, geothermal and hydro), boron (critical for wind and solar) and rare earths (critical for wind), whose export flows have HHI indexes of 0.63, 0.56, 0.34 and 0.25, respectively, indicating high levels of concentration. Among these materials, the export concentration of chromium has increased markedly in the last years, from 0.28 in 2012-2014 to 0.56 in 2019-2021. This was driven by the increase in the export share of South Africa from 49% to 74%. On the other hand, the export concentration of rare earths has decreased from 0.36 to 0.25, driven by a decline in the export share of China from 49% to 27% during the same period.

To analyse how trade concentration of critical raw materials affects the production of renewable energy goods, Figure 2.6 displays an index of import concentration of critical raw materials at the technology-country level. This index consists in the average HHI of critical raw materials' imports used in a specific renewable energy technology, weighted by the imports of each critical raw materials used for that technology (methodology in Annex A). For example, for wind power goods in Japan, this results in an index of import concentration of critical raw materials of 0.25 for Japan, with the higher influence driven by copper (given its high import share and moderate HHI) and rare earths (given its high HHI and high import share).

Figure 2.6. The most concentrated critical raw materials (weighted by their import contribution) for wind power and solar photovoltaics differ across importing economies

Import concentration index of critical raw materials at the technology level for wind and solar PV, decomposition by critical raw material. 2019-2021



Note: This index consists in a weighted average of the HHI of critical raw materials' imports used in wind and solar PV technologies, with weights being the imports of the specific critical raw material used in the production of the technology over all the imports of critical raw materials used for that technology (methodology in Annex A). The sample is constructed as follows: i) the top 20 exporters of wind and solar PV capital goods are kept; ii) the economies with a high domestic production in at least one critical raw material are dropped. Economies are considered to have a high domestic production of a raw material if their ratio exports/imports is higher than the global 90th percentile of the material.

Source: Own elaboration based on UN Comtrade database.

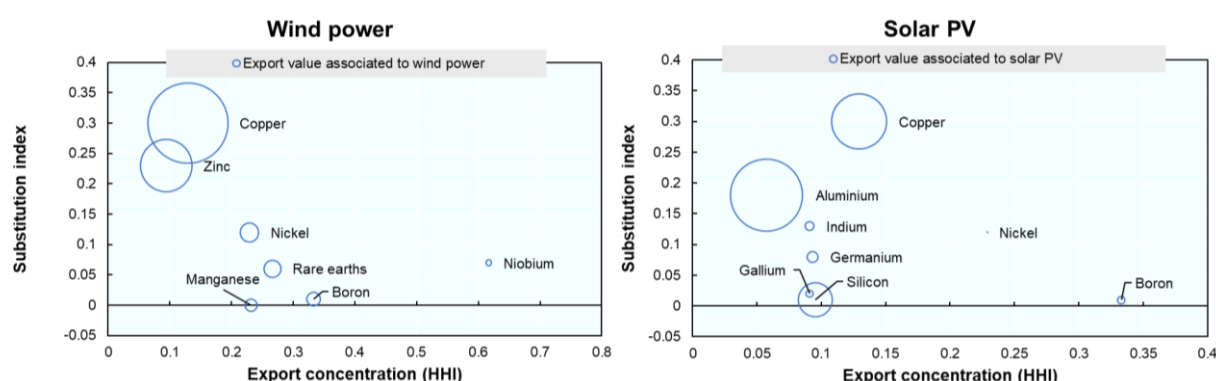
Two main conclusions can be drawn from Figure 2.6. First, the critical raw materials' imports of some countries are clearly more concentrated than in other countries, secondly, the more concentrated critical raw materials (weighted by their import contribution) differ across countries. For example, for wind power, the countries facing the highest import concentration of critical raw materials are Portugal, Malaysia and Denmark; while the incidence of each raw material is different for those countries, with the import concentration of raw materials (weighted by their import contribution) being driven by zinc in Portugal, rare earths in Malaysia and boron in Denmark. For solar PV, the countries facing the highest import concentration of critical raw materials are Portugal, Denmark and Cambodia, which are all primarily driven by aluminium. However, in countries like the Netherlands, the incidence of silicon is high.

The most concentrated critical raw materials for wind power and solar PV tend to have fewer substitutes

To design informed policy making for a resilient supply chain of critical raw materials, countries need to consider different aspects of the minerals, such as their degree of substitutability, export concentration and value-added contribution to the specific technologies. Figure 2.7 shows the interaction between these elements for the critical raw materials necessary for solar PV and wind power technologies.

Figure 2.7. The most concentrated critical raw materials for wind power and solar PV tend to have less substitutes

Substitution index against the Herfindahl-Hirschman index of export concentration for critical raw materials used in solar PV and wind power technologies.



Note: The size of the circles represents the export value that each raw material contributes to the specific technology, see Table A A.3. The substitution index was elaborated by the European Commission and was transformed in this paper in order to increase when the raw material is more substitutable (transformed index = 1 – original index) (European Commission, 2017^[18]).

Source: Own elaboration based on UN Comtrade database and the 'Methodology for establishing the EU list of Critical Raw Materials.' (European Commission, 2023^[12]).

The most concentrated critical raw materials for wind power tend to be also the least substitutable, this is the case for manganese, rare earths, boron and niobium. For solar PV, this is the case for boron and nickel, while the rest of materials have a relatively low export concentration and varying degrees of substitutability. The critical raw materials with highest value-added contribution for both technologies are not concentrated and have potential substitutes (aluminium and copper for solar PV, and zinc and copper for wind power). It is worth noting that the value-added contribution does not measure the criticality of the materials in the production process, and hence, should be interpreted with caution.

Some policy recommendations can be drawn from this evidence. First, for materials with low concentration and low substitutability (silicon, gallium, indium and germanium for solar PV), a viable strategy could be to diversify the source of imports through free trade agreements given the availability of several potential trade partners. Second, for the critical raw materials having both high levels of concentration and low substitutability (boron and nickel for solar PV; and niobium, boron, rare earths, manganese and nickel for wind power), a potential strategy could be to combine R&D support for potential substitutes and investment partnerships with third countries that have mineral reserves of the critical raw material but that still have limited extracting and exporting capacity. Finally, for materials with high value-added contribution (aluminium, copper and zinc) to solar PV and wind power applications, given their relatively diversified supply and the availability of substitutes, a continuous monitoring might be sufficient in the short-run.

Higher diversification could be achieved by promoting investment partnerships or free trade agreements with new trade partners that have a high potential in extracting and refining the materials. For **rare earths**, this would be the case of Brazil and India, which account for 16% and 5% of global reserves, respectively, but just for 0.2% and 1% of global production. For **metals**, this is the case of several materials, such as: i) nickel, for which Brazil owns 16% of global reserves but only accounts for 3% of global production; ii) bauxite (used to produce aluminium), for which Vietnam account for 19% of global reserves but just 1% of production; and iii) copper, for which Australia accounts for 11% of global reserves but only represents 4% of production. Finally, this type of analysis is not simple for **semiconductor materials** since they are generally extracted as a byproduct of different minerals.

Some recent industrial strategies include provisions to address supply chain bottlenecks of raw materials. These include the EU Critical Raw Materials Act (European Commission, 2023^[7]) and the Inflation Reduction Act (IRA). For example, the latter includes a tax credit of 10% of the production cost awarded to producers of critical raw materials used for renewable energy technologies (e.g. aluminium, rare earths, germanium and indium, among others). The EU Critical Raw Materials Act was enacted with the aim of ensuring a secure and sustainable supply of critical raw materials for Europe's industry in a context of dependencies on imports from non-EU countries and bottlenecks in their supply chain. For instance, for wind turbines, the highest risks exist at the raw materials stage where the EU just provides 1% of the raw materials required for global production of wind turbines (Bobbà et al., 2020^[19]).

Box.2.1 The EU Critical Raw Materials Act and supply chain resilience

The EU elaborated the Critical Raw Materials Act (European Commission, 2023^[7]) with the aim of ensuring a secure and sustainable supply of critical raw materials for Europe's industry in a context of dependencies on imports from non-EU countries. For the EU, an adequate supply of those raw materials is deemed as essential for the green and digital transitions, for long-term competitiveness and for strategic autonomy. The EU Critical Raw Materials Act aims to operate through concerted internal and external actions. Internally, it is intended to strengthen domestic supply chains, and externally, it reinforces international engagement to develop partnerships with third countries.

In practice, the Critical Raw Materials Act aims to strengthen the capacity in all stages of the value chain by reducing dependencies, increasing preparedness, and promoting supply chain sustainability through the following actions:

Defining the critical and strategic materials. Critical and strategic raw materials are defined based on a specific methodology and analysis (see European Commission (2023^[12])). Critical raw materials are those that are important for the whole European economy and that face a high risk of supply disruption (e.g. niobium and aluminium), while strategic raw materials are characterised by high strategic importance and projected global supply/demand imbalances (e.g. rare earths, lithium, boron and silicon).

Setting 2030 benchmarks for strategic raw materials. The target EU content of domestic annual consumption for extracted, processed and recycled strategic raw materials is set to be 10%, 40% and 15% over the total, respectively. There is no EU content requirement for critical raw materials.

Building European capacities and establishing partnerships. This consists of identifying strategic projects in the Union and third countries for extraction, processing or recycling of strategic raw materials. These projects would benefit from easier and faster permitting procedures and from improved access to finance. In order to receive those benefits, the projects should be assessed against a set of criteria, including technical feasibility and sustainability. Regarding partnerships with third countries, the EU has already signed agreements with Argentina, Canada, Chile, Kazakhstan, Namibia, and Ukraine. For example, the most recent of these partnerships is the one signed with Chile in July 2023, which consists in stimulating joint investment projects in raw materials' value chains (specifically lithium and copper), cooperating on R&D and infrastructure, and strengthening capacities through training and skills development (European Commission, 2023^[20]).

Improving resilience. A European Critical Raw Materials Board composed of the European Commission and member countries will be formed with the objective of monitoring critical raw materials and performing stress testing of supply chains. The stress testing should assess the vulnerability of the EU supply chain of strategic raw materials to disruptions by estimating the impact of different shocks and their potential effects. Furthermore, the EU Critical Raw Materials Act considers the following actions with the purpose of ensuring resilience: creating a critical raw materials club with non-EU

countries interested in strengthening supply chains; coordinating the development of national strategic stocks to mitigate the risk associated with supply disruptions; enhancing the network of free trade agreements; and expanding the network of strategic raw materials partnerships with third countries.

Promoting a more sustainable and circular critical raw materials economy. This will be ensured by incentivising the recycling of raw materials from waste products and mining waste, while increasing the share of recycled materials used in manufacturing, with a particular emphasis on permanent magnets. In terms of concrete actions, member states shall adopt and implement national programmes, which might include financial incentives such as discounts, monetary rewards or deposit-refund systems associated with the specific recycling activities. Countries will be asked to provide information on the adoption and progress of the programmes.

Source: European Commission, 'Establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations' (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020, 2023.

3 Technological leadership in renewable energy

This section uses patent and complementary data to analyse emerging trends that are likely to deeply affect the renewable energy ecosystem over the coming decades. It complements the value chain approach by i) identifying new actors that could become major players in the ecosystem in the future; ii) highlighting the market microstructure of the ecosystem in terms of sector, firm age and M&A dynamics; and iii) showing recent innovation efforts intended to substitute and recycle critical raw materials.

Achieving the goal of limiting global warming to 1.5°C-2°C as agreed in the Paris Climate Agreement requires huge investments in innovations for renewable energy technologies to reduce their cost and enable their large-scale deployment. Furthermore, and as has been highlighted in some studies, innovations might have a relevant role in shaping competitiveness of countries in the sectors that adopt the new or improved technologies due to a series of reasons such as productivity improvements (Cassiman, Golovko and Martínez-Ros, 2010^[21]) and upgrading in the value chain (Caliari et al., 2023^[22]). Renewable energy technologies are not the exception. For instance, Elia et al. (2021^[23]) show through a systematic review that innovations in renewable energy technologies have a strong role in reducing the cost of those technologies with learning-by-doing and learning-by-researching spillovers being important drivers. Caravella et al. (2024^[24]) show, for the case of solar PV, that reinforcing technological specialisation in the upstream segments may help mitigating strategic dependencies and would foster the overall productive capacities of the value chain.

As mentioned in the introduction, the Climate Neutral Industry Competitiveness Scoreboard (European Commission, 2022^[9]) shows innovation trends of renewable energy technologies along with information about its overall competitiveness. The results of this report are aligned with the one presented in the beginning of this section with respect to the competitive role of the EU in wind, smart grid, hydrogen and hydropower innovations.

This section shows that, since 2010, there has been a decline in patenting activity for most renewable energy technologies, particularly for the solar photovoltaic technology. Although European countries lead the filling of new patents, new players as China or Korea are catching up rapidly. The technology specialisation reveals that OECD Members are leaders in green hydrogen, wind (with special relevance of European countries) and smart grid, whereas China demonstrated a significant technology advantage for solar photovoltaics. Moreover, empirical evidence reveals a positive correlation between technology leadership and improved export performance a decade later.

Examining the microstructure of innovation in renewable energy technologies, this paper shows that public research organisations and young firms play a more important role than in other technologies on average, indicating that renewable energy are still relatively immature. This analysis also shows that, on top of the global decrease in renewable patents, the share of young firms in renewable innovation is decreasing, leading to potential concerns about the future of radical and upstream innovation in renewable technologies.

Two-thirds of renewable energy innovations come from the manufacturing sector. Wind energy patents are mainly filled by companies operating in machinery, while solar photovoltaic and smart grid inventions are mainly filled by companies from the computer and electronics sector.

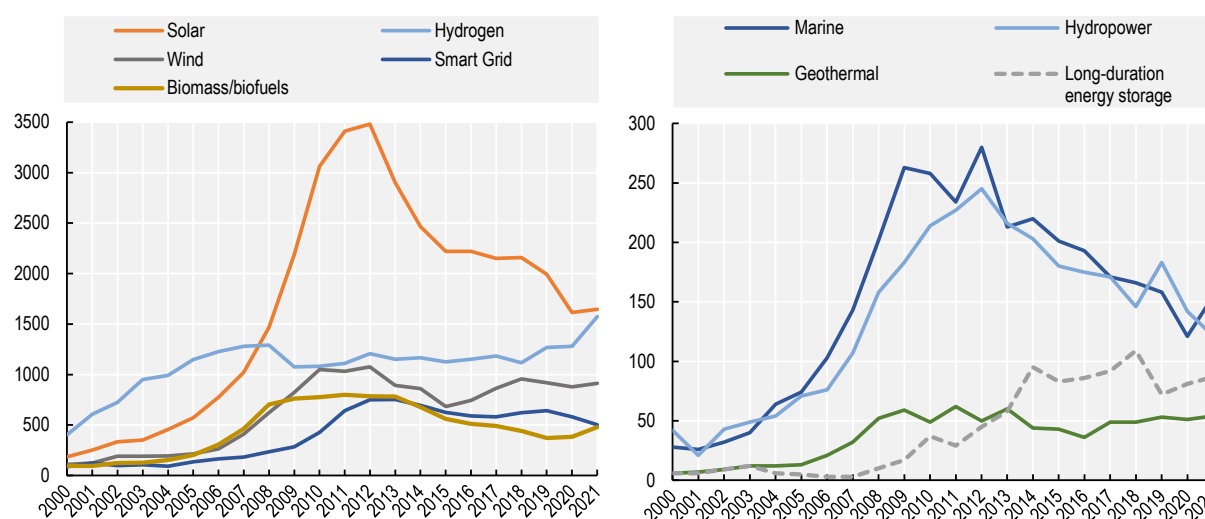
M&A transactions primarily target firms with a specialisation in solar and smart grid technologies, while wind power is underrepresented.

For solar panels, but also for many other technologies, innovation may also play a role in reducing dependencies, through the development of alternative materials, recycling or reducing the material intensity. Nonetheless, more efforts are needed to develop substitutes for materials used in wind turbines, such as boron and rare earths, given their low substitutability and high export concentration.

A recent decline in patenting activity for most renewable technologies

Patent filings in renewable energy have experienced a declining trend in most technologies since the early 2010s (see Box A B.1 for details on the use of patents as a measure of innovation activity). As shown in Figure 3.1, the number of patents filed to protect inventions in solar photovoltaics decreased by one-half, at an average rate of -8% a year between 2012 and 2021. Inventions related to hydropower (-7.5%/year), marine (-6.4%/year), biomass and biofuels (-5.3%/year) follow a similar downward trend. However, two sets of renewable energy technologies show an upward trend: patented inventions in LDES nearly doubled since 2012, while the number of patents related to green hydrogen technologies also increased at a slower pace (+3% per year on average since 2012).

Figure 3.1. Patents in technologies related to renewable energy



Note: Data refer to the number of patent applications filed under the Patent Co-operation Treaty (PCT), by earliest filing date. Patents are allocated to renewable energy technologies on the basis of the search strategy presented in Table A B.1

Source: OECD, STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats>, January 2024.

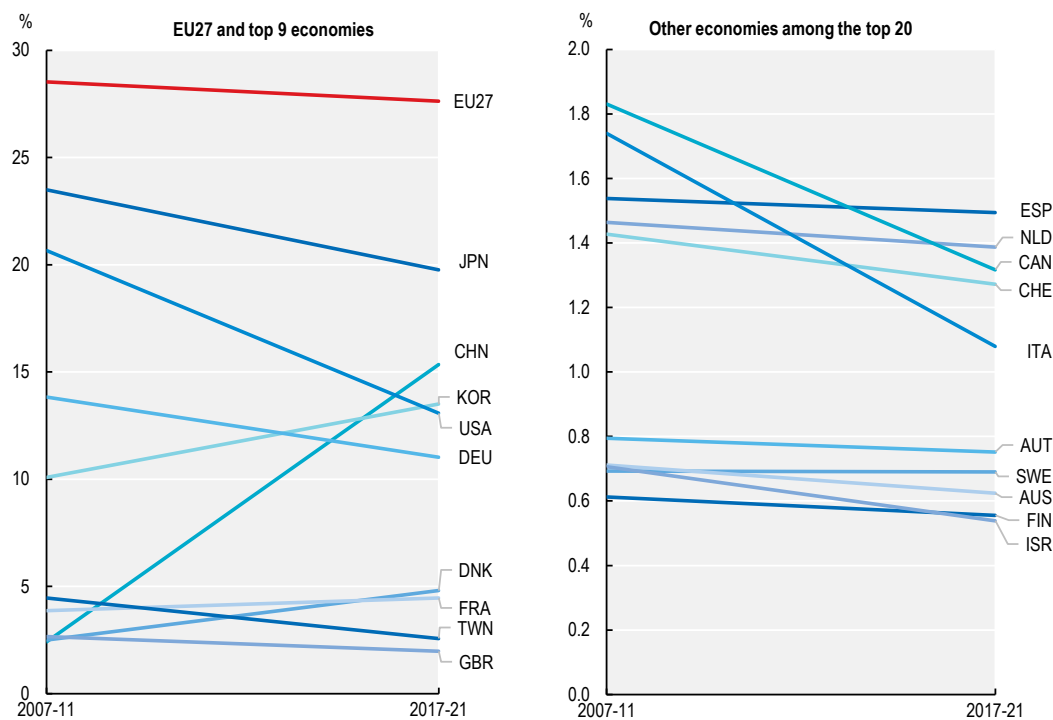
This difference in trends across renewable energy technologies can be at least partly explained by differences in maturity, but some common factors may explain the decline in renewable energy patenting, such as low natural gas prices and cuts in renewables subsidies in some EU countries. In solar PV, it has been argued that China's dominance may hinder solar energy innovation: benefiting from lower costs, Chinese producers displaced American, German and Japanese firms that produced more expensive solar panels but were also more innovative (Carvalho, Dechezleprêtre and Glachant, 2023^[25]). More generally,

reduced innovation activity may be a symptom of increased M&A, which is the result of a highly competitive sector (see below).

The EU27 as a whole ranked first in terms of the number of renewable energy patents in 2017-21, with 27.6% of total filings of renewable patents – a slight decrease of one percentage point as compared to its level in 2007-11 (Figure 3.2). Japan is the economy that contributed the most to the development of renewable energy patents over the past decade, even though its share in total renewable energy patents has been decreasing over time (from 23.4% in 2007-11 to 19.8% in 2017-21). Three economies saw their shares in total renewable patents expand over time: China and Korea surpassed the United States in terms of number of inventions in renewables, contributing to respectively 15.4% and 13.5% of patents in 2017-21. Denmark increased its relative share of patents in renewable fields, gaining more than two percentage points over the period considered. The proportion of renewable energy patents from Germany decreased to 11%, nearly three percentage points less than its level in the late 2000s.

Figure 3.2. Renewable energy technologies developed by economies, 2007-11 and 2017-21

Top 20 economies' share in total renewable energy patents



Note: Data refer to IP5 patent families in all renewable energy technologies, by earliest filing date and location of the applicants, using fractional counts. Only the top 20 economies with renewable energy patents in 2017-21 are presented.

Source: OECD, STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats>, January 2024.

In 2017-21, EU27 economies are leading the developments in wind energy technologies (58% of total wind) and in biomass and biofuels (40% of total patents in biomass and biofuels). They contributed to more than one-fourth of patents related to hydropower (30%), marine (26%), geothermal (25%) and hydrogen (25%). About 15% of inventions on solar photovoltaics and LDES were developed in EU. Within EU, Germany, France and Denmark are the leading economies with renewable energy patents. In 2017-21, Germany ranked among the top five economies for almost all renewable technologies, except for marine technologies. France filed more than 10% of patents for inventions related to biomass and biofuels, in second position after the United States. Denmark increased its leadership in wind energy, with almost 25%

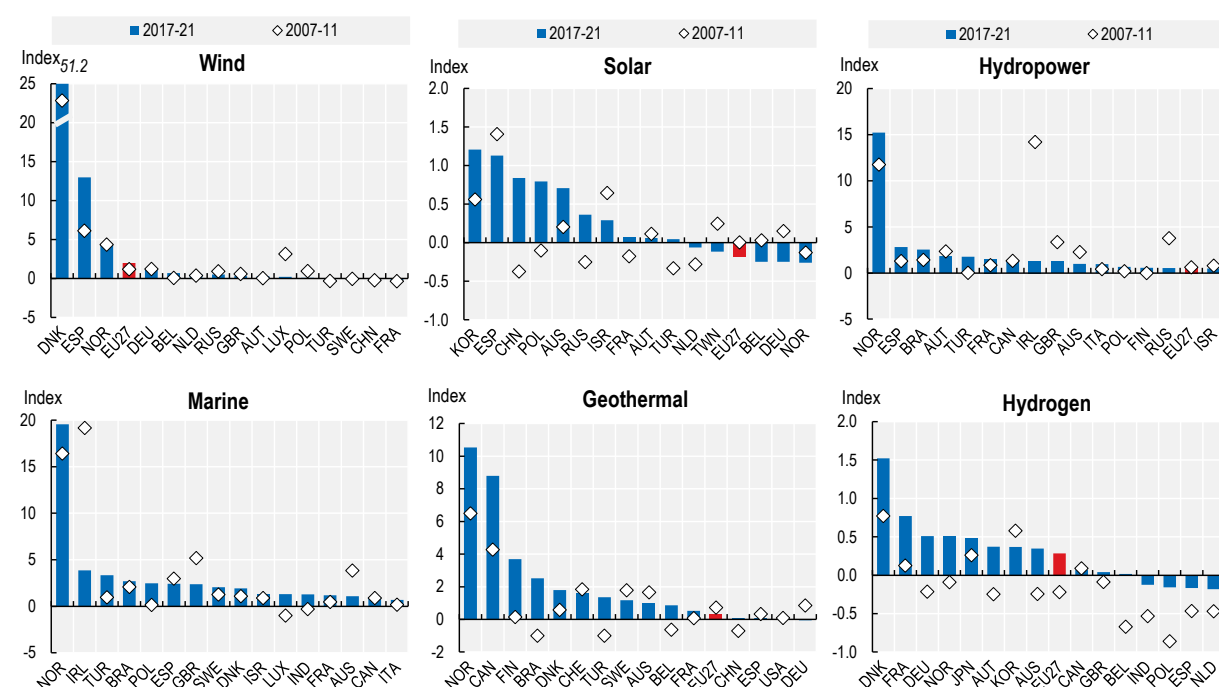
of patents in this technology between 2017 and 2021, twice as much as compared to its level in 2007-11 (12%).

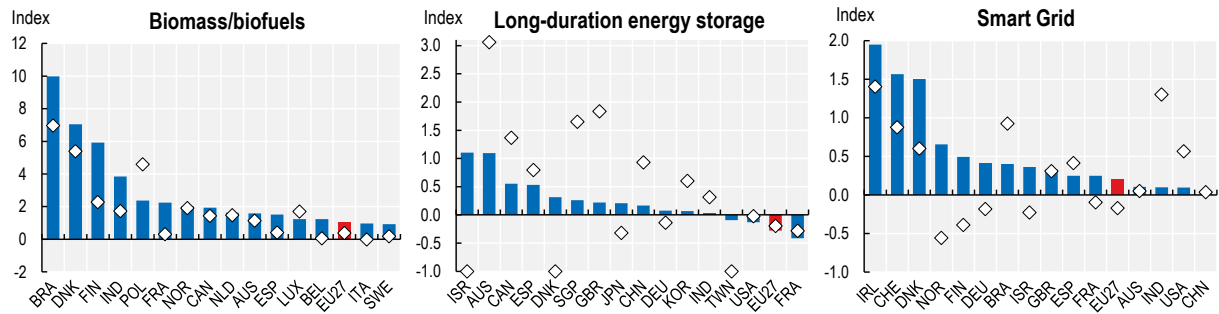
Japan ranked among the top five economies when looking at the different technologies. It contributed to more than 36% of inventions related to hydrogen (Figure 3.3), and to 30% of LDES technologies. It ranked second for inventions on hydropower (13%) or smart grid (18%). China saw its share in renewable energy patents expand in all fields, notably in hydropower (16%), marine (19%) and solar photovoltaics (25%). The United States remained in the first position in fields related to biofuels and biomass (22%), geothermal (20%) and smart grid (21%).

A high number of patents in renewable technologies can signal either overall innovation performance, which depends on the size of the economy, or a focus of the economy on the developments in renewables. The revealed technology advantage (RTA) indices help disentangle these issues and highlight the relative specialisation of economies in specific technology fields. The RTA index is obtained by dividing each economy's share of patents in a technology with the global share of patents in the same technology. For example, if renewable patents represent 1% of all patents filed by Spain, but 0.5% of all patents, then Spain would get an RTA of 2 in renewable energy.

Figure 3.3. Revealed technology advantage (RTA) of economies in renewable energy, 2007-11 and 2017-21

Top specialised economies





Note: Data refer to IP5 patent families in selected renewable energy technologies, by applicant location and first filing date, using fractional counts. Only economies with more than 1 000 IP5 patent families in total and ten patent families in the given technology domain for each period are included.

Source: OECD, STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats>, January 2024.

The RTA index in a technology field t and economy c is compiled as the share of patents in the technology filed by applicants in economy c divided by the share of patents filed by the same economy in all technologies. It can be expressed as follows:

$$RTA_{ct} = \frac{\frac{P_{ct}}{\sum_c P_{ct}}}{\frac{P_c}{\sum_c P_c}} \quad \text{Equation 2}$$

Where P_{ct} represents the number of patents filed by economy c in the technology t , and P_c represents the total number of patents filed by economy c . For representation purposes, RTAs shown in Figure 3.3 are centred around 0 values by subtracting 1 to the RTA indices: RTA indices above 0 reflect a relative technology advantage and RTA indices below 0 indicate a relative disadvantage.

OECD Members are leaders in green hydrogen, in wind - especially within Europe - and smart grid technologies. Although it contributed to a significant share of patents globally, the United States features a relative disadvantage in most renewable energy technologies in 2017-21, except for smart grid where its RTA index remains positive. Among emerging economies, China demonstrates a significant technology advantage in solar photovoltaics, and, to some extent, in LDES. Brazil and India are among the most specialised economies in technologies related to biomass and biofuels.

Denmark stands out as having an undisputed leadership in wind technologies, as well as a strong position in green hydrogen, smart grid, and biomass/biofuels technologies. Indices for Spain reveal a relative specialisation in hydropower, solar photovoltaics and wind. Norway has the highest RTA indices in marine, hydropower and geothermal in 2017-21.

At the country level, technology leadership and export performance are linked

As stressed in the literature (Caliari et al., 2023^[22]), countries with a technological leadership in a sector might also exhibit a better export performance due to a number of reasons, such as productivity improvements associated to innovation (Cassiman, Golovko and Martínez-Ros, 2010^[21]) and the upgrading to higher value-added activities within the technology-specific value chain (Caliari et al., 2023^[22]) (Caliari et al., 2023^[22]). To explore this relationship for renewable energy technologies, this study compares countries' RTA and RCA for renewable energy technologies where data is available for both patents and exports of capital goods. This analysis focuses on wind, hydro and solar power, for which the relative comparative advantage can also be calculated.

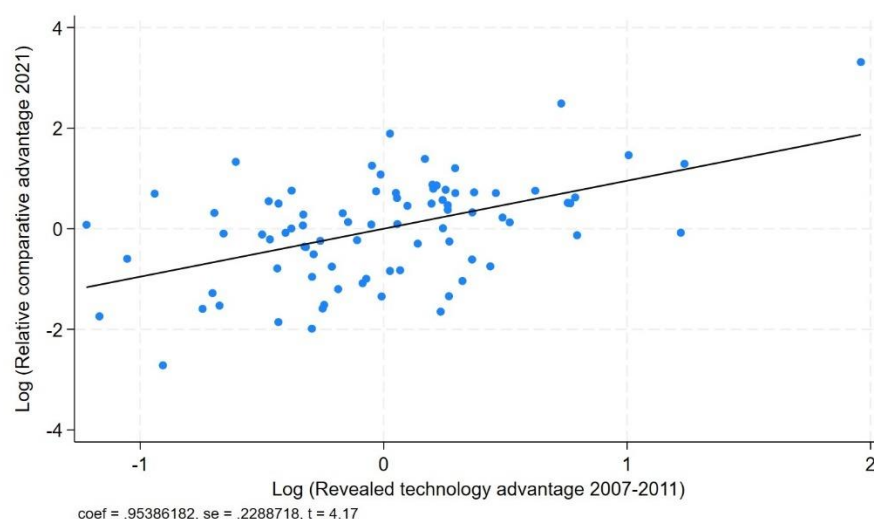
The evidence shows that countries with a RTA for wind and hydro power technologies tend to also display a relative comparative advantage for exporting the capital goods associated to those technologies (Figure A B.1). For instance, for wind power, the four countries with highest relative technology advantage in 2017-2021 (Denmark, Spain, Norway and Germany) also have relative comparative advantage in those technologies, while most of the countries with revealed technology disadvantage have also relative comparative disadvantage. In the case of technologies used in solar energy, the relationship is less strong but still positive.

These results cannot be interpreted as a causal relationship, as many factors (e.g. human capital or past investments in the technology) can jointly determine RCAs and RTAs. In addition, causality could also go both ways, with the technology advantage being the source of the comparative advantage, or conversely an important domestic production allowing for more domestic innovation. To provide more insights on this potential relationship, it is possible to look at the correlation between RCAs and past RTAs, and vice versa. This remains suggestive evidence, and does not establish a causal relationship.

When looking at cross-country correlations, the evidence shows that more technology leadership correlates with a better export performance 10 years later, controlling for the initial level of export performance (Figure 3.4). These results are driven by hydro and wind power, highlighting that export performance in solar PV is less related to technological performance. A similar analysis shows that past RCAs do not help predict the current RTA (insignificant coefficient).

Figure 3.4. Technology leadership correlates with a better export performance 10 years later

Cross-country regression of the logged relative comparative advantage in trade in capital goods used for solar, wind and hydro technologies in 2021 on the logged RTA in those technologies in 2007-2011, controlling for the initial level of export performance



Note: This regression is pooling all technologies together and controlling for technology and country fixed effects. Also, this regression controls for relative comparative advantage in the base year (2012). A placebo test was performed by regressing RTA in 2017-2021 on relative comparative advantage in 2012, this correlation was still positive but with a much lower coefficient (0.09 vs 0.9) and t-values (1.79 vs 4.17) than in the original specification.

Source: Own elaboration based on OECD, STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats> and UN Comtrade database.

Who innovates in renewable energy?

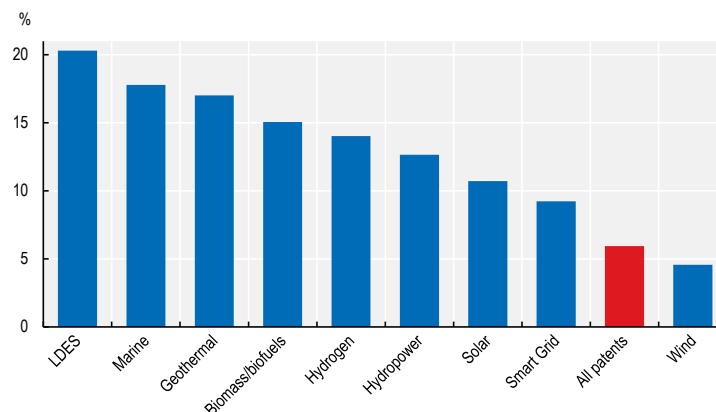
This subsection first explores respectively the role of public research organisations and the private sector for each renewable technology, and then describes the characteristics of firms innovating in those technologies.

The role of public research organisations

Innovation in renewable energy technologies mainly occur within private companies. In 2017-21, 80% of patents in renewable energy were filed by companies, against 8% of patents originating from public research organisations (PROs), including universities, public research centres, government institutions and hospitals. As shown in Figure 3.5, the share of renewable energy patents owned by PROs is relatively larger than that observed for all patents (6%). PROs are most active in LDES (20%), marine energy (18%) and geothermal (17%). Wind power appears as the technology where public research organisations are least involved, with less than 5% of wind-related patents filed by PROs. The heterogeneous role of PROs can be linked to the maturity of technologies: government R&D support and related patenting seems higher for less mature technologies such as LDES or marine, while for more mature technologies such as wind, further technology developments and patenting are driven by industry.

Figure 3.5. Renewable energy patents developed by public research organisations, 2017-21

As a share of total patents



Note: Data refer to IP5 patent families, by renewable energy technologies and earliest filing date, using fractional counts. Names of applicants were allocated to institution types according to the EEE-PPAT dataset produced by the Centre for Research & Development Monitoring (ECOOM) of Belgium. Patents filed by PROs refer to those owned by applicants identified as universities, government institutions or hospitals. Source: OECD, STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats>, January 2024.

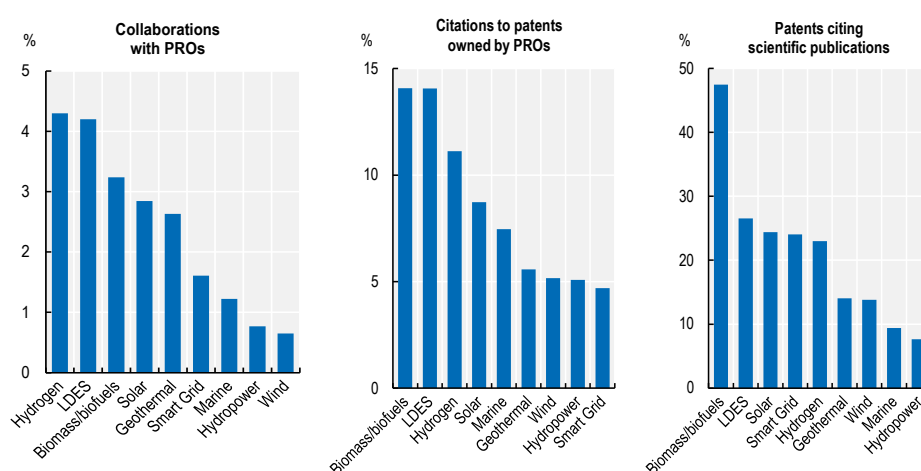
The contribution of public research to private innovation in the field of renewable energy can be identified using three additional indicators. The direct collaboration between firms and PROs is measured as the share of patent applications that were jointly filed by companies and by public research institutions. The share of patents that cite patents filed by PROs indicates the extent to which inventions in a given filed rely on previous technologies developed by public research institutions. The last indicator measures the contribution of scientific knowledge to private innovation and is based on the share of patents that cite academic publications. The indicators are displayed in Figure 3.6 for each renewable energy technology.

Green hydrogen, LDES and biomass/biofuels rely most on collaboration with PROs. During the period 2010-21, more than 4% of inventions related to green hydrogen and LDES were the result of a collaboration between firms and PROs (Figure 3.6). This share exceeds 3% in the case of biomass and biofuels, while

less than 1% of patents in hydropower and wind energy were developed jointly with public research institutions. Patents in biomass and biofuels, and LDES, have the largest proportion of citations to PROs patents (14% of total citations made), indicating close relationships with inventions developed by public research organisations. Additionally, as shown in the third panel of Figure 3.6, technologies related to biomass and biofuels rely most on scientific literature: 47% of patents in this field include at least one reference to a scientific article. In the case of renewable energy using marine or hydropower, the reliance on basic research is the lowest, with about 8-9% of patents featuring references to scientific articles.

Figure 3.6. Links between renewable energy technologies, public research organisations and science, 2010-21

Share of collaboration with PROs in total patents, share of patents citing patents filed by PROs, and share of patents citing scientific publications.



Note: Data refers to IP5 patent families. Collaborations with academic institutions are identified as patent families with at least two applicants, one of them being a firm and another a PROs e.g., universities, government institutions, hospitals. Patents filed by PROs only include patents for which the type of applicant (individual, company, government entity, etc.) is identified. A patent is labelled as citing PROs patents if at least one application in the patent family cited a patent filed by a PRO. A patent family is labelled as citing the scientific publications if at least one patent in the patent family contains a non-patent reference to scientific articles, chemical abstracts, or biological abstracts. When labelling a patent family as citing the non-patent literature, the sample is restricted to those patent families that have at least one patent application at the European Patent Office (EPO), United States Patent and Trademark Office (USPTO), or WIPO (PCT applications). This restriction is necessary as non-patent literature citations are only available for patents filed in one of these three offices. For USPTO patents, references to articles are derived from Marx and Fuegi (2020^[26]).

Source: OECD, STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats>, January 2024.

The characteristics of firms patenting in renewable energy technologies

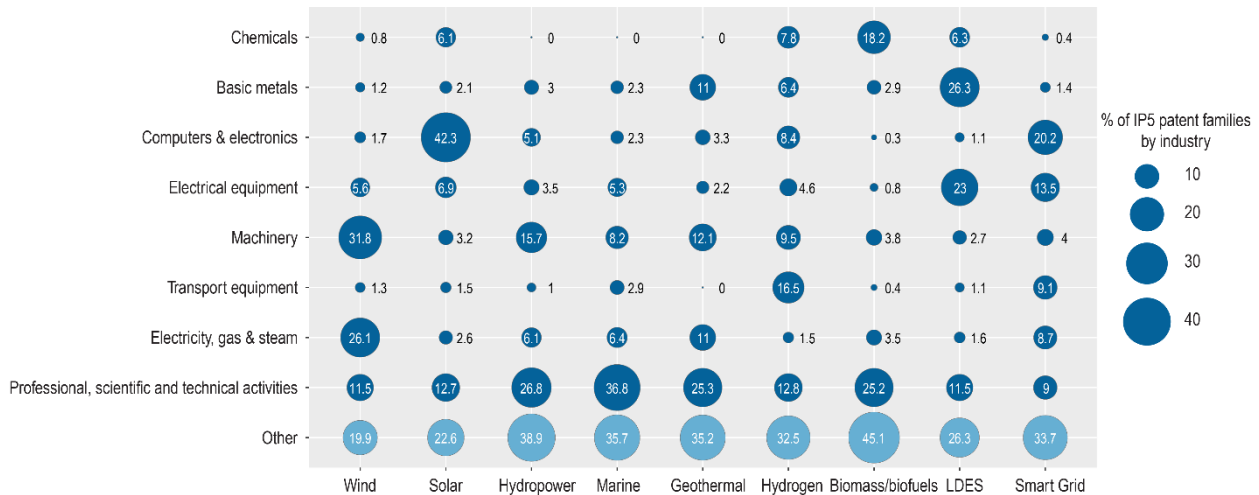
Technological developments in renewable energy are mostly driven by the private sector. To obtain information on applicants, data on patents were linked to two sources of firm-level data: the ORBIS® database – a private business register dataset maintained by Bureau van Dijk – and the OECD Startup database, which merges data from two private providers (Crunchbase and Dealroom). The links were established using series of string-matching algorithms that compare the patent applicants' names to company names in both data sources (see 0 for further details on the matching process). The economic sector of patenting companies is based on the International Standard Industrial Classification of All Economic Activities (ISIC, rev.4).

The distribution of the patent portfolio of firms by industries indicates that two-thirds of renewable energy innovations come from the manufacturing sector. The breakdown of patents by sector is presented in

Figure 3.7, for each technology domain. Wind energy patents are mainly filled by companies operating in machinery (32%) and in electricity, gas, and steam (26%). Companies from the Computer and electronics sector contributed to more than 40% of patents for solar photovoltaics inventions, and to 20% of inventions related to smart grids. In 2017-21, 25% to 37% of technologies related to hydropower, marine, geothermal, biomass and biofuels were developed by firms conducting science and technology activities.

Figure 3.7. Renewable energy technologies developed by industries, 2017-21

Distribution of patents in selected technologies, main sector



Note: Data refer to IP5 patent families, according to the main sector of performance of the applicants, by earliest filing date. Patent applicant names were linked to the company names as provided in ORBIS® database. Only countries with matching rates above 60% are included in the figure, namely: Australia, Austria, Belgium, China, Denmark, Finland, France, Germany, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, Norway, Portugal, Saudi Arabia, Sweden, Switzerland, United Kingdom and United States. The industry class corresponds to the core sector provided in ORBIS®, converted to ISIC rev.4 classification. Patents owned by PROs (universities, government institutions or hospitals) are excluded.

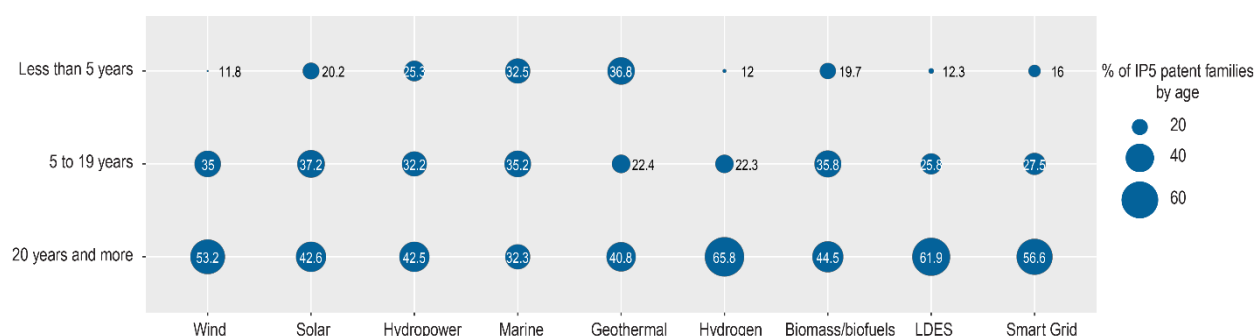
Source: OECD calculations based on STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats>, and ORBIS®, version 2022.1, Bureau van Dijk, January 2024.

Renewable energy patents are mainly developed by incumbent firms. In 2017-21, 52% of the patent portfolio in renewable energy was owned by firms aged 20 years and more at the time of filing. As shown in Figure 3.8, patents related to green hydrogen are principally due to old firms (more than 65%). While the number of patents in technologies related to marine or geothermal energy is relatively small as compared to more mature fields such as wind energy, about one-third of those technologies are developed by firms aged 5 years or less.

While incumbent firms (aged 20 years or more) file most inventions related to renewable energy, this is simply a reflection of their size, and they are not specialised in those fields. Figure A B.2 displays RTA indices compiled by age of the patent owner, for each technology field. A positive index indicates that firms from this age group file a disproportionately high number of patents in that technology, relative to their contribution to overall patenting. Firms aged 20 years or more feature a negative RTA in most renewable energy technologies, except for green hydrogen, smart grid and LDES. Younger firms, on the contrary, feature clear specialisation in renewables. This is notably the case for geothermal and marine energy, hydropower, solar and biomass/biofuels.

Figure 3.8. Age of companies developing renewable energy technologies, 2017-21

Distribution of patents in selected technologies, by age bands



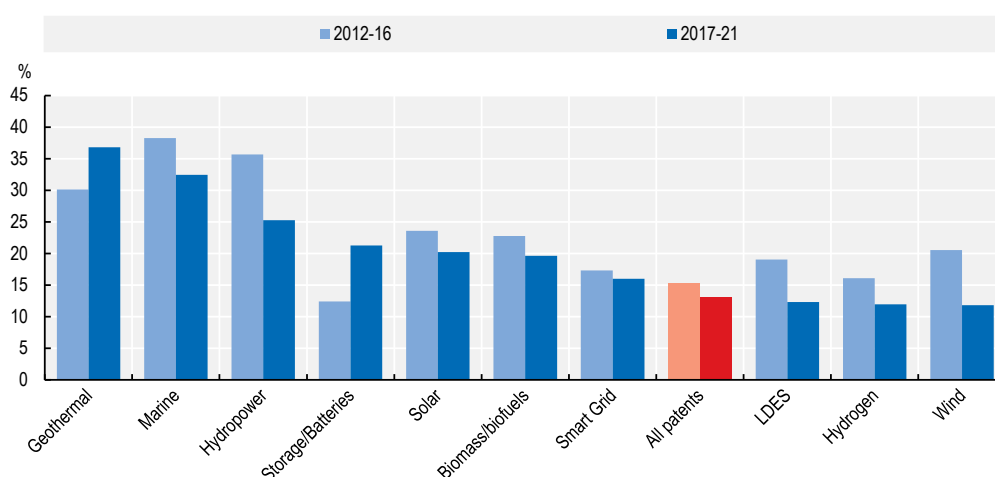
Note: Data refer to IP5 patent families, according to the age of the patent owner, by earliest filing date, using fractional counts. The age of the firm is defined as the difference between the patent filing date and the date of incorporation of the firm, using the links established between patent applicant names and company names available in ORBIS® database. When missing, the date of incorporation corresponds to that of startup data to which patent applicant names were also linked. The remainder was proxied by the date at which an applicant first filed for a patent at any Intellectual Property (IP) office worldwide, lagged by one year.

Source: OECD calculations based on STI Micro-data Lab: Intellectual Property Database, OECD Start-ups Database and ORBIS®, version 2022.1, Bureau van Dijk, January 2024.

As shown in Figure 3.9, the role of young firms in the development of renewable energy technologies has however decreased over time: the proportion of patents in most renewable energy technologies filed by young firms has decreased in the period 2012-21 (Figure 3.9), with this decrease being stronger for technologies such as hydropower (38% to 18%), marine (43% to 32%) and wind power (23% to 10%). The same trend is however observed for the share of young firms in total patents.

Figure 3.9. Patents in renewable energy technologies owned by young firms

As a percentage of total patents in each technology



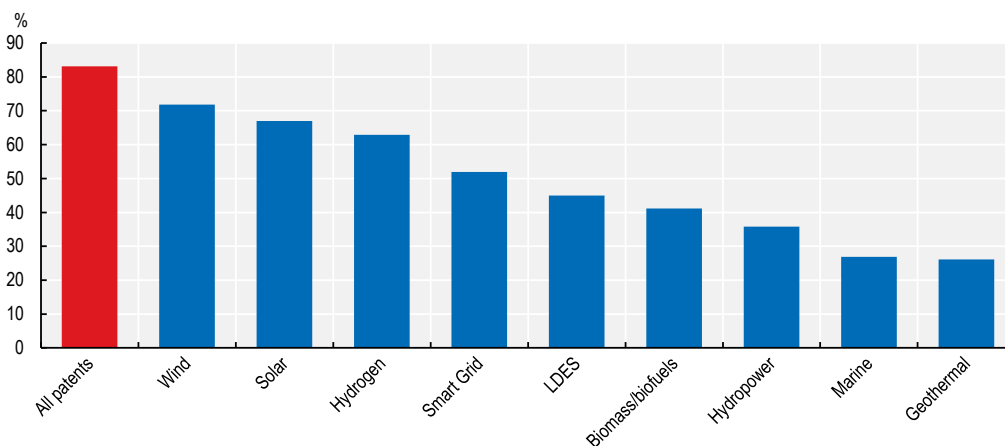
Note: Data refer to IP5 patent families, according to the age of the patent owner, by earliest filing date, using on three-year moving average. The age of the firm is defined as the difference between the patent filing date and the date of incorporation of the firm, using the links established between patent applicant names and company names available in ORBIS® database. When missing, the date of incorporation corresponds to that of startup data to which patent applicant names were also linked. The remainder was proxied by the date at which an applicant first filed for a patent at any IP office worldwide, lagged by one year. Young firms are those below 5 years of age at the date of the patent filing. 'All patents' correspond to the share of young firms in the whole universe of IP5 patent families.

Source: OECD calculations based on STI Micro-data Lab: Intellectual Property Database, OECD Start-ups Database and ORBIS®, version 2022.1, Bureau van Dijk, January 2024.

The portfolio of patents in renewable energy is relatively less concentrated than the overall portfolio of companies but remains highly concentrated for a few technologies. In 2017-21, nearly 73% of patents in wind were due to 10% of applicants worldwide (Figure 3.10), ten percentage points less than the global patent portfolio of firms. The top decile of applicants was responsible for 68% of patents in solar, and 64% for green hydrogen. In turn, lower concentrations are observed in technologies such as geothermal and marine, where the top 10% applicants accounted for less than 30% of patents in the fields.

Figure 3.10. Concentration of patents in renewable energy fields, 2017-21

Cumulative share of patents owned by top 10% of applicants



Note: Data refer to IP5 patent families for selected renewable energy fields, according to the patent owner, by earliest filing date, using fractional counts. Counts are sorted by decreasing order in terms of applicant's patent portfolio in each technology.

Source: OECD, STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats>, January 2024.

Innovation to develop alternatives to and improve recovery and recycling of critical raw materials

As highlighted in the EU Raw Materials Act (European Commission, 2023^[7]), innovation for renewable technologies does not only cover the development or the improvement of the goods used for renewable energy production. It can also support the diversification of critical raw materials supply, through the use of alternative materials or improvements in the recycling of critical raw materials.

Semiconductor materials have a relatively low number of substitutes for renewable energy technologies. Nevertheless, perovskite solar cells can replace silicon solar cells²¹ and the carbon nanotube and graphene coatings are a substitute to Indium tin oxide (ITO) coatings used in solar cells (US. Geological Survey, 2023^[17]).

Some substitutes to **rare earths'** magnets are currently being developed²². Tetraenite is a natural alloy of iron and nickel that exhibits similar magnetic properties as rare earths, but is only found in meteorite rocks. Some institutions like the Northeastern University's College of Engineering and the University of Cambridge patented methods to synthesise tetraenite on an industrial scale. Another potential substitute is the Iron-Nitride super magnet, which is built with iron and nitrogen, and is more than twice as magnetic as rare earth magnets, with applications such as renewable energy generation, electric vehicles and other technologies.

There is a relatively wide range of substitutes for raw materials in the ‘**metals**’ category. For instance, niobium and nickel alloys can be replaced by molybdenum, titanium, tantalum and vanadium in corrosion-resistant steel; zinc by cadmium in coatings to protect against corrosion; and copper by titanium in heat exchangers (US. Geological Survey, 2023^[17])

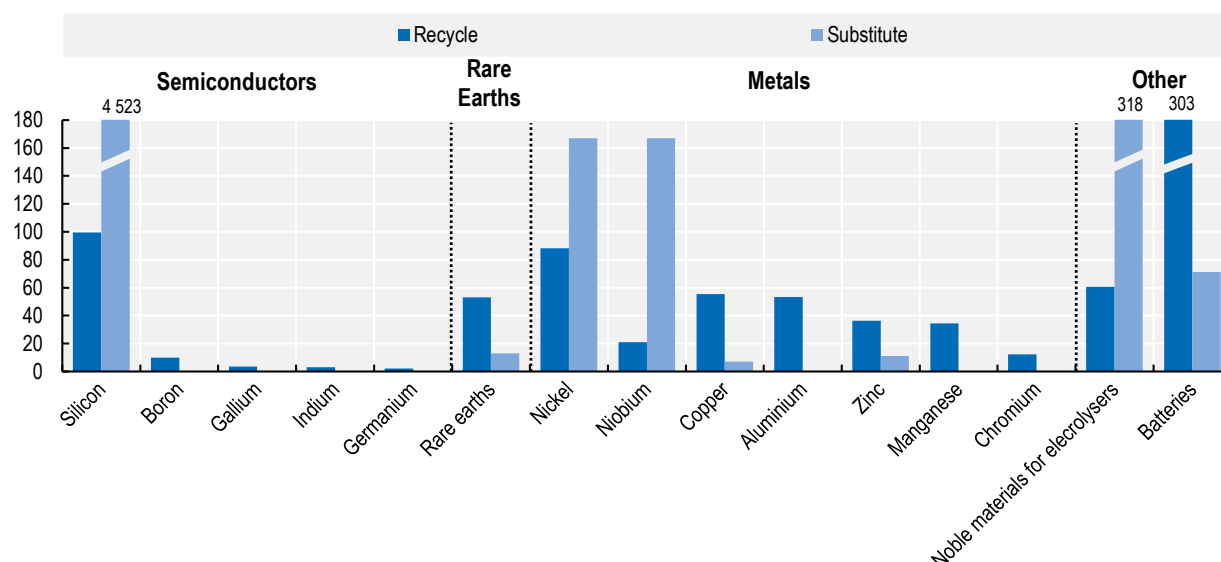
Innovation to develop more substitutes is a key step to enhance the resilience of the renewable energy supply chain by developing alternatives to critical raw materials and improving their recovery and recycling, as highlighted by the EU (European Commission, 2023^[7]) and IRENA (Gielen, 2021^[27]). By relying on the information contained in patent abstracts, Figure 3.11 identifies patents related to the substitution or recycling of the main critical raw materials identified in Section 2.

Efforts to develop substitutes to critical raw materials focus by far on substitutes to silicon (4 523 patents over the period 2017-2021). This is followed by substitutes to nickel (167 patents) and niobium (167 patents), both in the metals category. Developing substitutes for silicon, nickel and niobium are integral to a resilient supply chain in the renewable energy sector given the low substitutability of the former, and the low substitutability and high export concentration of the latter two. However, more efforts are needed to develop substitutes for critical raw materials such as boron and rare earths, given their low substitutability and high export concentration.

In comparison with patents protecting substitutes to critical raw materials, patents protecting recycling and recovery processes are much less numerous but cover nearly all materials that are critical for renewable energy technologies. Recent efforts have focused on recycling batteries, silicon and nickel, but recycling of metals and rare earths is also developing.

Figure 3.11. Patents in recycling or substitution of critical raw materials, 2017-21

Patents in recycling or substitution of critical raw materials, 2017-21



Note: Data refer to IP5 patent families by filing dates. Patents for recycling or substitute for raw materials are identified using the search strategy described in Annex Table A B.2 and Table A B.3.

Source: OECD, STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats>, January 2024.

A few economies feature stronger specialisation in patents for recycling or substitute for critical raw materials. Figure A B.3 displays the RTA of economies in critical raw materials that contribute to solar (panel 1) or wind energy (panel 2) technologies. Korea, China, Saudi Arabia and Poland are the only ones featuring a positive technology advantage in recycling/substitute to silicon. RTA indices for China are larger

than 1 in all raw materials related to solar or wind energy technologies, while Korea's RTAs show a positive specialisation in a few technologies only (indium, nickel, niobium and silicon). Japan and the United States, in turn, are relatively unspecialised in recycling or substitute to critical raw materials.

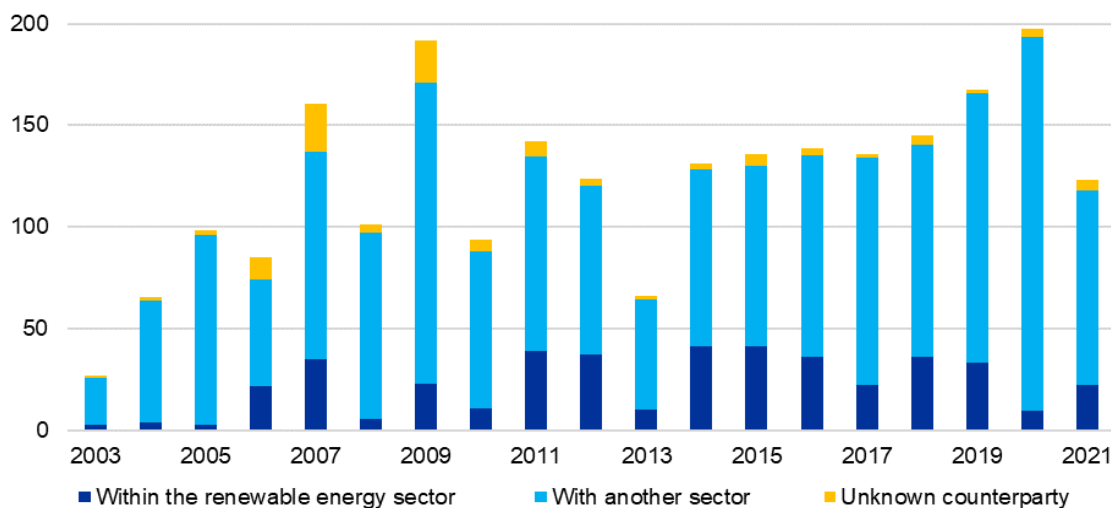
M&As have increased in the renewable energy ecosystem and are mainly focused on solar and smart grid

This subsection describes M&As in the renewable energy ecosystem and their relationship with the innovation activity of acquiring and acquired firms. Overall, M&As can signal forward-looking developments in a sector by providing insights about the potential of emerging technologies or the expected consolidation of existing ones. This subsection shows that M&A activity involving renewable energy firms has grown significantly over the last two decades and is mainly focused on solar, smart grid and, to a lesser extent, hydrogen. This growth partly reflects the increasing role of M&As to acquire external knowledge, know-how and talents.

Based on the Zephyr database (version 2022), companies associated with the renewable energy sector are identified as firms operating in the “production of renewable energy” (according to the North American Industry Classification System [NAICS] classification) and firms that have filed at least one renewable energy patent during the ten years before the first acquisition date. M&A activity involving renewable energy firms (either as an acquirer or as target) has grown significantly over the last two decades (Figure 3.12). Deals involving at least one firm outside the renewable energy sector (either on the target or the acquirer side) significantly contributed to this growth, driven by financial firms acquiring renewable energy firms²³. Potential reasons behind these cross-sectoral activities could be operational or financial synergies and a potential “green premium” of being associated with renewable energy firms (Yoo, Lee and Heo, 2013^[28]).

Figure 3.12. Value of deals involving at least one firm from the renewable energy sector, by year and by type of deal partners.

(Current USD billions)



Note: Data on patents refer to IP5 patent families. This figure covers the deals in the following categories: “genuine acquisition”, “further acquisition”, “minority stakes” and “joint venture”. The renewable energy sector contains those firms belonging to the production of renewable energy according to the NAICS classification or with at least one renewable energy patent in its patent portfolio. The patent portfolio is constituted as the stock of patents accumulated on a 10-year window before the first acquisition date. The latest observations are for 2021.

Source: OECD calculations based on Zephyr (v.2022), STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats>, and ORBIS®, version 2022.1, Bureau van Dijk, January 2024.

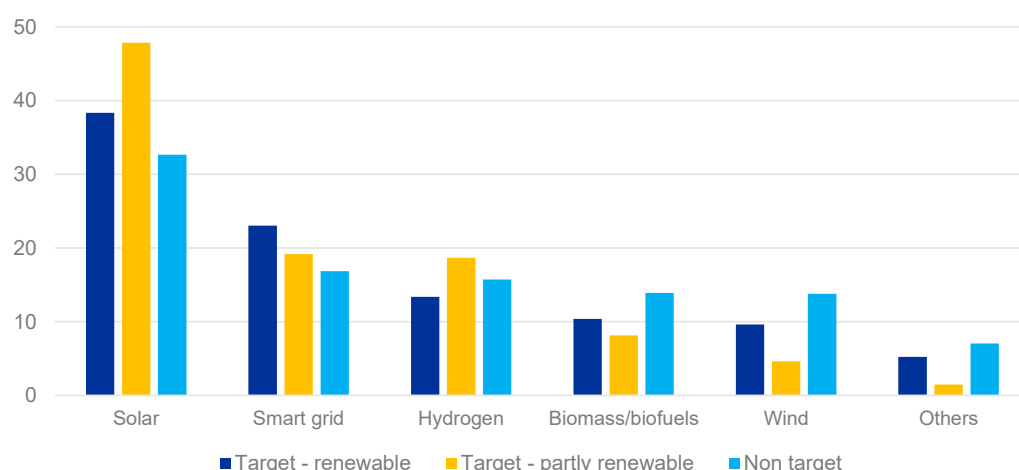
The cross-border M&A activity is driven by firms from the United Kingdom, the United States and Canada on the acquiring side and by firms from the United States, China, and Italy on the target side.

M&A is often cited as a strategy to acquire external knowledge (Cassiman et al., 2005^[29]; Phillips and Zhdanov, 2012^[30]). If this is indeed the case, the patent portfolio of target firms would provide information on the technologies of interest for acquiring firms.

Figure 3.13 shows the distribution of target firms by technology area. Firms are classified into a specific technology area based on the prevalence of that technology within the company's patent portfolio over the 10-year period before the acquisition date. Target firms with a share of renewable patents in total patents over 50% are labelled "renewable", target firms with a share of renewable patents in total patents below 50% are labelled "partly renewable". A benchmark group composed of firms that have at least one renewable energy patent and were not an M&A target is shown for comparison purposes. Figure 3.13 shows that acquiring firms have focused on firms innovating in solar and smart grid technologies with respectively around 40% and 20% of transactions, these shares being larger than the proportion of solar and smart grid companies in the population of non-target companies. On the other hand, there is a lower share of target firms innovating in biomass/biofuels and wind technologies when compared to non-target firms.

Figure 3.13. Distribution of firms by main patent technology, 2017-21

(%)



Note: Data on patents refer to IP5 patent families. This figure covers the deals in the following categories: "genuine acquisition", "further acquisition", "minority stakes" and "joint venture". Each firm is classified into a specific technology category based on the prevalence of that technology within the company's patent portfolio. For target firms, the patents portfolio is constituted as the stock of patents accumulated on a 10-year window before the acquisition date. For non-target firms, the patent portfolio corresponds to the stock constituted in a 10-year window up until 2021. Target firms with renewable patents, but with a share of renewable patents on total patents below 50% are categorised under the target - partly renewable group. Target firms with a share of renewable patents on total patents over 50% are categorised as target- renewable. Geothermal, hydropower, LDES and marine technologies are grouped in the 'Others' category.

Source: OECD calculations based on Zephyr (v.2022), STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats>, and ORBIS®, version 2022.1, Bureau van Dijk, January 2024.

The technological area of acquired firms varies significantly across acquiring economy (Figure A B.4). Firms from most of the top acquiring countries (Canada, the United States, Norway and the Netherlands, among others) disproportionately target firms operating in solar energy, while firms from Australia and Germany mostly acquire firms specialised in smart grid.

4 Skills demand for the development and the deployment of renewable energy

The green and digital transition requires the labour-intensive production and deployment of complex and highly technological goods, prompting concerns about potential labour shortages and skill. In the United States alone, the number of wind energy related online vacancies roughly tripled, and the number of solar energy related jobs almost quintupled between 2013 and 2019 (Curtis and Marinescu, 2023^[31]). Since 2021, online vacancies in the EU for green jobs increased by 12% according to the Future of Work and Inclusive Growth in Europe project at Bruegel (Gotti, Güner and Stefany, 2024^[32]).

Globally, the World Energy Employment 2024 report identified an additional 6.2 million jobs in clean energy sectors between 2019 and 2023, bringing the total to over 36 million jobs by 2023 (International Energy Agency, 2024^[33]). Key sectors contributing to this growth included solar photovoltaics, wind, electric vehicles and battery manufacturing, heat pumps, and critical minerals mining, collectively employing approximately 10 million workers. Construction and manufacturing, which represent over half of energy jobs, have seen substantial growth, adding around 3 million jobs since 2019.

However, employment related to renewable energy will likely be geographically concentrated. In European countries, Ortega et al. (2020^[34]) estimates that employment stemming from the deployment of photovoltaics, onshore wind and offshore wind will be concentrated in Germany, Spain, Italy, the United Kingdom, France and Denmark by 2050, with the highest creation of additional jobs taking place in the United Kingdom, France, Italy, the Netherlands and Spain.

This trend indicates a substantial increase in the need for skilled workers across all sectors in response to the energy transition, regardless of the scenario assumed, i.e. the adoption pace, deployed technologies, or investment scales (Černý et al., 2024^[35]). For instance, investments required to retrain and re- or upskill workers for the production of strategic net-zero technologies up to 2030 are estimated to range between EUR 1.7 billion and EUR 4.1 billion in the EU, creating an additional 198 thousand to 468 thousand jobs in the manufacturing sector (European Commission, 2023^[36]).²⁴ To accommodate the heightened demand for the installation of wind and solar photovoltaics technologies alone, projections suggest an estimated 100 thousand additional jobs across all scenarios, driven primarily by demand in construction and services. However, the construction sector, essential for building power plants or installing solar panels, already faces severe labour shortages (International Energy Agency, 2023^[37]).

Therefore, anticipating labour demand and the associated skills today is key in order to adapt educational curricula and enable a low-carbon transition. Recent evidence from US and UK online vacancies reveals substantial heterogeneity across occupational groups but generally indicates that, compared to more generic jobs, low-carbon²⁵ ones demand cognitive, IT, management, social and technical skill groups more frequently, and a wider variety of these skills (Saussay et al., 2022^[38]; Sato et al., 2023^[39]). Emerging skill shortages as a result of the green transition may hence be amplified considering that IT skills are also integral to the digital transformation. Focusing on green jobs²⁶, skills and tasks associated with recycling,

waste management and renewable energy are among the most sought-after across the EU with an increasing share of online vacancies also mentioning knowledge about environmental protocols over time (Gotti, Güner and Stefany, 2024^[32]). Although all occupations appear to engage in green activities to some extent in the EU, green jobs are concentrated among Professionals, followed by Technicians and Associated Professionals as well as Craft and Related Trades Workers.

With the anticipated expansion of renewable energy in the coming decades, it is crucial to better understand the human capital necessary for producing and maintaining the complex technological goods deployed in the renewable energy sector. This section relies on online vacancy data from specific European countries to explore the demand for workers in this field. It differs from previous research in several respects, in particular by its geographical coverage including European countries, its focus on renewable energy jobs (rather than the broader concept of green jobs) and a breakdown by renewable energy technologies. It aims to distinguish various technology clusters found in renewable energy vacancies, pinpoint the occupations and sectors seeking future workers, and identify the expected skill bundles employers seek in these prospective employees. This exercise sheds light on the composition of green skills in different fields of the renewable energy ecosystem and on the role that complementary non-green skills play.

This section shows that, despite the increased relevance of green technologies, the share of online vacancies linked to renewable technologies remains modest, between 0.6 and 2.1%. In 2022, among the countries under analysis, Spain exhibited the highest share of renewable energy vacancies, followed by Germany, Italy, France, Switzerland and the United States. The scope of renewable energy employment spans across numerous sectors with the majority being in Manufacturing, Power generation, and Professional services, reflecting the complexity of the value chain. Noteworthy, administrative and commercial managers, science and engineering professionals, electrical trade workers and business and administration professionals stand out as the most sought-after occupations. Socio-emotional skills, computer literacy, business acumen and technical expertise form essential components of the human capital necessary to work in the renewable energy ecosystem. Proficiency in repair and sales, as well as language skills in European countries also emerge.

Data and methodology

This analysis relies on online vacancy data provided by Lightcast to identify the demand for jobs and skills across all sectors and occupations related to the renewable energy ecosystem in selected European countries, namely France, Germany, Italy, Spain and Switzerland in 2022. For comparison, online vacancies in the United States are also explored.

Lightcast, formerly Burning Glass Technologies and Emsi Burning Glass, is an employment analytics and labour market information company that scrapes data from firms' websites and online job boards. The company further deduplicates postings and collects structured data from the vacancy text including, if available, job title, occupation, industry of the employer, skills and education requirements, to name just a few. These data have been used in the literature to study labour market trends like the role of artificial intelligence (AI) (Squicciarini and Nachtigall, 2021^[40]; Samek, Squicciarini and Cammeraat, 2021^[41]; Alekseeva et al., 2021^[42]; Acemoglu et al., 2022^[43]; Green and Lamby, 2023^[44]; Borgonovi et al., 2023^[45]), skill requirements (Deming and Kahn, 2018^[46]; Deming and Noray, 2020^[47]; Blair and Deming, 2020^[48]), or the impact of the green transition (Saussay et al., 2022^[38]; Curtis and Marinescu, 2023^[31]; Sato et al., 2023^[39]). While most of the latter tend to focus on the United States due its data quality advantage, this analysis is one of the first to use online job vacancy data sourced from Lightcast to shed light on labour market dynamics focusing on the occupations and skills most demanded in the renewable energy ecosystem across European countries.

Limitations associated to job vacancy data

Although job vacancies provide novel and high-frequency information on current labour demand, notably in terms of skills, they also come with several important limitations that should be kept in mind when interpreting the results of this section.

First, vacancies lack comprehensive information on existing workforce demographics or labour supply. Therefore, rather than using advertised wages, which can be of poor quality or missing (Batra, Michaud and Mongey, 2023^[49]; Lafontaine, Saattvic and Slade, 2023^[50]), to account for tensions in the labour market, this paper compares renewable energy vacancies to overall demand at the occupation level.

Second, several factors (e.g. regulations, type of job, characteristics of jobseekers, and labour supply) may impact companies' job posting and hiring behaviour (Cedefop, 2019^[51]; Curtis and Marinescu, 2023^[31]), possibly under- or overestimating the demand for workers.

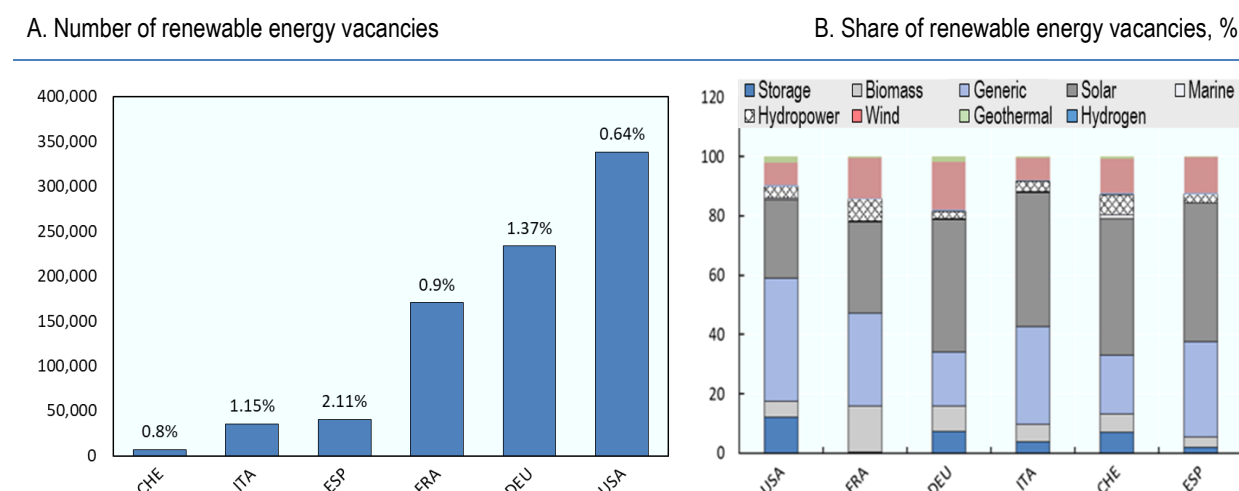
Third, despite employing de-duplication algorithms to address the fact that employers may post on multiple portals, replicated online vacancies may still remain, resulting in inaccurate data representation.

Fourth, online vacancies tend to favour high-skilled professional occupations, potentially skewing the representation of certain jobs (Cammeraat and Squicciarini, 2021^[52]; Napierala and Kvetan, 2022^[53]; Lancaster, Mahoney-Nair and Ratcliff, 2019^[54]; Tsvetkova et al., forthcoming^[55]).

Finally, caution is warranted in interpreting temporal trends as the substantial rise in job postings over time poses challenges in discerning whether this increase results from a genuine surge in demand, or changes in data collection methods. Therefore, the analyses that follow concentrate on shares of identified renewable energy vacancies rather than levels, and focus on the year 2022. A more detailed discussion about the limitations of the data is provided in Annex C.

The share of online vacancies linked to renewable technologies remains modest

The proportion of renewable energy vacancies remains relatively modest. Among the European countries observed in 2022, Panel A in Figure 4.1 shows that Germany exhibits the highest number of renewable energy vacancies, with almost 250 000 online vacancies accounting for 1.4% of all vacancies in Lightcast. This is followed by France, with 170 000 vacancies and a share of 0.9%. Spain and Italy also contribute to the renewable energy job market, with more than 40 000 vacancies in Spain (2.1% of total vacancies) and more than 35 000 vacancies in Italy (1.2% of total vacancies). Switzerland has the lowest proportion of renewable energy vacancies among the European countries observed, with 0.8% of total vacancies (almost 7 000). In comparison, the United States has a smaller share, with just 0.6% of total vacancies, although this percentage reflects almost 350 000 vacancies.

Figure 4.1. Technology contributions to renewable energy vacancies

Note: Panel A displays the number of renewable energy vacancies in 2022 by country, featuring the number of renewable energy vacancies as the share of all vacancies in the Lightcast database atop each bar. Countries are sorted in ascending order by the highest number of renewable energy vacancies in 2022. Results for all countries are produced using an exact matching algorithm. Renewable energy vacancies are assigned to technologies based on the keywords used to identify them. Panel B details the composition of these vacancies in terms of technology groups, employing fractional counting for cases involving multiple technologies. However, if a vacancy has been tagged through both a generic and a specific keyword, only the specific technology is considered. Countries are sorted in ascending order by percentage of vacancies belonging to the solar renewable energy technology.

Source: Own elaboration based on Lightcast data.

These shares are derived from the aggregate demand for vacancies recorded in the Lightcast database, thus constituting a flow measure indicative of current developments in the labour market and subject to the caveats of these data mentioned previously. Comparing this flow measure with a stock one, the latest International Renewable Energy Agency's Annual Review on Renewable Energy and Jobs (2023^[56]) estimates approximately 1.5 million and 1 million direct and indirect jobs in the renewable energy ecosystem in 2022 in the EU and the United States, respectively, with Germany driving the demand in Europe, especially when it comes to wind-related jobs.

A commonality across all countries is the substantial contribution of solar renewable technologies to these vacancies. Panel B of Figure 4.1 illustrates that this specific renewable technology alone constitutes between 26% (in the United States) and 46% (in Spain) of renewable energy vacancies. This can be in part attributed to the mature and widespread adoption of solar technology, as noted earlier, with solar, wind and hydropower collectively representing more than 97% of the renewable electricity installed capacity. Indeed, wind-related vacancies represent more than 16% of all renewable energy vacancies in Germany, while hydropower is particularly common in France and Switzerland (each around 7%). Biomass also attracts many jobs, especially in France (15% of all vacancies) and Germany (9%). In the United States, storage-related vacancies are particularly common – coming after generic renewable and solar jobs. Although the remaining technology groups, namely marine, hydrogen and geothermal collectively represent only about 1% to 3% of renewable energy vacancies in most observed countries, their contributions vary. For instance, geothermal accounts for more than 2% of renewable vacancies in the United States, whereas hydrogen is more prominent in Germany (0.6%), the United States and Switzerland (each 0.5%). Generic renewable energy vacancies that contain in their vacancy text keywords like 'renewable electricity' and 'clean energy' (but lack keywords associated with other technology groups) are also important, especially in the United States, where they account for more than 40% of total renewable vacancies.

Due to the substantial rise in job postings over time, which can be attributed to factors other than increases in demand, such as a change in Lightcast coverage, the evolution over time by country is not further explored. Disentangling the impact of labour market trends from artefacts arising due to expanded data coverage is indeed challenging, particularly in analysing the evolution of renewable energy jobs over time.

Renewable energy jobs span a large number of sectors, reflecting the complexity of the value chain

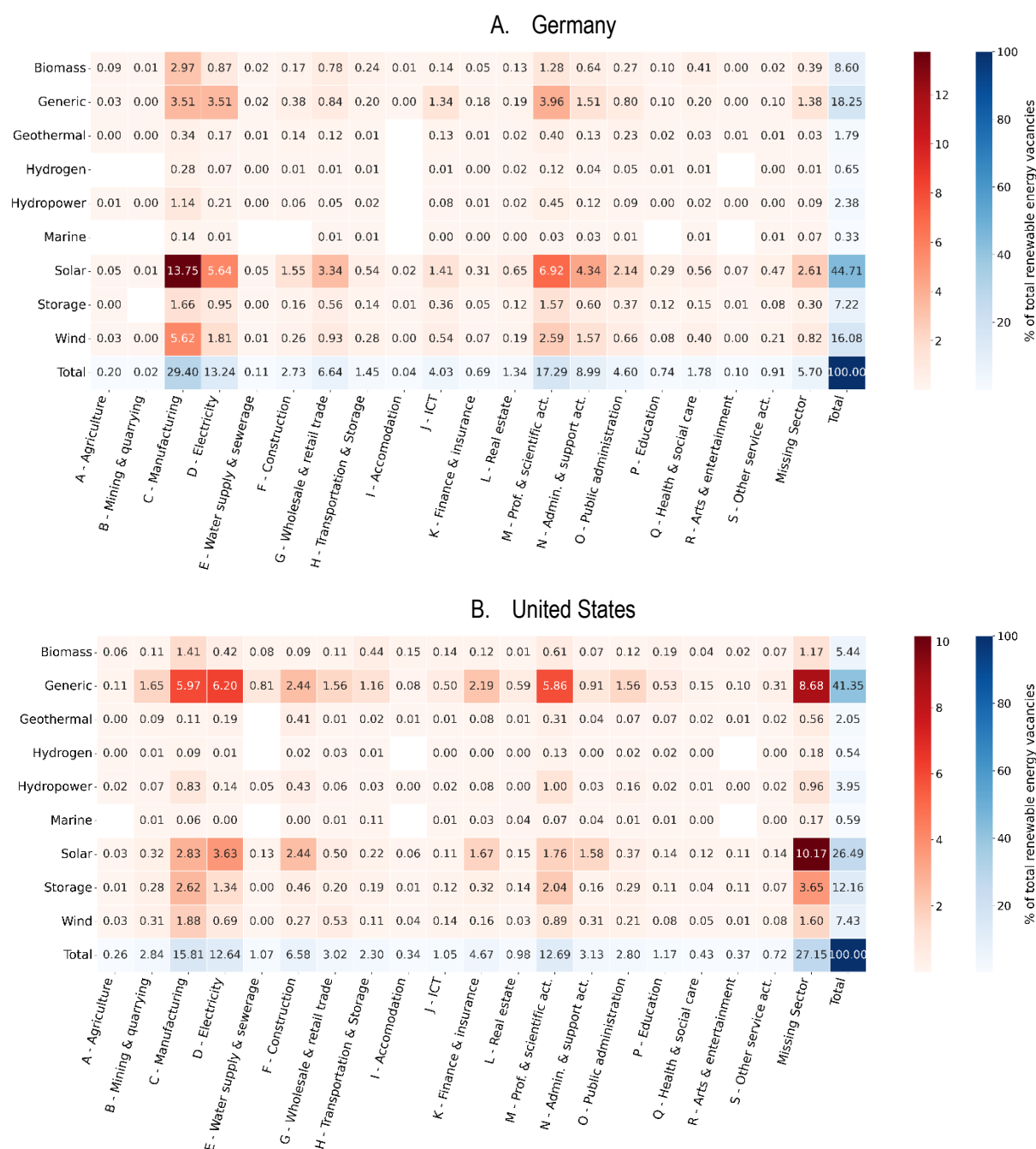
Renewable energy vacancies are prevalent across various industries, irrespective of the observed country or the technology group in focus, with Manufacturing (C), Electricity, gas, steam, and air conditioning supply (D), and Professional, scientific, and technical activities (M) consistently hosting the majority. This is evident from Figure 4.2, which shows the sectoral distributions of the previously identified renewable energy vacancies in Germany (Panel A) and the United States (Panel B) across the different technology groups. Distributions of the remaining countries are presented in Figure A C.2.

Many renewable energy vacancies are also in Administrative and support service activities (N), and Information and communication (J), but concentration varies by country. For instance, renewable energy vacancies in the United States are more dispersed across industries²⁷, whereas a notable concentration in specific sectors is observed in European countries. In Germany, the largest share of renewable energy vacancies, with almost one-third, is evident in Manufacturing (C) while renewable energy vacancies in the remaining European countries under analysis are concentrated in the Electricity sector (D). In Spain and Switzerland, between one-fifth and one-fourth, and in Italy, France and Germany more than 15% of all renewable energy vacancies are also found in Professional, scientific, and technical activities (M).

As was evident from Panel B in Figure 4.1, the majority of renewable energy vacancies are centred around generic renewable and solar technologies. As expected, the aforementioned prominent sectors are also dominated by those two technologies, but some sectors exhibit a wider range of technologies. For instance, renewable energy vacancies in Manufacturing (C) frequently also reference wind and biomass in Germany, and wind in Spain. In France, Administrative and support service activities (N) is also relevant, not only among solar and generic renewables, but also among biomass and wind. Hydropower-related vacancies, which are relatively more prominent in France, as shown by Panel B in Figure 4.1, extend across various sectors in the country, including also Construction (F).

Zooming in at the sectoral (2 digit) level, and taking the example of France, the sectors within Manufacturing (C) that absorb more workforce in the ecosystem are Manufacture of machinery and equipment (C28), Manufacture of computer, electronic and optical products (C26) and Manufacture of basic metals (C24). While C28 and C26 predominantly focus on generic and solar-related technologies, one-fourth of vacancies in C24 are wind-related. Turning to Germany, the picture is markedly different. While C24 and C28 remain important, the leading sector among renewable energy Manufacturing is Manufacture of electrical equipment (C27). This sector alone accounts for 2.5% of all the renewable energy vacancies, with approximately half of them associated with solar technologies.

Figure 4.2. Sectoral distribution of renewable energy vacancies, 2022



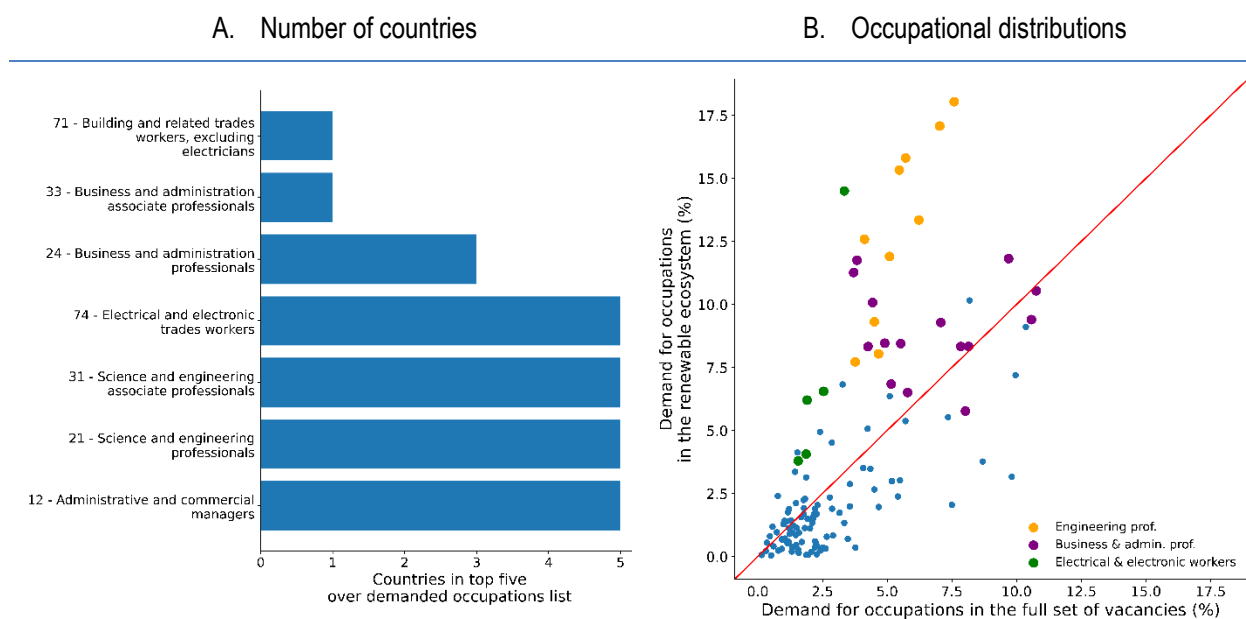
Note: The figure displays the distribution of renewable energy vacancies across sectors and technology groups in 2022 for Germany (Panel A) and the United States (Panel B). The intensity of red corresponds to the share of vacancies, with all red cells collectively summing up to 100%. The intensity of blue corresponds to the sum of shares either across rows or across columns. Industry information is sourced through NAICS in the United States and Statistical Classification of Economic Activities in the European Community (NACE) in Germany and is aggregated into one-digit sections for better comparability. Fractional counting is employed for cases involving multiple technologies. If a vacancy has been tagged through both a generic and a specific keyword, only the specific technology is considered. Technology groups are assigned to renewable energy vacancies based on the keywords used to identify them.

Source: Own elaboration based on Lightcast data.

Engineering and managerial professions are the most sought-after in the renewable energy ecosystem

Data on labour shortages or other labour market tensions, especially in the renewable energy ecosystem, are limited in the absence of reliable wage information. Therefore, the occupational distribution of renewable energy vacancies in each country is here compared to the distribution across all vacancies. Panel A of Figure 4.3 displays the number of countries in which each occupation is in the top five over-demanded occupations (at the 2-digit level) across the five selected European countries under analysis. Panel B plots the share of renewable energy vacancies for each occupation in each country (on the y-axis) against the full set of vacancies in Lightcast (on the x-axis). Over-demand for each occupation is calculated as the difference between the occupational distribution of renewable energy vacancies and the distribution across all vacancies. Administrative and commercial managers (ESCO 12), Science and engineering professionals (ESCO 21), Science and engineering associate professionals (ESCO 31) and Electrical and electronic trades workers (ESCO 74) are among the top 5 over-demanded occupations in all five countries. As shown in Panel B of Figure 4.3, the demand for these engineering professions is between 4.5 and 10 percentage points higher in the renewable ecosystem. Business and administration professionals (ESCO 24) and Business and administration associate professionals (ESCO 33) are also among the top five over-demanded occupations in few of the countries. Building and related trade workers, excluding electricians (ESCO 71) appear in the top five over-demanded occupations in one country.

Figure 4.3. Top five over-demanded occupations in the renewable energy ecosystem



Note: Panel A shows the top five over-demanded occupations along with the number of countries where each occupation ranks within the top five. The top five are identified based on the difference between the occupational distribution of renewable energy vacancies and the distribution across all vacancies, using the 2-digit level European Skills, Competences, Qualifications and Occupations (ESCO) classification of occupations. Panel B features a scatterplot illustrating both distributions. Each point represents a specific occupation in one of the five European countries analysed in 2022, namely France, Germany, Italy, Spain and Switzerland, while the red line is a 45-degree line. 'Engineering professionals' encompass ESCO 21 (Science and engineering professionals) and 31 (Science and engineering associate professionals). 'Business & administrative professionals' contains ESCO 12 (Administrative and commercial managers), 24 (Business and administration professionals) and 33 (Business and administration associate professionals). 'Electrical & electronic workers' represents ESCO 74 (Electrical and electronic trades workers). Between 0.003% (Germany) and 4.5% (Spain) of renewable energy vacancies in Lightcast do not have any occupational information, with the specific percentage varying by country.

Source: Own elaboration based on Lightcast data.

These occupations are generally more demanded in the renewable energy ecosystem possibly because managers are essential for overseeing renewable energy projects, managing resources and coordinating teams, while scientists and engineers have the knowledge of renewable energy technologies and the expertise in designing renewable energy systems (Vona et al., 2018^[57]). Employers in the renewable energy ecosystem also demand operational occupations that install and maintain renewable technologies like Electrical and electronical trade workers. The combination of industry growth, specialised skill requirements, technological advancements, regulatory factors and the resulting over-demand of such occupations could pose future labour market tensions if the supply cannot keep up with the demand.

Main distinct skill bundles: Business acumen, technical expertise and sales

As mentioned previously, Lightcast employs distinct taxonomies for extracting skill and competency information from vacancies in English-speaking and European countries. Notably, the US data relies on a more detailed skill taxonomy compared to the ESCO hierarchy used for European countries. Consequently, the subsequent analyses primarily focus on the United States, supplemented with additional insights drawn from European countries.

As shown in Figure A C.3, skills related to communication, teamwork and collaboration, Microsoft office, especially Excel, problem solving and physical abilities are most frequently demanded in renewable energy vacancies in the United States in 2022, irrespective of the specific technology group the vacancy is associated with. Competencies related to research activities and the running of business or projects, such as budgeting, project management, planning and scheduling, also appear frequently among the top ten skills. These findings resonate well with the existing literature, which shows that green jobs – a superset of renewable energy jobs – are intensive in abstract non-routine analytical and interactive skills, like problem solving, management and team coordination (Consoli et al., 2016^[58]).

Some technology groups demonstrate a more specialised focus, requiring additional expertise in their respective domains. For example, expertise in geothermal heating, cooling and ventilation (HVAC) is highly sought after in jobs related to geothermal technologies. Positions related to wind energy call for knowledge in wind turbine maintenance and wind power systems, while workers in the hydrogen field are expected to possess expertise in fuel cells and hydrogen production systems. Interestingly, employers in the solar energy field not only ask for knowledge in the respective field but also appear to have a strong interest in sales acumen and customer service. Repair skills are common across vacancies related to biomass, geothermal, hydropower and marine technologies.

However, existing literature shows that socio-emotional skills, such as communication and teamwork skills are generally highly valued by employers and hence are not necessarily unique to the human capital needed in the renewable energy ecosystem. When exploring the skills that are mentioned more often in renewable energy vacancies relative to all vacancies in Lightcast, it becomes apparent in Figure 4.4 that creative problem solving, technical expertise, project management and business acumen are required to navigate the complexities of renewable energy projects and initiatives effectively.

Figure 4.4. Over-demanded skills in renewable energy vacancies

Top ten over-demanded skills pooled across European countries, 2022



Note: The word cloud shows the top ten over-demanded skills, where the size of the word is representative of the skill over-demand. They are identified based on the difference between the skill distribution of renewable energy vacancies and the distribution across all vacancies in France, Germany, Italy, Spain and Switzerland in 2022, controlling for the number of skills in each vacancy.

Source: Own elaboration based on Lightcast data.

To better understand the skill bundles that employers expect their future workers to be endowed with, Figure 4.5 and Figure 4.6 illustrate pairwise correlations between skill pairs for the United States and France, respectively. These are some of the countries under analysis with the highest vacancy counts in the renewable energy ecosystem. Skill networks of the remaining European countries are presented in Figure A C.3 and corroborate the findings that follow. More specifically, the network focuses on the top 20 skills identified across all renewable energy vacancies, irrespective of their technology groups, as well as the skills they are most correlated with. Each skill is represented by a blue node, where the size of the node reflects the frequency with which the individual skill appears in renewable energy vacancies in the respective country. The width of the yellow edge between nodes represents the correlation, indicating how frequently two skills are mentioned together rather than separately. However, for the sake of clarity, only most correlated skill pairs and labels of the most frequently demanded skills are displayed. The distance between nodes has no meaningful interpretation in this network.

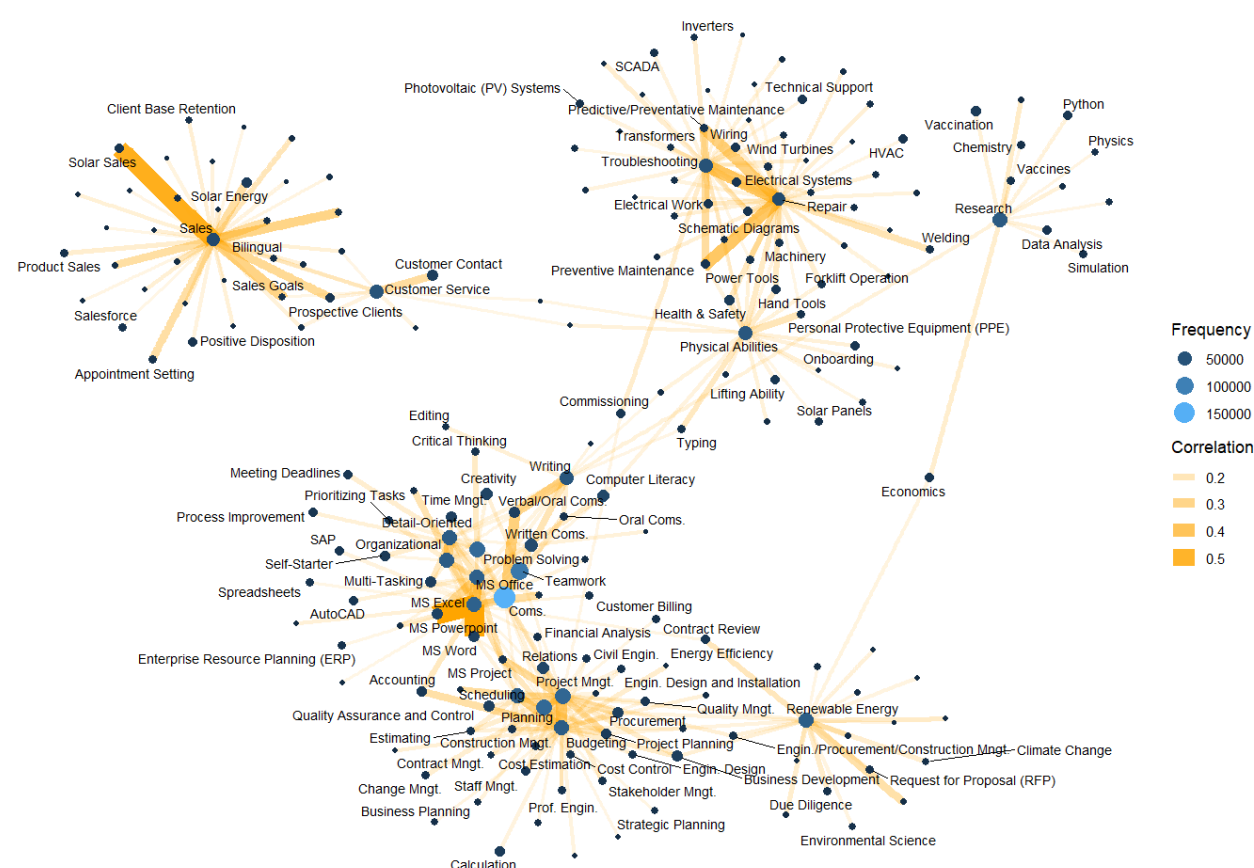
Naturally employers in the renewable energy ecosystem require knowledge about the renewable energy field and technical expertise, such as in engineering or repair and maintenance. However, these competencies are strongly associated with socio-emotional skills (e.g., problem solving, teamwork and communication skills), software proficiency, computer literacy and business acumen (e.g., project management, budgeting/accounting, scheduling and procurement), forming essential components of the human capital necessary to work in the renewable energy ecosystem. Research skills and analytical thinking, especially related to the management and analysis of data, also emerge as significant attributes sought by employers.

It is evident from Figure 4.5 and Figure 4.6 though that also distinct thematic skill bundles beyond this core set of skills emerge, which relate to sales and technical know-how. Sales proficiency is typically linked to solar energy related technologies and requires strong customer service and client retention abilities as well as expertise in marketing and pricing. Technical expertise can encompass a wide range of areas. In the United States preventative maintenance, troubleshooting, and various specialised tasks like welding, wiring, painting, or plumbing are of importance. Such tasks often require working with hand or power tools, and hence are also associated with physical abilities, such as lifting. In France (Figure 4.6) and the

remaining European countries (Figure A C.3) emphasis is rather on engineering principles and upholding quality standards, especially in the production process.

Figure 4.5. Skill network, United States

Correlation of top 20 skills and their pairs in renewable energy vacancies, United States, 2022



Note: The network shows the 20 skills most frequently mentioned in renewable energy vacancies in the United States in 2022 together with skills they are most correlated with. Skills in the United States are categorised using the Lightcast Skills taxonomy. The size of the nodes reflects the frequency with which the individual skill is mentioned in all identified renewable energy vacancies. The width of the edge between nodes shows the correlation between skill pairs. For visual presentation purposes, only edges with correlation exceeding 0.1 are displayed and skill labels for nodes exceeding 6 000 vacancies.

Source: Own elaboration based on Lightcast data.

As skills networks for European countries utilise the ESCO skill taxonomy, Figure 4.5 and Figure 4.6 are not directly comparable. It is nonetheless evident that socio-emotional skills, computer literacy, sales, customer service and project management also feature in France's skill landscape. The network further highlights the importance of creativity (brainstorming ideas, creative thinking, innovation), time management, adaptability to change, independence, proactivity, and leadership, underscoring the demand for individuals with technical and socio-emotional skills in France's renewable energy ecosystem. Particularly noteworthy is also the heightened emphasis on language proficiency in European countries. Foreign and local languages emerge as common requirements, likely highlighting the importance of

5 Policies for the renewable energy ecosystem

Based on several databases covering complementary, although sometimes overlapping, policy instruments, this section describes support to the renewable energy ecosystem. Relying on the OECD Effective Carbon Rates and the Climate Actions and Policies Measurement Framework (CAPMF) databases, the first subsection shows indirect support to renewable energy production, through instruments such as carbon pricing mechanisms and environmental regulation. The second subsection describes support to businesses, both the stock of existing policies, based on the Quantifying Industrial Strategies (QulS) database, and the recent announcements in the COVID recovery package (through the Low-Carbon Technology Support database). The final section zooms in on the support provided for research, development and demonstration, both directly to business, but also through public research institutions.

This section shows that policy support to the renewable energy ecosystem has taken many forms and has substantially increased in recent years. For instance, indirect support such as carbon pricing and bans on the construction of coal power plants has grown driven by European countries. Most of the direct support provided to firms linked to renewable energy focuses on the production of renewable electricity and has been strongly bolstered by the recent COVID recovery packages. Even if it remains small compared to public support to deployment of renewable technologies, research, development and demonstration support (RD&D) to the ecosystem have also grown pushed by emerging technologies such as hydrogen and smart grid.

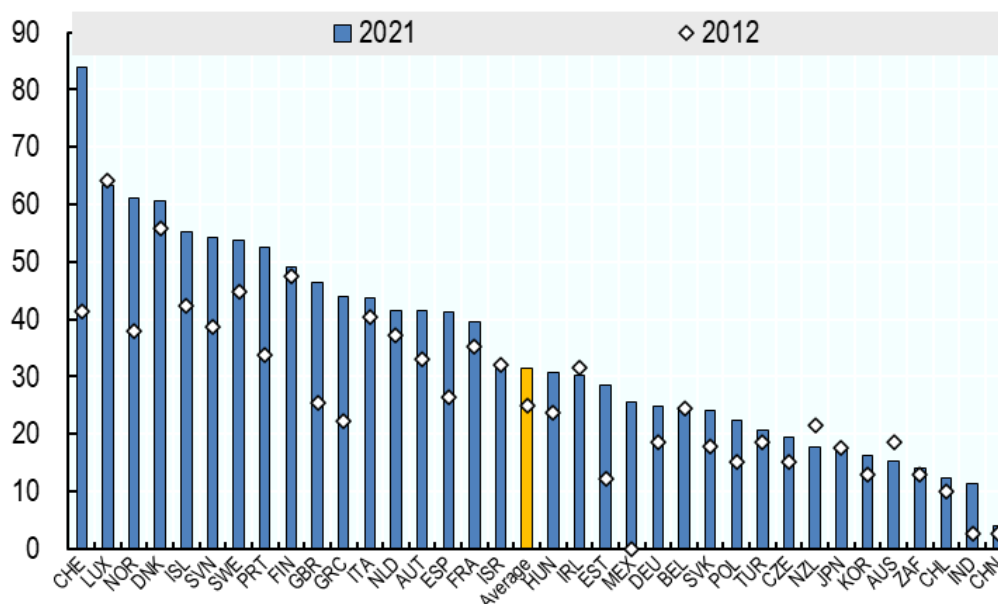
Indirect support to renewable energy production has increased in recent years

Countries have increasingly adopted a number of instruments to reduce CO₂ emissions such as carbon pricing mechanisms and regulatory measures. These policies can be useful in incentivising the production and use of renewable energy, especially if used in combination of well-designed direct support in a broader green industrial strategy.

Countries belonging to the *International Programme for Action on Climate (IPAC)* have boosted their carbon pricing in the last decade, mainly driven by European countries²⁸. Indeed, when considering carbon taxes, fuel excise taxes and tradeable carbon emission permits together, these countries have augmented their share of priced emissions from 25% to 31%, on average (Figure 5.1). This increase is mostly driven by countries such as Switzerland, Mexico, Norway, Greece and the United Kingdom, which incremented their carbon pricing rate by 43, 26, 23, 22 and 21 percentage points (pp), respectively. Moreover, the boost of the carbon pricing rate has also been notable in some EU countries such as Portugal (19 pp), Slovenia (16 pp), Spain (15 pp), Sweden (9 pp) and Austria (8 pp).

Figure 5.1. IPAC countries have increased their carbon pricing in the last decade, mainly driven by European countries

Share of emissions priced through carbon taxes, fuel excise taxes and tradeable carbon emission permits. IPAC countries

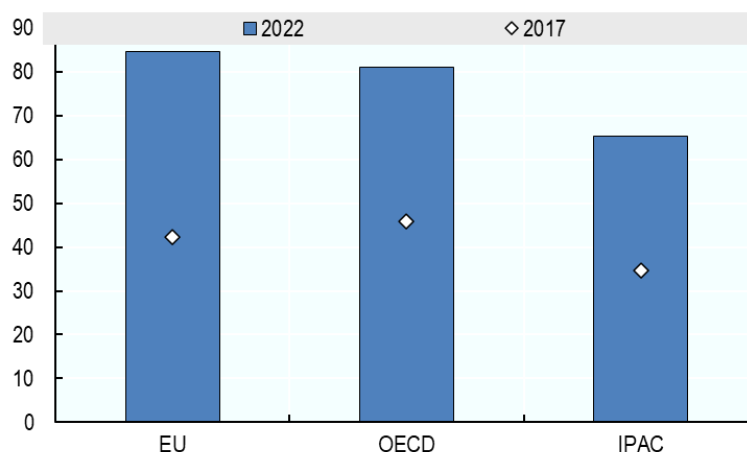


Source: Own elaboration based on the OECD Effective Carbon Rates (ECR) database, <https://stats.oecd.org/?datasetcode=ECR>.

A key regulatory measure with the potential of re-directing the source of energy production from fossil fuels to renewable sources is banning the construction of new coal power plants. This type of regulation has importantly increased in the last years of available data, primarily in the EU and the OECD (Figure 5.2). Concretely, the share of EU countries implementing these types of measures increased from 42% to 85%, while it increased from 46% to 81% in the OECD, and from 35% to 65% in IPAC countries.

Figure 5.2. Regulation measures such as bans on the construction of new coal power plants have importantly increased in recent years

Share of countries implementing bans on the construction of new coal power plants



Source: Own elaboration based on the CAPMF database.

Beyond carbon pricing and bans, there are a large number of other regulatory instruments that can support the deployment of renewable energy and reduce the bottlenecks. For instance, the EU NZIA was enacted in 2023 (Box A D.1) and establishes a series of packages such as regulatory easing, access to information, public procurement, auctions and training. These measures are expected to increase the competitiveness of firms manufacturing renewable energy technologies in the EU and to reduce the EU's strategic dependencies on technologies that are key for the green transition.

Support to businesses in the renewable energy ecosystem mainly focuses on electricity production

An important element of the renewable energy policy mix is direct support for businesses. The QuIS database collects those instruments and its initial version is available for nine OECD Member countries. QuIS covers grants, tax expenditures, as well as financial instruments extended to businesses (Criscuolo, Lalanne and Díaz, 2022^[59]; Criscuolo et al., 2023^[60]). This paper focuses on a subset of the green industrial policy instruments in QuIS, corresponding to direct support to businesses for renewable energy production, renewable energy purchase, R&D and innovation in renewable energy technologies and manufacturing of goods in the renewable energy value chain.

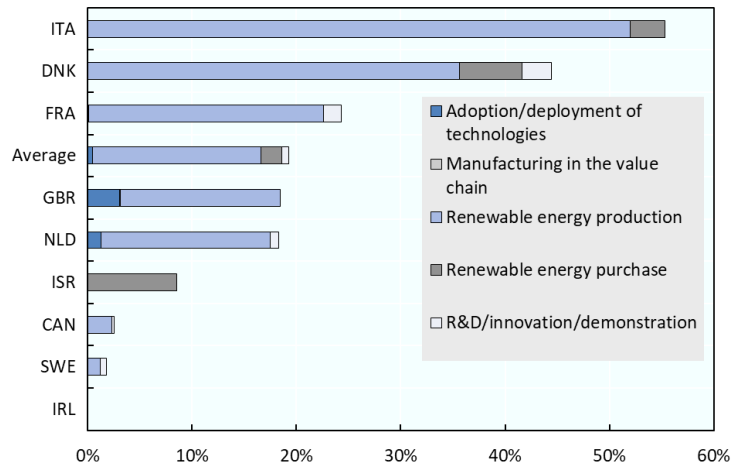
For the countries in the QuIS sample, support to renewable energy for businesses mainly focus on energy production (Figure 5.3), which represents an average of 0.16% of Gross Domestic Product (GDP) over the 2019-2021 period. The other objectives represent a much lower share of direct business support: 0.02% of GDP corresponds to support to renewable energy demand by businesses; 0.007% of GDP to support for R&D, innovation or demonstration; 0.005% of GDP to support for adoption and deployment of renewable energy technologies; and 0.0001% of GDP to support for manufacturing of the renewable energy value chain. The countries of the sample with highest support to renewable energy for businesses are Italy (0.55% of GDP), Denmark (0.44% of GDP) and France (0.24% of GDP), all of them strongly supporting renewable energy production.

Among the countries in the QuIS sample, support to renewable energy represents the majority of green industrial policy expenditure (~57% in 2021 on average, see Figure 5.4), reflecting the priority that countries are giving to renewable energies for the decarbonisation of their economies over other green objectives such as energy efficiency and electrification of transport.

With respect to instrument design, support to renewable energy for businesses is mainly channelled through grants (Figure A D.1), which take many forms. For example, among the diversity of instruments, Italy uses a Feed-in tariff (FIT) scheme to support the production of solar PV ('Conto Energia', 0.18% of GDP in 2021), the United Kingdom uses an auction mechanism (contract for difference) to support renewable energies in general²⁹ (0.01% of GDP in 2021) and Denmark uses a production subsidy for upgrading and purification of biogas ('Tilskud til opgradering eller rensning af biogas', 0.10% of GDP in 2021).

Figure 5.3. Direct support to businesses linked to renewable energy mainly focuses on energy production

Business support to the renewable energy ecosystem by objective (average 2019-2021), % of GDP

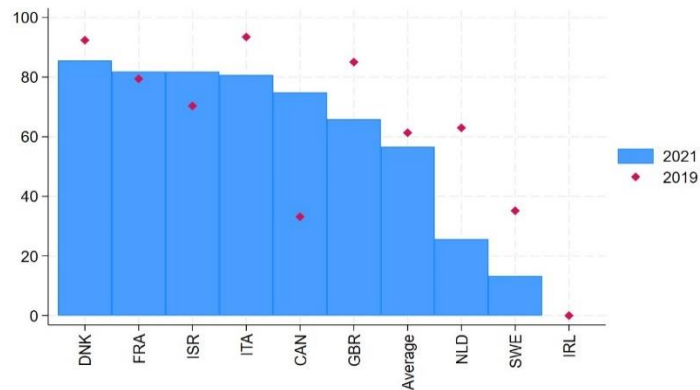


Note: Policies supporting the renewable energy ecosystem are a subset of the instruments labelled with the 'Green' eligibility criteria in QuIS. Specifically, they refer to green policies supporting renewable energy production, renewable energy purchase, adoption of renewable energy technologies, R&D and innovation in renewable energy technologies and manufacturing of goods in the renewable energy value chain.

Source: QuIS database, <http://oe.cd/quis>.

Figure 5.4. Support to renewable energy represents the majority of green industrial policies

Business support to the renewable energy ecosystem over total green business support



Note: Policies supporting the renewable energy ecosystem are a subset of the instruments labelled with the 'Green' eligibility criteria in QuIS. Specifically, they refer to green policies supporting renewable energy production, renewable energy purchase, adoption of renewable energy technologies, R&D and innovation in renewable energy technologies and manufacturing of goods in the renewable energy value chain.

Source: QuIS database, <http://oe.cd/quis>.

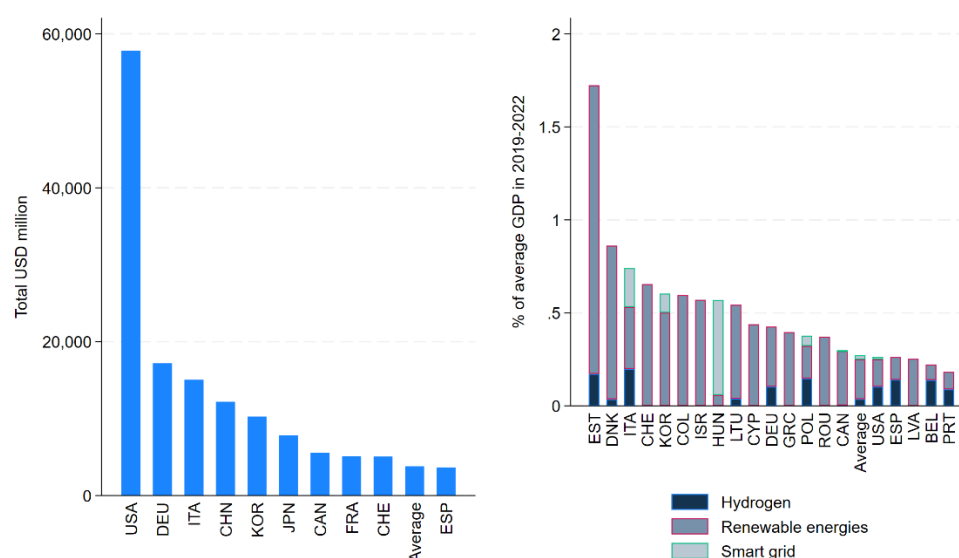
Support to renewable energy has also been an important part of COVID recovery packages

While the QuIS database covers the stock of business support measures for the renewable energy ecosystem, other databases such as the OECD Low Carbon Technology Support database and the IEA Energy Spending Tracker cover the flow of newly announced measures in the period 2019-2022 in the context of the COVID recovery packages. To analyse this flow of new measures, this subsection uses a subsample of the OECD Low Carbon Technology Support database corresponding to direct support to businesses in the renewable energy ecosystem, which is in turn complemented by remaining measures from the IEA Energy Spending Tracker.

Support to renewable energy technologies has been a significant part of COVID recovery packages. Newly announced business support measures for the renewable energy technologies in the period 2019-2022 represented USD 163.8 billion in the countries covered in the OECD Low Carbon Technology Support database and the IEA Energy Spending Tracker (Figure 5.5, left panel). The United States is by far the country that announced the largest amount of support (USD 58 billion) driven by the IRA, followed by Germany, Italy and China (USD 17 billion, USD 15 billion and USD 12 billion, respectively). Besides the IRA, some examples of other measures announced are the grants to smart grid infrastructure announced by Italy (USD 4.2 billion), the Thor Offshore Wind Farm in Denmark (USD 1 billion) and the amended FIT scheme in Estonia to produce renewable energy (USD 532 million).

Figure 5.5. Support to renewable energy has also been a crucial part of COVID recovery packages

COVID recovery packages supporting the renewable energy ecosystem, in total USD million (left-hand side) and as a % of average GDP (right-hand side) in 2019-2022



Note: The top 10 countries are shown in the left-hand side figure (support in absolute terms) and the top 20 countries are shown in the right-hand side figure (support in relative terms). The OECD Low Carbon Technology Support database, which covers newly announced measures from 2019 to 2021, is complemented with the IEA Energy Spending Tracker, which also covers measures announced in 2022. The scope corresponds to business support to firms targeting the renewable energy technologies considered in this project.

Source: OECD Low Carbon Technology Support database complemented with IEA Energy Spending Tracker.

In relative terms, newly announced measures accounted for 0.3% of GDP over 2020-2022³⁰, on average. Countries that announced the most substantial spending for renewables as part of their recovery packages, in relative terms, include Estonia (1.7% of GDP), Denmark (0.9% of GDP), and Italy (0.7% of GDP). In contrast, the United States' support to renewable energy in the recently announced measures is close to the average (~0.3% of GDP).

An interesting feature of the recently announced recovery packages for the renewable energy ecosystem is the importance of policies supporting green hydrogen and smart grid, representing ~28% and ~6% of the total budget announced. This sheds light on the strategic objectives of countries, as they increase their efforts to incentivise the use of renewable energies in hard-to-abate sectors through green hydrogen and in the efficient distribution of renewable energy through smart grids. Countries focusing on green hydrogen include Estonia, Italy, Germany and the United States, among others (Figure 5.5, right panel); while countries announcing significant support to smart grid include Italy, Korea, Hungary and Poland.

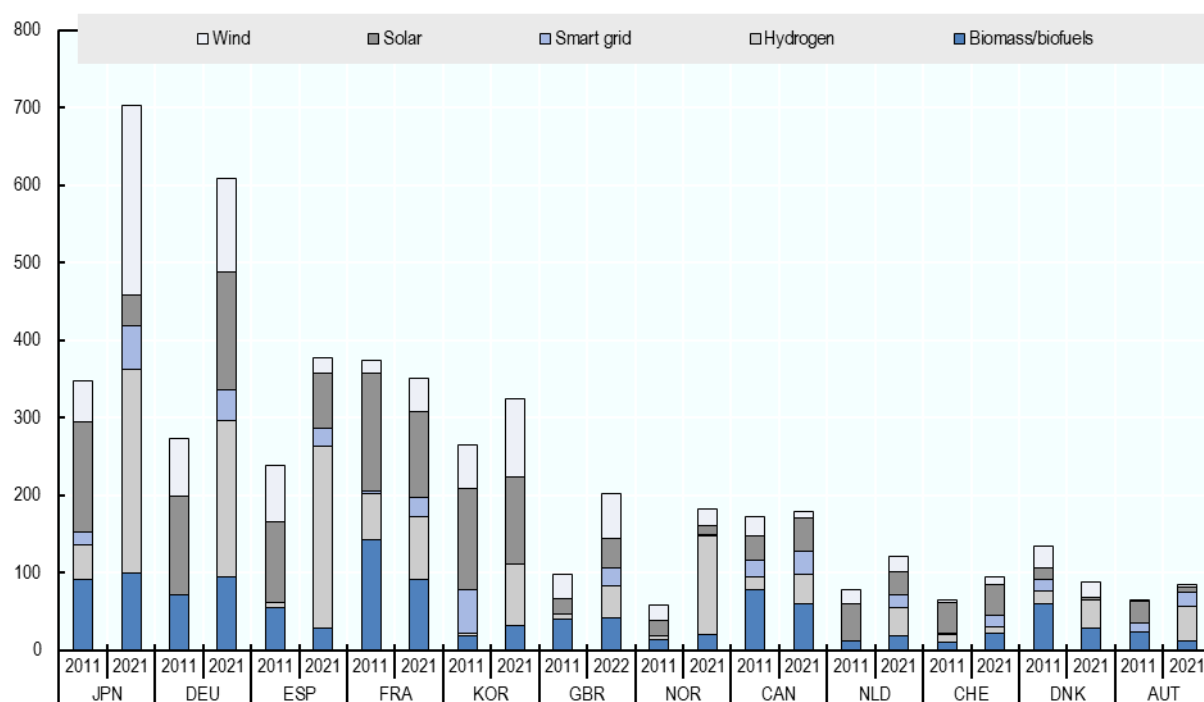
Countries are increasingly supporting new renewable energy technologies through R&D and demonstration schemes

Countries are increasing their R&D and demonstration support (RD&D) to the renewable energy ecosystem, driven by new technologies such as green hydrogen and smart grid (Figure 5.6). Indeed, countries such as Japan and Germany more than doubled their RD&D support to renewable energy technologies; while countries such as Spain, Norway and the United Kingdom also increased it considerably. The common characteristic driving the increase in all these countries is the emergence of RD&D support to hydrogen, which was small in 2011 (in some countries non-existent) but has become significant in 2021. For the top 12 OECD Member countries in terms of public RD&D expenditures in renewables, the share of RD&D support to green hydrogen over total RD&D support for renewable energy technologies increased from an average of 6% to 28%. This increase is most significant in Japan, Germany, Spain and Norway. On the other hand, the share provided to smart grid increased from an average of 5% to 9%, driven by Japan, Germany, Spain and France.

The recent increase in RD&D support is most welcome as evidence indicates that OECD Member countries have so far put a strong emphasis on deployment policies compared with direct R&D support. For example, European countries spent USD 458 million in 2018 to support RD&D in wind and solar power. The subsidies for the deployment of wind and solar technologies that same year represented USD 78 billion - 150 times more than public RD&D expenditures (Figure 5.7). The emphasis is also clearly on deployment in the US and in Japan, but the ratio is smaller.

Figure 5.6. Countries are increasing their R&D and demonstration support towards the ecosystem driven by new technologies such as green hydrogen and smart grid

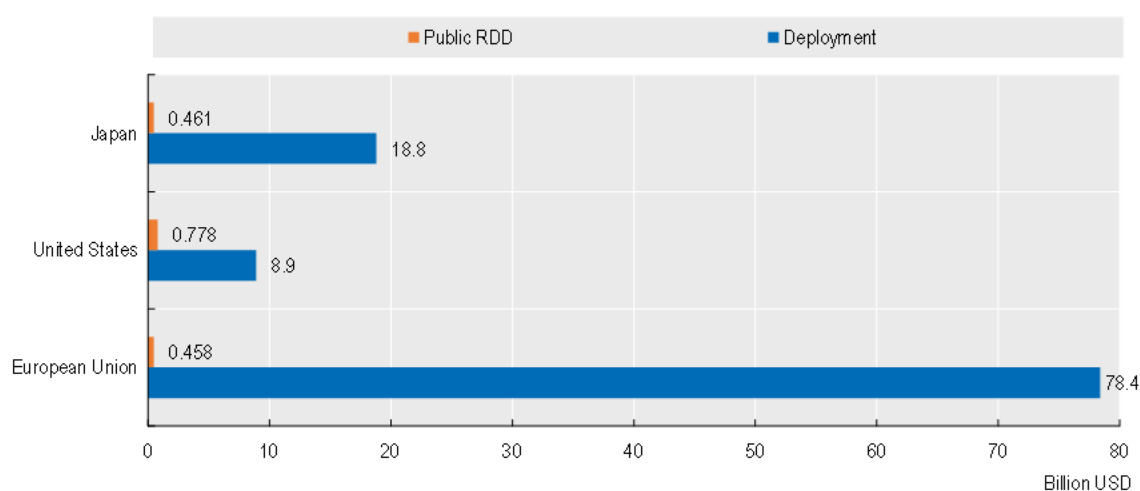
RD&D support to renewable energy technologies in 2021 and 2011 (Sample: top 12 countries providing highest RD&D support in 2021)



Note: The United States is not in the sample since they stop providing RD&D data in 2016. The sample consists of the top 12 countries providing higher RD&D support for renewable energy technologies in 2021. The IEA scope includes publicly financed energy RD&D performed in any establishment or organisation, at home or abroad, such as: (i) public establishments; (ii) any of the other three domestic sectors (business enterprise, private non-profit, higher education); as well as (iii) abroad programmes.

Source: R&D and demonstration support data from the IEA Energy Technology RD&D database: <https://doi.org/10.1787/data-00488-en>.

Figure 5.7. Public RD&D vs deployment support in renewable energy, 2018 (bn USD)



Source: IEA Energy Technology RD&D Budgets database, December 2022; Taylor, Michael (2020), Energy subsidies: Evolution in the global energy transformation to 2050, International Renewable Energy Agency, Abu Dhabi.

Endnotes

¹ A recent forecast of the IEA (2024^[3]), shows that China is expected to reach its national 2030 target for wind and solar PV installations in 2024, while the world as a whole, under existing policies and market conditions, would fail to reach the global target by 2030 (11 000 GW).

² Through measures such as faster permitting procedures, public procurement, demand incentives and training programmes, among others.

³ Through measures such as faster permitting procedures and improved access to finance for strategic projects related to extraction, processing or recycling of critical raw materials.

⁴ Such as two-way contract-for-differences schemes, where EU countries guarantee a stable price to producers and consumers and redirect excess revenue to those with losses.

⁵ Additional research conducted at a more granular level, but on a restricted set of countries, include the SCAN methodology developed by the European Commission, for more details see (Bonnet and Ciani, 2023^[78]).

⁶ P contains all the goods available in the UN Comtrade database.

⁷ Denmark is a global leader in wind power generation. In 2021, 43.8% of the country's electric consumption came from wind energy (Jørgensen, Madsen and Remler, 2022^[76]).

⁸ By March 2023 Mexico was the country with the highest number of installed solar process heat systems, far above Germany, India or China (Weiss and Spörk-Dür, 2023^[75]).

⁹ Greece is a leader in solar thermal technology, which covered 5.1% of energy demand in buildings in 2020, the highest share among IEA member countries. Nonetheless, the share of demand covered by solar thermal has increased only marginally in recent years (IEA, 2023^[77]).

¹⁰ The HHI threshold adopted for bilateral dependencies is higher than the one used for global trade concentration. This comes from the fact that a country's imports tend to be more concentrated than global imports. For instance, the simple median HHI across the commodities listed in **Error! Reference source not found.** and years is 0.4.

¹¹ The methodology used by the European Commission (2023^[12]) - and adopted by Kowalski and Legendre (2023^[13]) - consists in calculating a criticality index for each material based on economic importance and supply risk. The economic importance factor provides insight into the importance of a raw material in terms of final-use applications and value-added contribution to manufacturing. The supply risk factor is based on the concentration of primary supply of raw materials from producing countries. On the other hand, the IEA (2021^[14]) defines critical raw material based on their relative importance in the total demand from producers of renewable energy technologies. Kowalski and Legendre (2023^[13])

include more materials than Bobba et al. (2020^[19]) since they adapted the initial methodology designed for the EU to the OECD Member countries.

¹² It is worth noting that cobalt and lithium, used to manufacture batteries for renewable electricity storage, are not included since those batteries still represent a minor share of global battery capacity additions compared to electric vehicles' batteries (~500 GWh compared to ~6 200 GWh, according to the IEA (2021^[14])), which are not in the scope of the renewable energy ecosystem.

¹³ **Silicon** is used in wafer-based crystalline silicon and thin-film amorphous silicon solar cells; **Gallium and indium** are used in the copper indium gallium selenide thin solar cell (CIGS); **Germanium** is used in multi-junction solar cells (IEA, 2021^[14]); and **Boron** is used in magnets and lubricants for wind turbines (Bobba et al., 2020^[19]) and as dopant for the silicon-based wafers in solar cells.

¹⁴ [US curbs on China's microchip industry could throttle Xi Jinping's tech ambitions | CNN Business.](#)

¹⁵ [Germanium, gallium: China hits back in the chip war with export curbs on key raw materials | CNN Business.](#)

¹⁶ [China exported no germanium, gallium in August after export curbs | Reuters](#)

¹⁷ <https://idealmagnetsolutions.com/knowledge-base/grain-boundary-diffusion/> and <https://hastingstechmetals.com/rare-earths/praseodymium/>.

¹⁸ [What China's Ban on Rare Earths Processing Technology Exports Means \(csis.org\).](#)

¹⁹ **Aluminium** is critical for solar PV and CSP: it is used to produce the frames around solar panels and the reflectors for CSP systems. **Chromium** is critical for Concentrating Solar Power (CSP) and geothermal energy: it is used to produce the material-intensive central tower systems in CSP and the heat resistant steel used in geothermal reservoirs; **Copper** is critical for solar, wind, biomass and hydro energy. It is used as an input for solar cells, cables, wires, grids, generators, and heat exchangers, among others. **Nickel** is critical for geothermal energy technologies. It is used to produce Nickel-stainless steel for pipework and process equipment in geothermal plants due to its resistance to highly corrosive environments. **Niobium** is used as a key element in the steel embodied in wind energy towers and turbines due to its high-strength qualities and its resistance to corrosion. **Zinc** is deemed as critical for wind and solar energy. It is used as a thermal spray to protect off-shore wind energy towers from corrosion and on galvanised steel support structures on solar installations for the same reason.

²⁰ It is worth noting that this only refers to the total value embodied in the goods and not to the criticality of the material.

²¹ [Perovskites, a 'dirt cheap' alternative to silicon, just got a lot more efficient \(rochester.edu\)](#)

²² <https://www.thomasnet.com/insights/what-are-alternatives-to-rare-earth-elements/>.

²³ Financial firms belonging to the NAICS sectors '523910: Miscellaneous Intermediation', '523920 - Portfolio Management' and '525920 - Trusts, Estates, and Agency Accounts'.

²⁴ The lower estimate corresponds to the status quo where the 2022 market shares of EU manufacturing of net-zero technologies are maintained. The higher end is the scenario under the NZIA proposed by the

European Commission where the shares are increased to the indicative technology-specific objectives set in the NZIA and all the demand is met by EU manufacturing.

²⁵ Saussay et al. (2022^[38]) identify low-carbon vacancies in Lightcast based on a list of 250 low-carbon related keywords and natural language processing applied to a pre-existing list of green O*NET tasks and PRODCOM products.

²⁶ Jobs were identified as green if online vacancies provided by Lightcast contained at least one skill related to skill clusters, such as solar, wind, waste, nuclear and clean energy, or climate change to name just a few.

²⁷ It is important to highlight that a significant portion of identified vacancies lacks sectoral information in the data base for the United States, which is a well-known fact (Cammeraat and Squicciarini, 2021^[52]).

²⁸ EU countries belonging to the *IPAC*

²⁹ Contract for difference mechanisms involve long-term contracts, usually with government-owned distributors, that guarantee a price for the electricity supplied by renewable energy firms. The support provided to electricity producers consists in the difference between the 'strike price' (a price for electricity reflecting the cost of investing in a particular low-carbon technology) and the 'reference price' (a measure of the average market price for electricity in the market). If this difference is negative, producers might have to pay the relevant authorities.

³⁰ These numbers are not directly comparable to those from QuIS. While QuIS focuses on realised yearly expenditures, the LCTS numbers correspond to measures announced over the period and whose expenditures usually cover several years. Both are scaled by yearly GDP.

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[28]

Annex A. Setting the scene: Scoping the renewable energy ecosystem and its value chain

Capital goods used for renewable energy

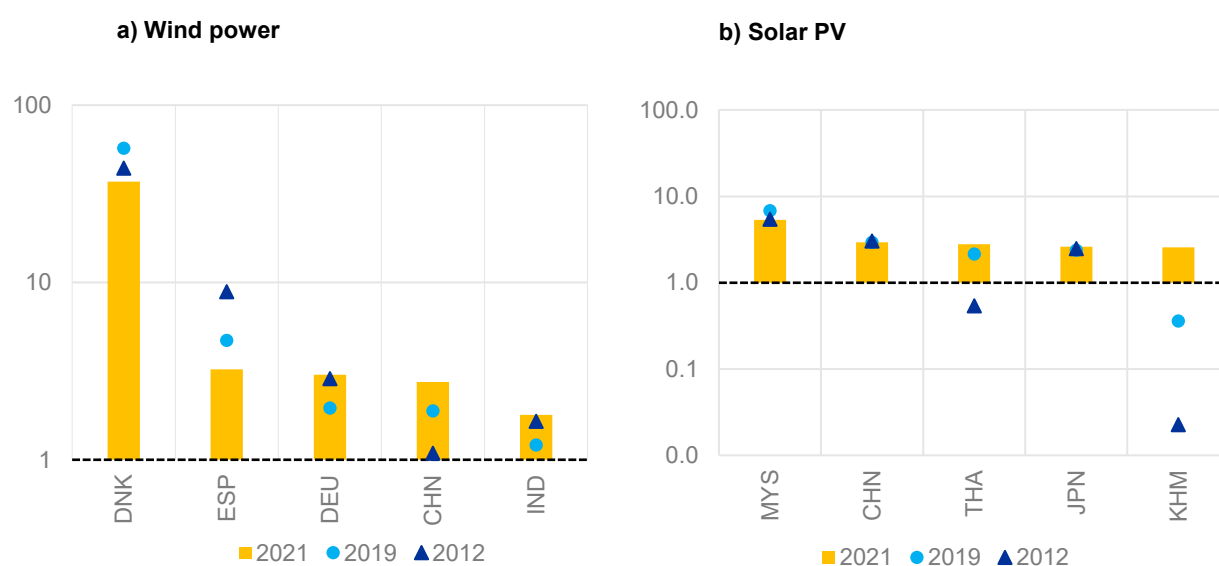
Table A A.1. List of goods used for the production of the different renewable technologies.

HS code	Renewable technology associated	Label
841011	Hydro power	Turbines; hydraulic turbines and water wheels, of a power not exceeding 1000kW
841012	Hydro power	Turbines; hydraulic turbines and water wheels, of a power exceeding 1000kW but not exceeding 10000kW
841013	Hydro power	Turbines; hydraulic turbines and water wheels, of a power exceeding 10000kW
841090	Hydro power	Parts (incl. regulators) of the hydraulic turbines & water wheels of 8410.11–8410.13
841919	Solar thermal	Instantaneous/storage water heaters, non-electric (excl. of 8419.11)
850231	Wind power	Electric generating sets; wind-powered, (excluding those with spark-ignition or compression-ignition internal combustion piston engines)
850511	Wind power (partially)	Magnets; permanent magnets and articles intended to become permanent magnets after magnetisation, of metal
850519	Wind power (partially)	Magnets; permanent magnets and articles intended to become permanent magnets after magnetisation, other than of metal
854140	Solar PV	Photosensitive semiconductor devices, incl. photovoltaic cells whether/not assembled in modules/made up into panels; light emitting diodes

Source: Own elaboration based on 'HS to ISIC to End-use conversion key' of OECD, TiVA / STAN Team - Directorate for Science, Technology, and Innovation (STI).

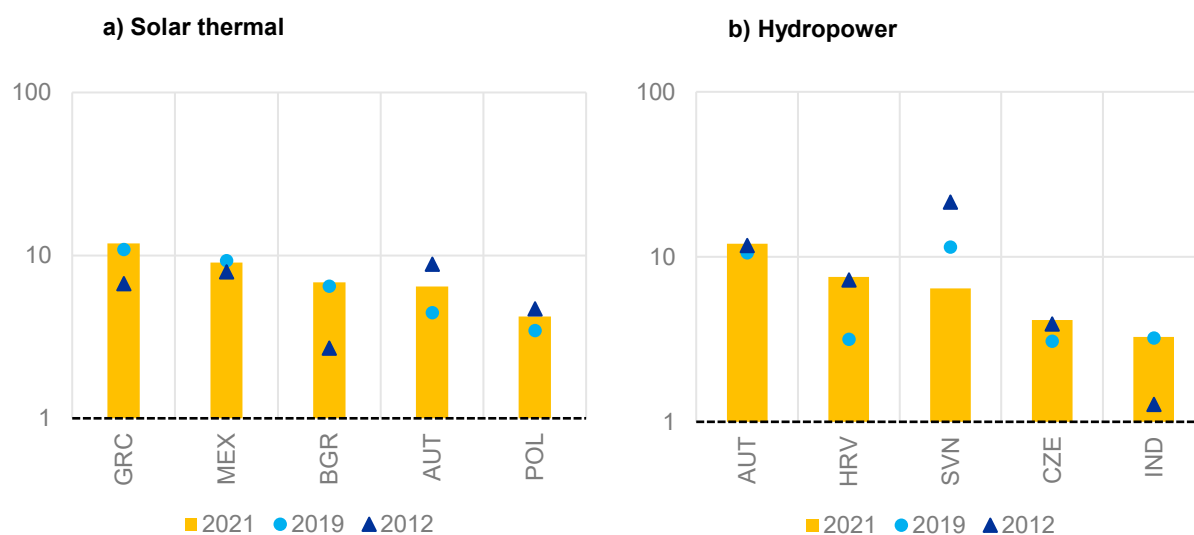
Notes: [1] Magnets are not only used for wind power. The share of neodymium demand related to wind energy is estimated to be, based on the announced pledged scenario, 13% in 2022, according to the IEA Critical Minerals Data Explorer (Critical Minerals Data Explorer – Data Tools - IEA). Neodymium is the main rare earth used in the production of permanent magnets (European Commission, 2023^[12]). Using a 5-year average reference period (2016-2020), results show that 80% of neodymium is used in magnets, which means that around 16% of magnets are used in wind turbines. [2] While the Comtrade HS Nomenclature 2012 version does not allow for the disaggregation of the various components within the code 854140, recent data on extra-EU exports reveals a notable prominence of photosensitive semiconductor devices, incl. photovoltaic cells, over light-emitting diodes. For more details see Figure A A.5 of the annex.

Figure A A.1. Revealed comparative advantage for wind power and solar PV associated goods.
(RCA indicator – logarithmic scale)



Notes: The economies selected are the five economies with the highest RCA score among the largest 20 exporters.
Source: Own calculations based on UN Comtrade database.

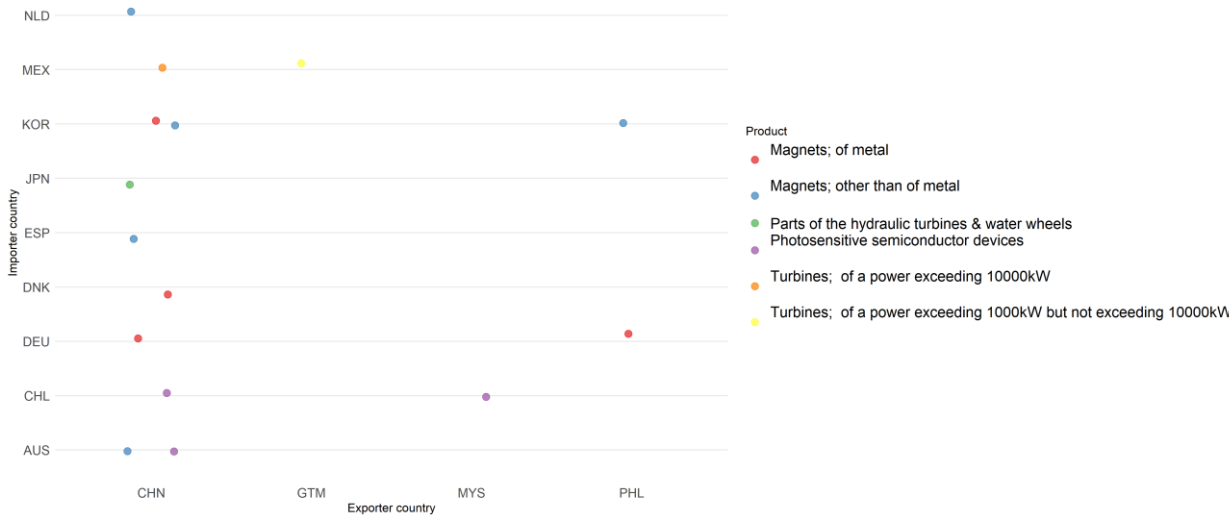
Figure A A.2. Revealed comparative advantage for solar thermal and hydropower associated goods.
(RCA indicator – logarithmic scale)



Notes: The economies selected are the five economies with the highest RCA score among the largest 20 exporters.
Source: Own calculations based on UN Comtrade database.

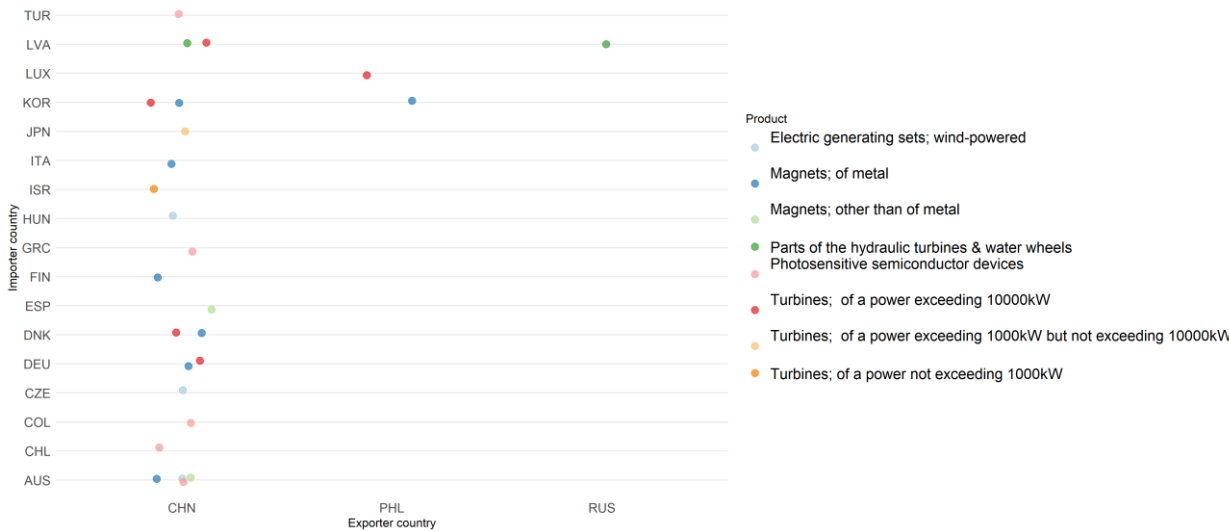
Detail on trade dependencies

Figure A A.3. Number of trade dependencies across countries and goods (2012-2014)



Source: Own elaboration based on UN Comtrade database.

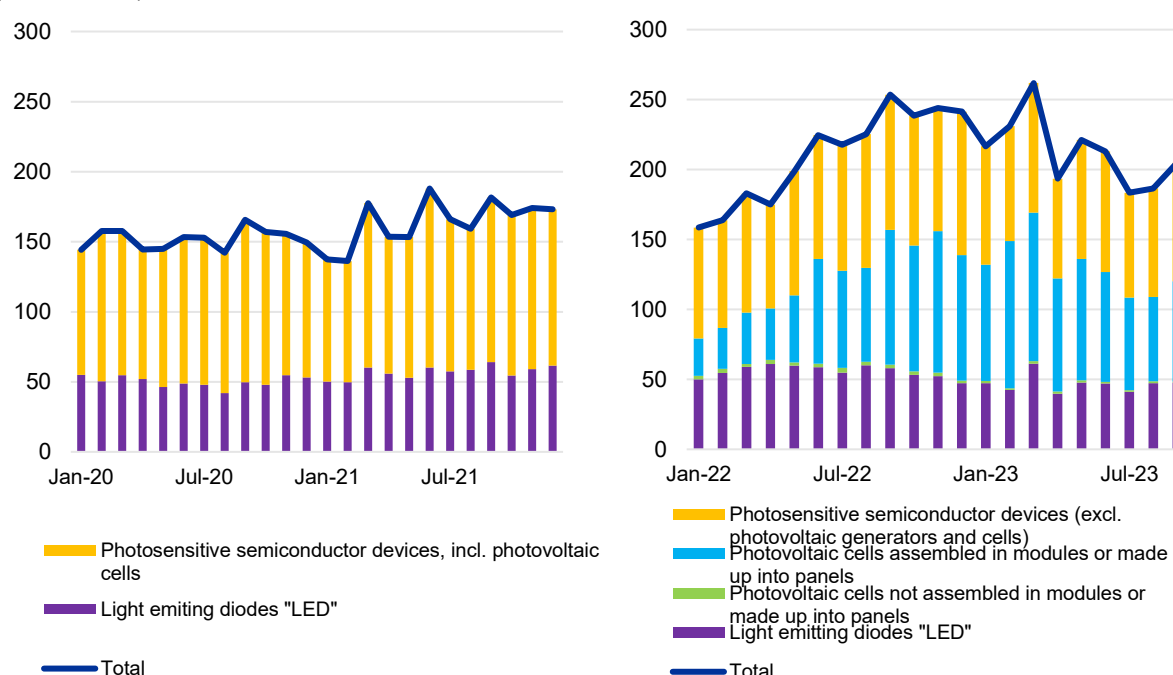
Figure A A.4. Number of trade dependencies across countries and goods (2019-2021)



Source: Own elaboration based on UN Comtrade database.

Figure A A.5. Extra-EU exports for photovoltaic semiconductor devices, photovoltaic cells, and LEDs

(Million euros)



Notes: The old nomenclature, corresponding to the HS 2012 and HS 2017 vintages, defines the code 854140 without further disaggregation. According to the CN8 nomenclature, this code is disaggregated for the EU with the codes 85414010 and 85414090 corresponding to Light-emitting diodes, incl. laser diodes (1999-2021); Light emitting diodes (1988-1994) and Photosensitive semiconductor devices incl. photovoltaic cells, respectively. In the new nomenclature, corresponding to the HS 2022 vintage, the code 854140 code disappears, and four new categories are created; 854141, 854142, 854143 and 854149 corresponding to Light-emitting diodes (LED), Photovoltaic cells not assembled in modules or made up into panels, Photovoltaic cells assembled in modules or made up into panels, and Photosensitive semiconductor devices (excl. photovoltaic generators and cells), respectively. The latest observations are for December 2021 for the left panel and September 2023 for the right panel.

Source: Eurostat

Critical raw materials - Methodology

This subsection describes the export value of the critical raw materials embodied in solar photovoltaic (PV) and wind power technologies, given data availability on material use shares for those technologies. In this context, it is useful to understand the value of the critical materials embodied in these goods. For this purpose, Table A A.2 shows the export value of the critical materials associated with solar PV and wind power by relying on the EU table of material use shares available from the European Commission (2023^[12]) and other sources (methodology below)¹. The first column shows the total exports of the raw materials in the period 2012-2021 (A), the second column displays the share of the raw material used for solar PV and wind power (B), and the third column applies the value-added shares (B) to the total material exports (A) to construct the value of exported raw materials embodied in each renewable energy technology ((A) x (B)).

Table A A.2. Export value of raw materials used in solar photovoltaics and wind power

Material	Total export value of the material 2012-2021, million USD (A)	Share used in the technology (B)	Export value used in the technology 2012-2021, million USD (A) x (B)
<u>Solar photovoltaics</u>			
<i>Aluminium (metal)</i>	622 867	5.83%	36 317
<i>Copper (metal)</i>	803 391	2.67%	21 474
Silicon	137 499	6.00%	8250
Germanium	11 754	7.14%	840
Indium	7 548	7.00%	528
Boron	19 227	2.00%	385
Gallium	7 548	5.00%	377
Nickel	53 872	0.01%	5
<u>Wind power</u>			
<i>Copper (metal)</i>	803 391	1.54%	12 406
<i>Zinc (metal)</i>	105 994	4.88%	5 176
<i>Nickel (metal)</i>	53 872	1.25%	671
Rare earths	4 576	11.67%	534
Boron	19 227	2.00%	385
Manganese	73 443	0.40%	294
Niobium	25 500	0.23%	58

Note: The two technologies analysed in this section were selected based on the availability of data to compute the value-added share of the critical raw material used in the respective technology. The value-added share is time invariant and is calculated based on information of the period with best data availability.

Source: Own elaboration based on UN Comtrade database, EU table of material use shares (European Commission, 2023^[12]), mineral's demand information from IEA data explorer and mineral's supply information from US geological survey.

Value-added share of critical raw materials in the production of renewable energy technologies

The value-added share of a critical raw material r used in the production of a specific renewable energy technology t is time invariant and obtained from three different sources depending on data availability. In order of priority:

1. The value-added share of critical raw materials embodied in renewable energy technologies taken from the 'Material uses shares' table of the European Commission's report 'Study on the Critical Raw Materials for the EU 2023' (2023_[12]). This is the case for boron, gallium, indium, niobium and silicon. The value-added shares available are the 5-year average for the period 2016-2020.
2. IEA data explorer from the Critical Minerals Market Review 2023 (2023_[37]): We used as a proxy the share of total material's demand for the specific technology application (demand measured in kilotons). This was the case for copper, nickel and rare earths (using the data of neodymium for rare earths since is the only rare earth available and is the most important one for permanent magnets used in wind turbines). The availability of data at the necessary detailed level is for 2022.
3. IEA data explorer from the Critical Minerals Market Review 2023 (2023_[37]) and US geological survey (2023_[17]): Since data on total material's demand is missing for some materials in the IEA data explorer (the denominator of the proxy calculated in the previous step), we calculated for those materials: The material's demand for the specific technology application (from the IEA data explorer) over the total supply of the material (from the US geological survey). This is the case for aluminium, chromium, germanium, manganese, niobium and zinc. The availability of data at the necessary detailed level is for 2022.

Import concentration of critical raw materials used for renewable energy technologies

For each country (c) in year (y), the indicator takes the following form for technology t :

$$IMPCON_critical\ raw\ materials_{cyr} = \sum_{r=1}^R \alpha_{cyr} HHI_{cyr} \quad \text{Equation 3}$$

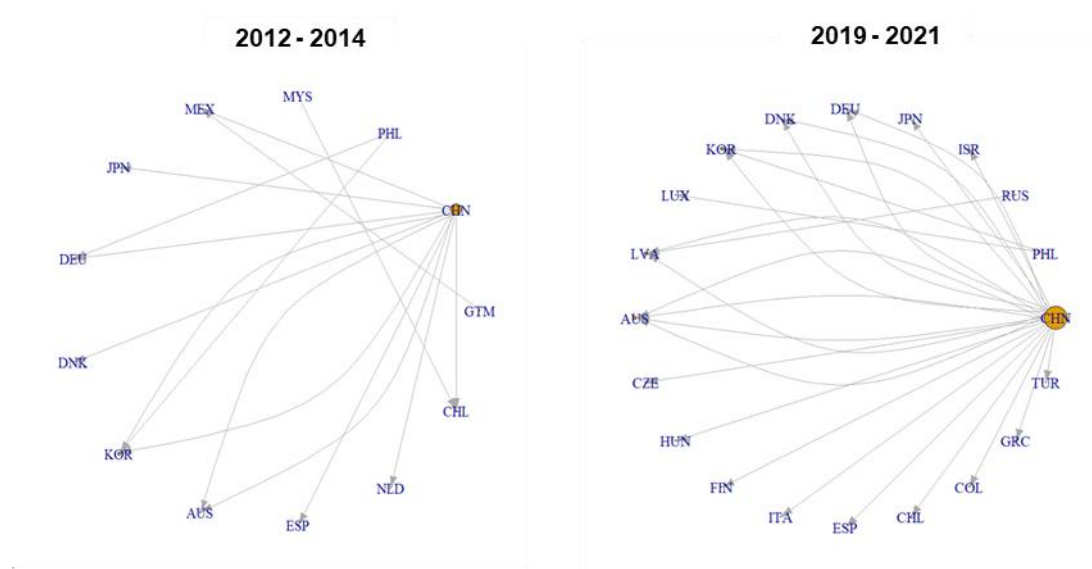
Where:

- r in $\{1, \dots, R\}$ indexes the critical raw materials.
- HHI_{cyr} : HHI of import concentration of each raw material r deemed critical for technology t , imported by country c in year y .
- $\alpha_{cyr} = \frac{\text{Imports of } r \text{ used in the production of technology } t_{cyr}}{\sum_r^R \text{Imports of } r \text{ used in the production of technology } t_{cyr}}$

And:

- $\text{Imports of } r \text{ used in the production of technology } t_{cyr} = \text{VA share of } r \text{ used in the production of technology } t_{rt} * \text{Imports}_{cyr}$
- $\text{VA share of } r \text{ used in the production of technology } t$ is explained in the previous page

Figure A A.6. Bilateral trade dependencies across countries



Notes: Each arrow denotes one dependency at the country-product level.

Source: Own calculations based on UN Comtrade database.

Table A A.3. Critical raw materials for renewable energy technologies

Material	Main origin	Coverage of data	Technology	Share of top 3 producers (2022)	Share of top 3 exporters (2021)	Subs. Index (0 = no substitution possible)	Potential substitutes (substitutes that are also critical materials marked in red)
Semiconductors							
Silicon	Quartzite	Primary and processed	Solar PV	China (68%), Russia (7%) and Brazil (5%)	China (25%), Germany (11%) and Norway (8%)	0.01	Perovskite (composed of calcium titanate) for Perovskite solar cells. Indium tin oxide, Aluminium, Magnesium and Calcium for organic solar cells.
Boron	Colemanite, rasorite, ulexite and tincal	Primary and processed	Wind, Solar PV	Türkiye (56%), Chile (10%) and China (10%)	Türkiye (57%), United States (19%) and Bolivia (5%)	0.01	
Gallium	Bauxite and zinc ores	Production data: Primary Trade data: Processed	Solar PV	China (98%), Russia (1%), Japan (1%).	China (30%), Brazil (13%) and the United States (10%).	0.02	Silicon for the amorphous silicon thin-film solar cell.
Germanium	Sphalerite (zinc ore)	Primary and processed	Solar PV	China (68%), Others (29%) ² and Russia (4%)	China (32%), the United States (10%) and Japan (10%)	0.08	Silicon for the amorphous silicon thin-film solar cell.

Indium	Sphalerite (zinc ore)	Primary and processed	Solar PV	China (59%), Korea (22%) and Japan (7%).	China (30%), Brazil (13%) and the United States (10%)	0.13	Carbon nanotube coatings and graphene have been developed to replace Indium tin oxide (ITO) coatings in solar cells.
Rare earths							
Rare earths	Monazite-(Nd) and kozoite-(Nd)	Production data: Primary Trade data: Processed	Wind	China (70%), the United States (14%) and Australia (6%).	Vietnam (38%), China (27%) and Australia (17%)	Dysprosium: 0.02 Neodymium: 0.03 Praseodymium: 0.04 Terbium: 0.16	Iron and nickel for tetraenite magnets. Iron and nitrogen for the Iron-Nitride super magnet.
Metals							
Manganese		Primary	Wind	South Africa (36%), Gabon (23%) and Australia (17%)	South Africa (43%), Gabon (19%) and Australia (10%)	0.00	No satisfactory substitutes
Chromium	Chromite ores	Primary	CSP, Geothermal, Hydro	South Africa (44%), Türkiye (17%) and Kazakhstan (16%).	South Africa (73%), Türkiye (10%) and Zimbabwe (5%)	0.07	
Niobium	Columbite	Production data: Primary Trade data: Processed	Wind	Brazil (90%), Canada (8%) and the Democratic Republic of Congo (1%).	Processed niobium: Brazil (77%), the Netherlands (10%) and Canada (8%)	0.07	Molybdenum, tantalum, titanium and vanadium for alloying elements in high-strength and corrosion-resistant steel.
Nickel	Pentlandite, millerite, nickeline and galena	Primary	Geothermal, Wind, Solar	Indonesia (48%), Philippines (10%) and Russia (7%).	Philippines (53%), France - New Caledonia (14%) and Russia (6%)	0.12	Titanium and molybdenum for nickel-free alloys used in corrosive environments.
Aluminium	Bauxite	Processed	Solar PV, CSP, Biomass, Hydro	China (58%), India (5.8%) and Russia (5.4%).	Canada (11%), India (11%) and Russia (11%)	0.18	Copper for electrical and heat-exchange applications.
Zinc	Sphalerite	Primary	Wind, Biomass, Hydro	China (32%), Peru (11%) and Australia (10%).	Peru (16%), Australia (14%) and the United States (10%)	0.23	Aluminium for aluminium alloys; and cadmium for cadmium coatings. Both intended to protect against corrosion.
Copper	Copper sulfides	Primary	Solar PV, Wind, Biomass, Hydro	Chile (24%), Peru (10%) and the Democratic Republic of Congo (10%).	Chile (29%), Peru (17%) and Indonesia (5%)	0.30	Aluminium for electrical equipment and power cables. Titanium for heat exchangers.

Source: US. Geological Survey (2023^[17]) for data on production and reserves; and Comtrade for data on exports.

Note: CSP = Concentrated Solar Power. Production and export data include primary and processed forms of the materials. HS codes of each material obtained from the US. Geological Survey (2023^[17]) and reported in the annex. Information on substitutes of critical materials were obtained from the US. Geological Survey (2023^[17]) and other sources, which are reported in the following subsections. The substitution index was elaborated by the European Commission and corresponds to the subtype related to 'economic importance', which is calculated as a weighted average of a cost performance parameter weighted by the share of the raw materials in an end-use application. This index was transformed in this paper so as to be increasing with respect to the level of substitutability (transformed index = 1 – original index) (European Commission, 2017^[18]). For Germanium: Production shares correspond to 2021 and 'Others' includes Belgium, Canada, Germany, Japan and Ukraine; the breakdown among these countries is not available.

Endnotes

¹ This subsection uses export values given the absence of monetary values of raw materials' production.

² For Germanium: Production shares correspond to 2021. 'Others' includes Belgium, Canada, Germany, Japan and Ukraine; the breakdown among these countries is not available.

Annex B. Technological leadership in renewable energy

Box A B.1. Patents as a measure of innovation in renewable energy

Patents provide a detailed source of information on the inventive activity of a country, and are frequently used as a proxy for innovation measures, following a long tradition in the literature Griliches (1990^[61]). Patents are used by companies, by research institutions or by individuals to protect inventions on a given market. Indicators on patents convey information on the output and on the processes of inventive activities, as described in the OECD Patent Statistics Manual (OECD, 2009^[62]).

The patent data derive from the IP data of the OECD Science, Technology and Innovation (STI) Micro-data Lab, that mostly relies on the Worldwide Patent Statistical Database maintained by the EPO, also known as PATSTAT Global, in its Autumn 2023 edition. The PATSTAT database includes information on patents filed worldwide, including their administrative steps, the origin of the invention (with the name and location of inventors or applicants), the technologies that are covered by the invention (e.g., the patent classes, the title, abstract and claims describing the invention), the countries in which the inventions are protected, the citations made to or by other patents, as well as references to the scientific literature. Data are curated, consolidated, and mapped to external sources (such as company-level data – as described in this Annex) to produce a comprehensive set of indicators at the level of countries, companies, and technologies.

Patents in renewable energy technologies are identified using a combination of classes in the Cooperative Patent Classification (CPC) system and keyword searches on the patent abstract, as described in Table A B.1

Patent indicators used throughout the report mainly rely on IP5 patent families that identify the most valuable patents protected on the largest markets, as discussed in Dernis et al. (2015^[63]) and Amoroso et al., (2021^[64]). The value of patents is often associated with the number of patent jurisdictions in which the invention is protected: patentees will only take on the additional costs and delays of extending protection to other countries if they deem it worthwhile in terms of economic returns (OECD, 2009^[62]). IP5 patent families are defined as sets of patent applications protecting the same invention filed in at least two IP offices — with at least one application filed in one of the five largest IP offices worldwide (IP5): the EPO, the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the State Intellectual Property Office of the People's Republic of China (CNIPA) or the USPTO.

The latest trends in renewable energy patents worldwide are shown using patent applications filed under the PCT: because of administrative delays observed during the patent filing process at different IP offices, IP5 patent families are less timely. Noteworthy, PCT patent applications aim to protect patents across multiple jurisdictions and therefore typically include patents of higher economic value than patents protected in a single jurisdiction.

Unless otherwise specified, indicators are reported according to the earliest filing date within the patent family (this date is closest to the date at which the invention took place) and patents are assigned to

the country where the applicant owning the patent is located, using fractional counts (if two companies located in two different countries jointly own a patent, each country gets assigned one-half of a patent). Owing to the scarcity of patent citation records in PATSTAT, citation-based measures only rely on EPO or USPTO patents.

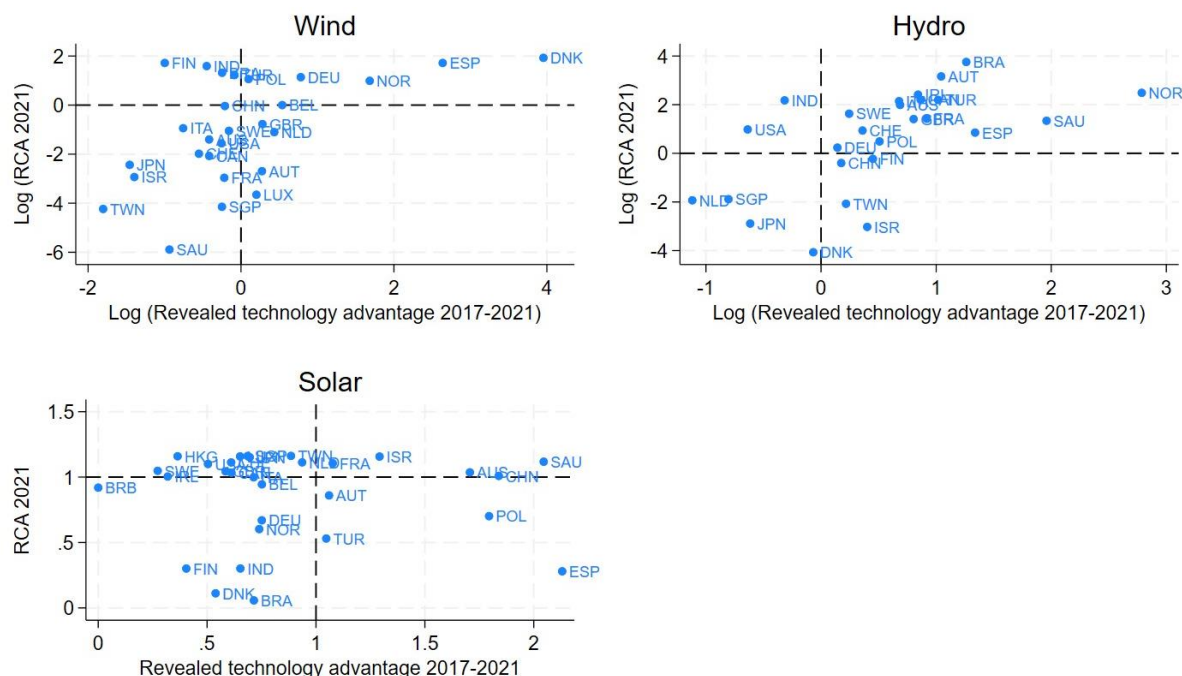
Note: For further details on the CPC, see <https://www.cooperativepatentclassification.org>.

Table A B.1. Search strategies for patents in technologies related to renewable energy

Technology	CPC and/or International Patent Classification (IPC) classes plus keyword(s) search in the English patent abstract when required	Source
Wind	F03D13/25 or F05B2240/95 or B63B2035/446 or (Y02E10/70 to Y02E10/76)	OECD detailed patent search strategies for the identification of selected environment-related technologies (ENV-TECH) (OECD, 2022 ^[65]) (Haščić and Migotto, 2015 ^[66])
Solar	(Y02E10/40 to Y02E10/47) or (Y02E10/50 to Y02E10/56) or Y02E10/60 or B63B2035/4453	
Hydropower	Y02E10/20	
Marine	Y02E10/30 or E02B9/08 or (F03B13/12 to F03B13/26) or B63B2035/4466 or F03G7/05	
Geothermal	Y02E10/10	
Hydrogen	((Y02E60/30 to Y02E60/36) or Y02E60/50) not Y02T*	
Biomass/biofuels	Waste: Y02E50/30 Biofuels: Y02E50/10	OECD own search strategy
Long-duration energy storage	(H01M4/525 and keywords {NCA or Ni-Co-Al or LiNi} and keywords {Al or aluminium or Mg or magnesium}) or (H01M10/054 and keywords {NIB or near((Na, ion), 2) or near((sodium, ion), 2)} and keywords {near((ion, batter*), 2)})) or (H01M8/188 and (keywords(near(redox, flow), 3) and near(redox, batter*), 6)) or keywords(near(flowing, electrolyt*), 3) and near(flowing, batter*), 6)) or ((F03B13/06 or F03B13/10 or F03D9/14 or F04D13/16 or H02J15/003 or E02B7/02 or E02B9/00) and keywords{pump* hydro*}) or ((H02J15/006 or H02J3/28 or F02C6/16 or F03D9/17) and keywords{energy or power} and keywords{stor* or accum*} and keywords{near((compress*, air), 2)})) or ((H02K7/025 or H02J3/30 or H02J15/007 or F03D9/12 or F03G3/08 or F05B2260/42 or F05D2260/42) and keywords{energ* or electric* or power*} and keywords{stor* or accum*} and keywords{flywheel or fly wheel})	
Smart grids	Y02B70/30* or Y02B90/20* or Y02E40/70* or Y04S10/* or Y04S20/* or Y04S40/* or Y04S50/*	(Gregoire-Zawilski and Popp, 2023 ^[67])

Figure A B.1. Revealed technology advantage and relative comparative advantage, by technology

Relative comparative advantage in trade in capital goods used for renewable energy technologies in 2021 plotted against the RTA in those technologies in 2017-2021

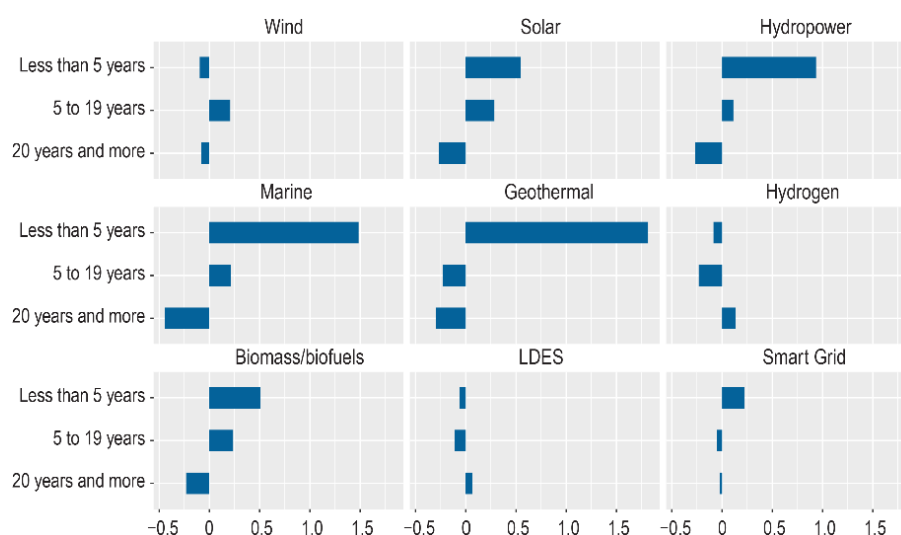


Note: The RTAs and RCAs of wind and hydro power technologies are log-transformed to reduce the dispersion caused by some outliers. Hence, RTA or RCA > 0 means the country has a relative advantage in those technologies.

Source: Own elaboration based on OECD, STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats> and UN Comtrade database.

Figure A B.2. Age of companies developing renewable energy technologies, 2017-21

Revealed technology advantage (RTA) in renewable energy, by age bands

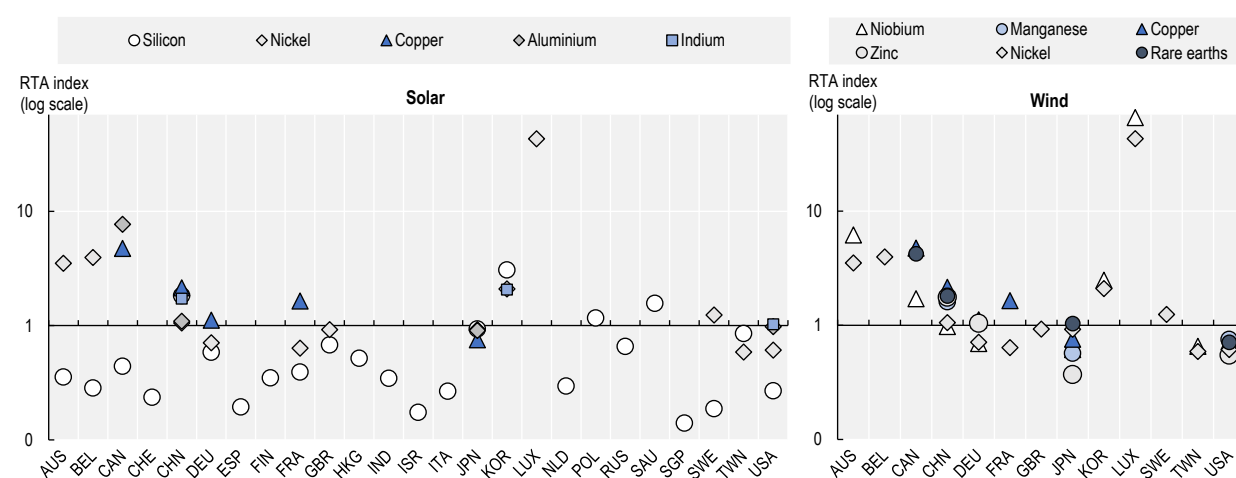


Note: The RTA index in a given technology field is compiled as the share of patents in the technology owned by applicants in a given age band divided by the share of patents owned by applicants in the same age band in all technologies. RTAs are centred around 0 values (by subtracting 1 to the index): RTA indices above 0 reflect a relative technology advantage and RTA indices below 0 indicate a relative disadvantage.

Source: OECD calculations based on STI Micro-data Lab: Intellectual Property Database, OECD Start-ups Database and ORBIS®, version 2022.1, Bureau van Dijk, January 2024.

Figure A B.3. Specialisation in recycling or substitute of critical raw materials, 2017-21

Revealed technology advantage (RTA) of economies (axis in logarithmic scale)

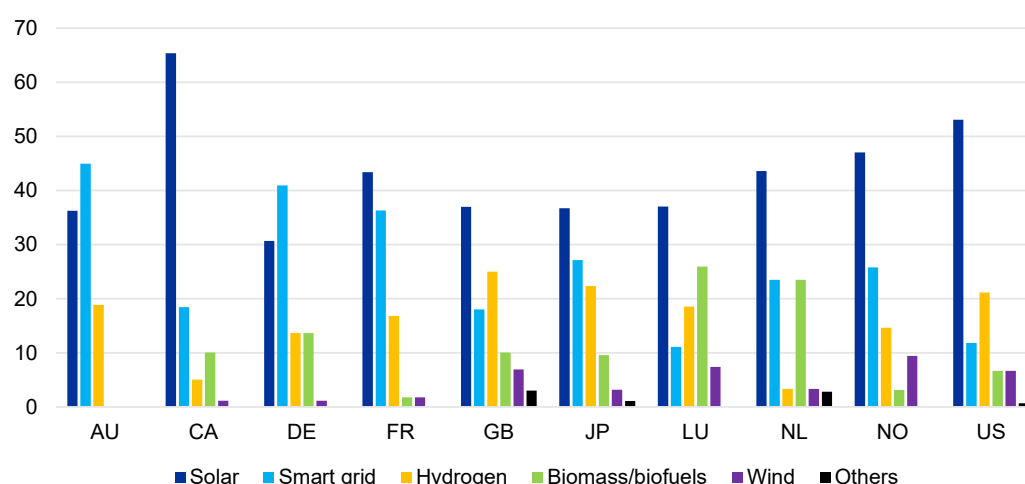


Note: Data refer to IP5 patent families by filing dates. Patents for recycling or substitute for raw materials are identified using the search strategy described in Annex Table A B.2 and Table A B.3. The RTA index in each technology field is compiled as the share of patents in the technology owned by applicants from a given economy divided by the share of patents owned by applicants from that economy in all technologies. Only economies with more than 250 patents and at least four patents in the technology considered are shown. For Luxembourg, the high RTA in inventions related to Nickel & Niobium are due to only one corporate group (ArcelorMittal).

Source: OECD, STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats>, January 2024.

Figure A B.4. Distribution of target firms by main patent technology and by acquiring economy, 2017-2021

(%)

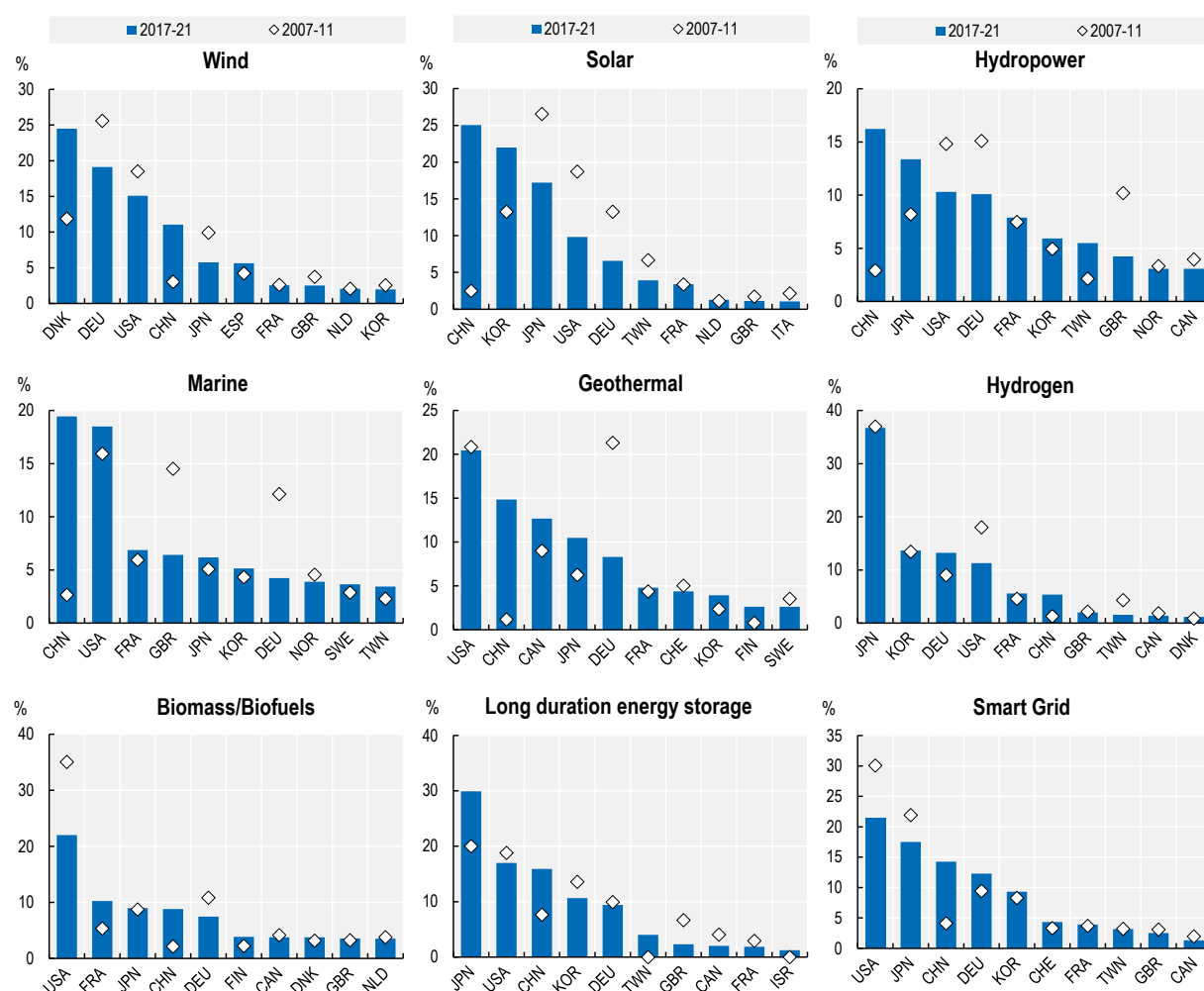


Note: Data refer to IP5 patent families. This figure covers the deals in the following categories: “genuine acquisition”, “further acquisition”, “minority stakes” and “joint venture”. Each firm is classified into a specific technology category based on the prevalence of that technology within the company’s patent portfolio. The patent portfolio is constituted as the stock of patents accumulated on a 10-year window before the acquisition date. The sample is restricted to cross-border deals and economies where firms have acquired at least 20 firms. Geothermal, hydropower, LDES and marine technologies are contained under the others category.

Source: OECD calculations based on Zephyr (v.2022), STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats>, and ORBIS®, version 2022.1, Bureau van Dijk, January 2024.

Figure A B.5. Share of economies in renewable energy technologies, 2007-11 and 2017-21

As a percentage of total patents in renewable energy technologies



Note: Data refer to share of economies in IP5 patent families for selected renewable energy technologies, by applicant location and first filing date, using fractional counts.

Source: OECD, STI Micro-data Lab: Intellectual Property Database, <http://oe.cd/ipstats>, January 2024.

Linking IP data to company-level data

The portfolio of patents for renewable energy technologies was linked to enterprise data, in order to better characterise the firms that developed inventions in the fields. The names of patent applicants, as provided in the patent administrative record, were matched to company names listed in two alternative source data: the ORBIS® database maintained by Bureau van Dijk – a private source dataset that collects business register data - and the OECD Startup database – a database combining information on start-ups from Crunchbase and from Dealroom. The matching exercise was carried out following the key steps described below:

- The name of companies and the names of applicants are separately harmonised, using country-specific dictionaries to deal with legal entities denomination (e.g. “Limited”, “Ltd”, “Aktiengesellschaft”, “Ag”), common names and expressions, as well as phonetic and linguistic

rules, which may affect the way in which company names are written. Such dictionaries help reducing spelling variations of a same company name.

- On the basis of harmonised names on both sides, a series of string-matching algorithms are applied – mainly token-based or string-metric bases, such as: weighted token overlap based on frequency, Levenshtein (1965^[68]) and Jaro-Winkler (Winkler, 1999^[69]) distances. These compare the harmonised names and provides a matching accuracy score for each applicant-company pair. High matching scores are imposed to select matched pairs, to maximise the precision and the recall of the match.
- A post processing stage is manually handled to review the results and improve the recall rate, by identifying false negative matches directly.

Such matching exercise may not systematically lead to unique pairs of names, as in many cases a patenting firm are linked to several entries in ORBIS database (e.g. multiple entries for the same name due to the existence of branches/affiliates featuring the same company name). As a consequence, further filtering and consolidation are applied: the information in company-level data – such as the company's address, its ownership structure, or the availability of financial information – are used to disambiguate records.

Noteworthy, matching rates vary depending on the country. This is due to the way in which names are provided or translated on patent documents, and also to availability of data in the company-level data, for instance. Only countries that feature a high proportion of matched patents were covered in the report.

Table A B.2. Search strategies for patents for recycling or substitution of critical raw materials: semiconductors and rare earths

Cooperative patent classes and/or keywords search in English language patent abstracts

Critical raw materials	Recycle	Substitute
Semiconductors		
Silicon	keywords{near(<i>silicon*</i> , (<i>recycl*</i> or <i>recover*</i>)),4)} or (keywords{ <i>silicon*</i> } and (C22B11/02 or C22B11/04 or (Y02W30/50 to Y02W30/80))) or (keywords{ <i>recycl*</i> or <i>recover*</i> } and C01B33/*)	[keywords{ <i>perovskite</i> or near((<i>calcium</i> , <i>titane</i>), 0) or near((<i>indium</i> , <i>oxide</i>),0) or near((<i>tin</i> , <i>oxide</i>),0)} and patent classified as <u>Solar</u>] or [Y02E10/542 or Y02E10/549 or H10K30/40 or H10K85/50 or C01P2002/34]
Boron	keywords{near(<i>boron</i> , (<i>recycl*</i> or <i>recover*</i>)),4)} or (keywords{ <i>boron</i> } and (C22B11/02 or C22B11/04 or (Y02W30/50 to Y02W30/80))) or (keywords{ <i>recycl*</i> or <i>recover*</i> } and C01B35/*)	
Gallium	keywords{near(<i>gallium</i> , (<i>recycl*</i> or <i>recover*</i>)),4)} or (keywords{ <i>gallium</i> } and (C22B11/02 or C22B11/04 or (Y02W30/50 to Y02W30/80))) or (keywords{(<i>recycl*</i> or <i>recover*</i>) and <i>gallium</i> } and C22B58/*)	
Indium	keywords{near(<i>indium</i> , (<i>recycl*</i> or <i>recover*</i>)),4)} or (keywords{ <i>indium</i> } and (C22B11/02 or C22B11/04 or (Y02W30/50 to Y02W30/80))) or (keywords{(<i>recycl*</i> or <i>recover*</i>) and <i>indium</i> } and C22B58/*)	keywords{near((<i>carbon</i> , <i>nanotub*</i> , <i>coating*</i>), 0) or near((<i>graphene</i> , <i>coating*</i>),0)} and patent classified as <u>Solar</u>
Germanium	keywords{near(<i>germanium</i> , (<i>recycl*</i> or <i>recover*</i>)),4)} or (keywords{ <i>germanium</i> } and (C22B11/02 or C22B11/04 or (Y02W30/50 to Y02W30/80))) or (keywords{ <i>recycl*</i> or <i>recover*</i> } and C22B41/*)	keywords{near((<i>amorphous</i> , <i>silicon</i> , <i>thin-film</i> , <i>solar*</i>), 1)} and patent classified as <u>Solar</u>
Rare earths	keywords{near((<i>rare earth*</i> or <i>monazite</i> or <i>kozoite</i>), (<i>recycl*</i> or <i>recover*</i>)),4)} or (keywords{ <i>rare earth*</i> or <i>monazite</i> or <i>kozoite</i> } and (C22B11/02 or C22B11/04 or (Y02W30/50 to Y02W30/80))) or (keywords{ <i>recycl*</i> or <i>recover*</i> } and C22B59/*)	keywords{near((<i>iron</i> , <i>nickel</i>), 2) or near((<i>iron</i> , <i>nitrogen</i>), 2)} and keywords{ <i>magnet</i> or <i>magnets</i> }
Noble materials	keywords{((<i>platinum</i> or <i>gold</i> or <i>silver</i> or <i>ruthenium</i> or <i>iridium</i> or <i>rhodium</i> or <i>palladium</i> or <i>rhenium</i> or <i>osmium</i>) and (<i>recycle*</i> or <i>recover*</i>)),4)} or (keywords{ <i>platinum</i> or <i>gold</i> or <i>silver</i> or <i>ruthenium</i> or <i>iridium</i> or <i>rhodium</i> or <i>palladium</i> or <i>rhenium</i> or <i>osmium</i> } and C22B11* and keywords{ <i>recycl*</i> or <i>recover*</i> })	[(C25B11/045 or C25B11/046 C25B11/049 or C25B11/075 or C25B11/089 or C25B11/091) and not (C25B11/081 or C25B11/093 or C25B11/097) and not keywords{ <i>platinum</i> or <i>gold</i> or <i>silver</i> or <i>ruthenium</i> or <i>iridium</i> or <i>rhodium</i> or <i>palladium</i> or <i>rhenium</i> }] or [(C25B11/047 or ((C25B11/04 or C25B11/075 or C25B11/091 or C25B11/077 or C25B11/079) and keywords{ <i>cerami*</i> or <i>carbide*</i> or <i>nitride*</i> }) and not keywords{ <i>platinum</i> or <i>gold</i> or <i>silver</i> or <i>ruthenium</i> or <i>iridium</i> or <i>rhodium</i> or <i>palladium</i> or <i>rhenium</i> }] or [C25B11/048 or C25B11/085 or C25B11/095] or [((C25B11/043 or C25B11/075) and keywords{BDD or <i>diamond*</i> or <i>diamant*</i> }) or C25B11/083]
Batteries	Y02W30/84	[H01M4/525 and keywords{near((<i>ni</i> , <i>rich</i> , <i>ncm</i>), 0) or NCM811 or NMC811 or near((<i>LiNiO</i> , <i>8CoO</i> , <i>1MnO</i> , <i>1O2</i>), 0)}] Or [H01M4/525 and keywords{ <i>ni</i> or <i>co</i> or <i>Al</i> or <i>NCA</i> or <i>LiNi</i> or <i>NiCo</i> } and keywords{near((<i>Al</i> , <i>aluminium</i>), 0) or near((<i>Mg</i> , <i>magnesium</i>), 0)}] Or [H01M10/054 and keywords{ <i>NiB</i> or near((<i>Na</i> , <i>ion</i>),1) or near((<i>sodium</i> , <i>ion</i>),1)} and keywords{near((<i>ion</i> , <i>batter*</i>), 1)}]

Note: Noble materials and batteries substitutes were identified based on EPO search strategies <https://www.epo.org/en/news-events/in-focus/clean-energy/energy-storage> and <https://www.epo.org/en/news-events/in-focus/clean-energy/renewable-energy>

Table A B.3. Search strategies for patents for recycling or substitution of critical raw materials: metals, noble materials, batteries

Cooperative patent classes and/or keywords search in English language patent abstracts

Critical raw materials	Recycle	Substitute
Metals		
Manganese	keywords{near(<i>manganese</i> , (<i>recycl*</i> or <i>recover*</i>)),4)} or (keywords{ <i>manganese</i> } and (C22B11/02 or C22B11/04 or (Y02W30/50 to Y02W30/80))) or (keywords{ <i>recycl*</i> or <i>recover*</i> } and C22B47/*)	
Chromium	keywords{near(<i>chromium</i> , (<i>recycl*</i> or <i>recover*</i>)),4)} or (keywords{ <i>chromium</i> } and (C22B11/02 or C22B11/04 or (Y02W30/50 to Y02W30/80)))	
Niobium	keywords{near(<i>niobium</i> , (<i>recycl*</i> or <i>recover*</i>)),4)} or (keywords{ <i>niobium</i> } and (C22B11/02 or C22B11/04 or (Y02W30/50 to Y02W30/80))) or (keywords{ <i>recycl*</i> or <i>recover*</i> } and C22B34/2*)	keywords{(<i>molybdenum</i> or <i>tantalum</i> or <i>titanium</i> or <i>vanadium</i>) and <i>steel</i> }
Nickel	keywords{near(<i>nickel</i> or <i>pentlandite</i> or <i>millerite</i> or <i>nickeling</i> or <i>galena</i>), (<i>recycl*</i> or <i>recover*</i>)),4)} or keywords{ <i>nickel</i> or <i>pentlandite</i> or <i>millerite</i> or <i>nickeling</i> or <i>galena</i> } and (C22B11/02 or C22B11/04 or (Y02W30/50 to Y02W30/80))) or (keywords{ <i>recycl*</i> or <i>recover*</i> } and C22B23/*)	keywords{(<i>molybdenum</i> or <i>tantalum</i> or <i>titanium</i> or <i>vanadium</i>) and <i>steel</i> }
Aluminium	keywords{near(<i>aluminium</i> , (<i>recycl*</i> or <i>recover*</i>)),4)} or (keywords{ <i>aluminium</i> } and (C22B11/02 or C22B11/04 or (Y02W30/50 to Y02W30/80))) or (keywords{ <i>recycl*</i> or <i>recover*</i> } and C22B21/*)	
Zinc	(keywords{near((<i>zinc</i> or <i>sphalerite</i>) and (<i>recycle*</i> or <i>recover*</i>)),4)} and keywords{ <i>alloy</i> or <i>coating*</i> }) or (keywords{ <i>zinc</i> or <i>sphalerite</i> } and (C22B11/02 or C22B11/04 or (Y02W30/50 to Y02W30/80))) or (keywords{ <i>recycl*</i> or <i>recover*</i> } and (C22B17/* or C22B19/*))	keywords{near((<i>aluminium</i> , <i>alloy*</i>), 1) or near((<i>cadmium</i> , <i>coating*</i>), 2)} and keywords{ <i>corrosion</i> }
Copper	(keywords{ <i>copper</i> and (<i>recycle*</i> or <i>recover*</i>)),4)} and keywords{ <i>electric*</i> or <i>power cable*</i> or <i>heat exchang*</i> }) or (keywords{ <i>copper</i> and (<i>electric*</i> or <i>power cable*</i> or <i>heat exchang*</i> }) and (C22B11/02 or C22B11/04 or (Y02W30/50 to Y02W30/80))) or (keywords{ <i>recycl*</i> or <i>recover*</i> } and C22B15/*)	keywords{near((<i>aluminium</i> , <i>power</i> , <i>cable*</i>), 4) or near((<i>aluminium</i> , <i>electric</i>), 4) or near((<i>titanium</i> , <i>heat</i> , <i>exchange*</i>), 4)}

Annex C. Skills demand for the development and the deployment of renewable energy

Identifying vacancies related to the renewable energy ecosystem

The keywords shown in Table A C.1 were selected based on technologies and other related terms identified through a number of sources. Firstly, terms extracted from patents allocated to renewable energy technologies on the basis of the search strategy presented in Box A B.1. and presented in Section 3 were used. Additional keywords were then incorporated through an iterative process, utilising relevant terms found in already identified renewable energy vacancies. Secondly, keywords for the identification of green start-ups in the renewable energy sector from the OECD Start-ups Database were leveraged to further enrich the list. Finally, the keyword list was completed by reviewing the International Renewable Energy Agency's Annual Review 2022 and 2023 on Renewable Energy and Jobs (IRENA and ILO, 2022^[70]; 2023^[56]), ensuring the inclusion of any relevant terms that were not previously identified.

Table A C.1. English keyword list and associated technology group

Keyword	Group	Keyword	Group
alternative energy	Generic	osmotic power	Marine
balance of system	Solar	otec	Marine
battery storage	Storage	permanent magnet	Wind
bess	Storage	photosensitive semiconductor device	Solar
bifacial panel	Solar	photovoltaic	Solar
bio diesel	Biomass	polysilicon	Solar
bio fuel	Biomass	pulsed power capacitors	Storage
biodiesel	Biomass	pv cell	Solar
bioenergy	Biomass	pv system	Solar
bioethanol	Biomass	renewable diesel	Biomass
biofuel	Biomass	renewable electricity	Generic
biogas	Biomass	renewable energy	Generic
biomass	Biomass	renewable fuel	Generic
cadmium telluride	Solar	renewable power	Generic
capacitor winding machine	Storage	renewable sources	Generic
clean energy	Generic	residential solar	Solar
concentrated solar power	Solar	salinity gradient	Marine
crystalline silicon	Solar	smart grid	Generic
dam	Hydropower	solar battery	Solar
electrode coating	Storage	solar boiler	Solar
energy storage	Storage	solar cell	Solar
eolic	Wind	solar charger	Solar
ethanol	Biomass	solar collector	Solar
fuel from waste	Biomass	solar concentrator	Solar
geo thermal	Geothermal	solar cooling	Solar

geothermal	Geothermal	solar electric	Solar
grid tied solar	Solar	solar energy	Solar
ground-based heat pump	Geothermal	solar farm	Solar
hydraulic energy	Hydropower	solar generation	Solar
hydraulic power	Hydropower	solar generator	Solar
hydraulic turbines	Hydropower	solar heating	Solar
hydro-electric	Hydropower	solar home	Solar
hydro energy	Hydropower	solar lamp	Solar
hydro power	Hydropower	solar light	Solar
hydro turbines	Hydropower	solar module	Solar
hydro-electric	Hydropower	solar off grid	Solar
hydro-energy	Hydropower	solar panel	Solar
hydro-power	Hydropower	solar plant	Solar
hydro-turbines	Hydropower	solar power	Solar
hydroelectric	Hydropower	solar pump	Solar
hydroelectricity	Hydropower	solar pv	Solar
hydroenergy	Hydropower	solar technology	Solar
hydrogen distribution	Hydrogen	solar thermal	Solar
hydrogen production	Hydrogen	solar tracker	Solar
hydrogen storage	Hydrogen	solar water heat	Solar
hydrogen tank station	Hydrogen	storage fuel cells	Storage
hydrolysis	Hydrogen	superconducting magnets	Wind
hydropower	Hydropower	thermal renewable energy	Geothermal
hydrotreated vegetable oil	Biomass	tidal energy	Marine
hydroturbines	Hydropower	tide energy	Marine
large scale battery	Storage	tide power plants	Marine
large scale capacitor	Storage	utility scale solar	Solar
magnet technology	Wind	waste energy	Biomass
magnet wire	Wind	waste fuel	Biomass
marine energy	Marine	waste to energy	Biomass
marine power	Marine	wastefuel	Biomass
ocean current energy	Marine	water hydrolysis	Hydrogen
ocean renewable energy	Marine	wave energy	Marine
ocean thermal energy conversion	Marine	wave power	Marine
off grid hydro	Hydropower	wind blade	Wind
off grid renewable	Generic	wind energy	Wind
off grid solar	Solar	wind farm	Wind
off-grid renewables	Generic	wind motors	Wind
offshore wind	Wind	wind power	Wind
onshore wind	Wind	wind turbine	Wind
osmotic energy	Marine	windpower	Wind

Source: Own elaboration based on terms extracted from patents allocated to renewable energy technologies (search strategy presented in Table A B.1), terms found in the already identified renewable energy vacancies, terms for the identification of green start-ups in the renewable energy sector from the OECD Start-ups Database and terms from the International Renewable Energy Agency's Annual Review 2022 and 2023 on Renewable Energy and Jobs. Each keyword was lemmatised and exact matching was applied.

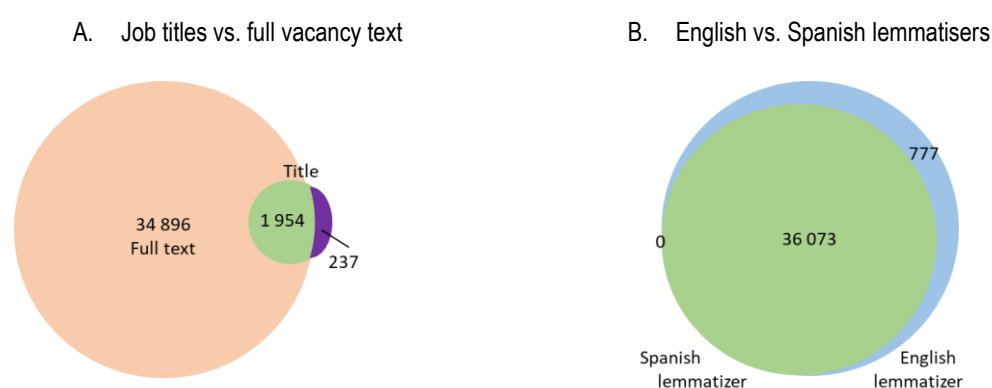
The role of the selected target text and matching approach

Renewable energy vacancies were identified through exact matching between a list of keywords and the full vacancy text. The choice to focus on the job title alone or on the full vacancy text significantly influences the number of vacancies identified, as demonstrated below by the example of Spanish online vacancies

posted in 2022. Job titles may be quite generic and cover a wide range of positions, both in the renewable ecosystem and beyond. The job text instead gives more details on the specific role and tasks that the employee is expected to undertake. Panel A of Figure A C.1 shows that the large majority of renewable energy vacancies (over 90%) were identified based on keywords found in the full vacancy text. Arguably, restricting the target text to only job titles is possibly more precise, but searching the entire vacancy text allows for the identification of novel or evolving positions, for variability in terminology and for inclusion of nuanced language and specific details (e.g. job responsibilities or requirements) that may not be accurately captured by job titles. With the majority of renewable energy vacancies identified through job titles also tagged in the full vacancy text, and less than 1% identified through job titles alone, using also job titles as the target text yields only marginal gains that are unlikely to significantly impact the results.

Figure A C.1. Comparison of target texts and lemmatisation approaches

Different target texts used, and different lemmatisation approaches applied to Spanish data, 2022



Source: Own elaboration based on Lightcast data.

Matching efficiency and accuracy between keywords and target text were further improved by initially lemmatising keywords and full vacancy texts, i.e. by reducing words to their root form (to their lemma). This critical pre-processing step addresses variations in word forms and improves the handling of related terms (Miller, 1995^[71]; Fellbaum, 1998^[72]). Given the analysis spans multiple countries with different languages, the original English keywords underwent translation into respective languages for non-English-speaking countries, utilising both language versions. Considering that different languages possess distinct grammatical structures and unique linguistic characteristics, language-specific lemmatisation models tailored to the intricacies of a particular language were used.¹ However, this exercise only yields marginal gains in the number of identified renewable energy vacancies, as illustrated by the results in Panel B of Figure A C.1, using again the example of Spain.

Online job vacancies

Lightcast uses distinct taxonomies for sectoral information, occupations and skills across different country groups. In the United States, industry information is based on the NAICS classification, which is directly linked to the employer's name in the vacancy post. For European countries, the Statistical Classification of Economic Activities in the European Community (NACE) is employed, and each vacancy is assigned to a NACE code through text matching focusing on the industry field of portals and categorising vacancies based on industry indicators. Subsequently, to further refine the categorisation process, Lightcast uses a machine learning model to analyse the entire vacancy text, with specific focus on sections describing the firm. For better comparability throughout the analysis, the data collected according to NAICS were aggregated into the one-digit sections of NACE.

Occupations in both European countries and the United States are derived from job titles and vacancy text. However, in the United States, they align with the Lightcast Occupation taxonomy, whereas in European countries, the mapping is based on the ESCO taxonomy. Similarly, in the United States, skills are categorised using the Lightcast Skills taxonomy, featuring over 32 000 unique competencies, knowledge, and specific software, while, for European countries, Lightcast resorts to the ESCO taxonomy, which encompasses 13 890 unique skills, competences, and knowledge.² It is essential to consider this caveat when making comparisons between the results obtained for European countries and the United States.

Identifying vacancies related to the renewable energy ecosystem

Online vacancies associated with the renewable energy ecosystem (referred to as renewable energy vacancies hereafter) are identified using a list of keywords, in line with what has been done to identify skills and vacancies in the field of AI (Squicciarini and Nachtigall, 2021^[40]; Samek, Squicciarini and Cammeraat, 2021^[41]; Alekseeva et al., 2021^[42]; Acemoglu et al., 2022^[43]; Green and Lamby, 2023^[44]; Borgonovi et al., 2023^[45]). The keywords were selected based on technologies and other related terms identified through a number of different sources and are presented in Table A C.1.

More specifically, these keywords were selected based on technologies and other related terms identified through a number of sources. Firstly, terms extracted from patents allocated to renewable energy technologies on the basis of the search strategy presented in Box A B.1. and presented in Section 3 were used. Additional keywords were then incorporated through an iterative process, utilising relevant terms found in already identified renewable energy vacancies. Secondly, keywords for the identification of green start-ups in the renewable energy sector from the OECD Start-ups Database were leveraged to further enrich the list. Finally, the keyword list was completed by reviewing the International Renewable Energy Agency's Annual Review 2022 and 2023 on Renewable Energy and Jobs (IRENA and ILO, 2022^[70]; 2023^[56]), ensuring the inclusion of any relevant terms that were not previously identified.

Vacancies pertaining to the renewable energy ecosystem were identified through exact matching between the lemmatised English keywords list (described above) and the lemmatised full text of each vacancy. For non-English-speaking countries, those keywords were also translated into the respective language(s) of interest³ and keywords in English and the other relevant languages were used to identify vacancies. Further details about the approach are provided in this annex.

To further analyse the technological areas and associated skills mentioned in each renewable energy vacancy, each keyword was allocated to one of nine technology groups, namely: generic (for overarching keywords like “alternative energy” or “renewable energy” that are too broad to be classified into a specific group), solar, biomass, hydropower, geothermal, energy storage, wind, marine and hydrogen. As renewable energy vacancies can potentially be tagged by multiple keywords⁴ belonging to different technology groups, fractional counting was utilised when necessary. However, generic technologies tend to be mentioned in many renewable energy vacancies, frequently also with more specific ones. Therefore, vacancies only fall under the generic group if no other specific technology is referenced in the vacancy.

Limitations associated to job vacancy data

Although job vacancies provide novel information on labour demand and its composition, notably in terms of skills, they also come with several important limitations that should be kept in mind when interpreting the results of this section.

First, vacancies primarily offer insights into the current demand for employment but lack comprehensive information about the existing workforce or labour supply. Some studies have attempted to use advertised wages as a proxy for mismatches between supply and demand or other tensions in the labour market (e.g. OECD (2023^[73])), Saussay et al. (2022^[38]) or Curtis and Marinescu (2023^[31]) but acknowledged the

introduction of possible bias due to the poor quality or lacking availability of explicit offered wage information for a subset of groups (Batra, Michaud and Mongey, 2023^[49]; Lafontaine, Saattvic and Slade, 2023^[50]). Therefore, this paper adopts a different approach, comparing the demand for renewable energy vacancies to overall demand at the occupation level. More specifically, the occupational distribution of the renewable energy vacancies in each country is compared to the distribution across all vacancies to identify the top five over-demanded occupations (at the 2-digit level).

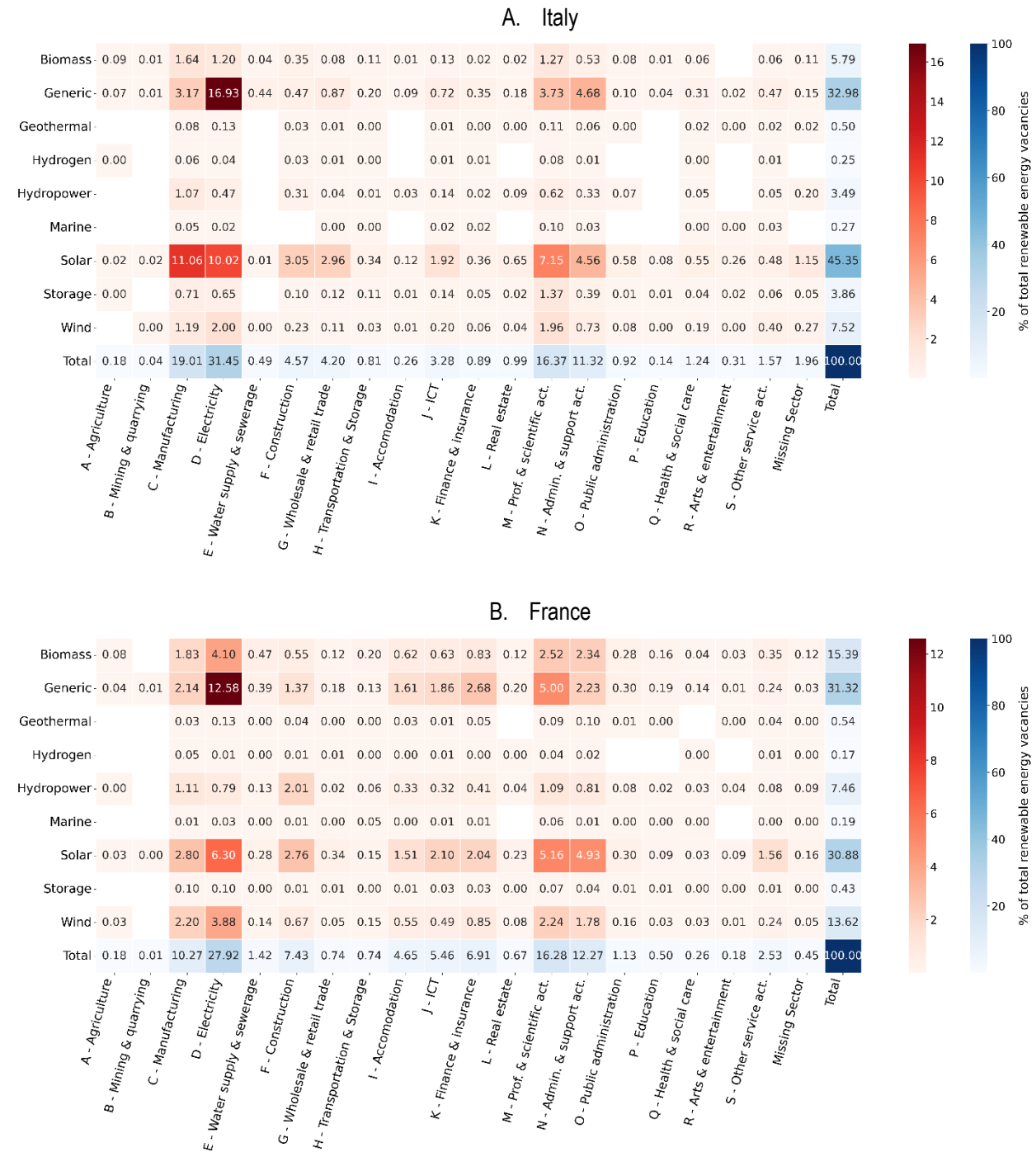
Second, several factors (e.g. regulations, type of job, characteristics of jobseekers, and labour supply) may impact companies' job posting behaviour (Cedefop, 2019^[51]). For instance, firms may refrain from posting job vacancies for which they can easily find workers offline or, on the contrary, if they do not expect to find suitable candidates through online postings. If employers decide not to post the vacancy online or choose to advertise a single advert representing multiple vacancies, the total number of available positions is underestimated. Additionally, demand may be underestimated because online vacancies typically do not cater to self-employed individuals. Lastly, employers may decide not to fill a vacancy at all, or they may fill them with workers performing different tasks than listed in the vacancy (Curtis and Marinescu, 2023^[31]).

Third, employers often post a vacancy on more than one portal, such as job search engines, public employment services, recruitment agencies or own company websites (Cedefop, 2019^[51]). While Lightcast employs a de-duplication algorithm, potential failures cannot be ruled out, e.g. because the same post may have different wages as a result of different imputation exercises carried out by job boards (Lafontaine, Saattvic and Slade, 2023^[50]).⁵ In that case, it may not be detected by the algorithm.

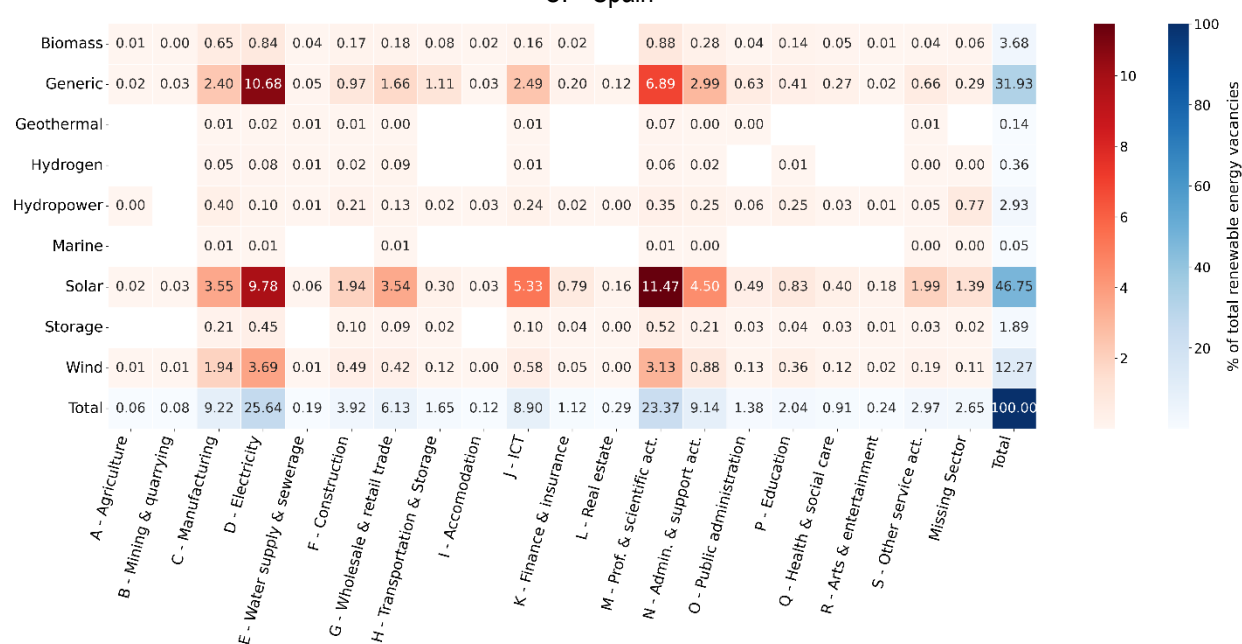
Fourth, online vacancies are known to be biased towards high-skilled professional occupations, such as business and financial, computer and mathematical, as well as healthcare occupations, often at the expense of jobs in construction, public administration and government, mining and logging, and accommodation and food services (Cammeraat and Squicciarini, 2021^[52]; Napierala and Kvetan, 2022^[53]; Lancaster, Mahoney-Nair and Ratcliff, 2019^[54]; Tsvetkova et al., forthcoming^[55]). However, notable exceptions exist as evidenced by a recent study indicating a higher prevalence of vacancies for skilled agricultural, forestry and fishery workers on Public Employment Services compared to Lightcast, relative to management and professional occupations (Vermeulen and Gutierrez Amaros, forthcoming^[74]). Although Sato et al. (2023^[39]), for instance, re-weight low-carbon jobs using US Bureau of Labor Statistics employment shares, sources like Public Employment Services or business surveys tend to count vacancies differently (e.g., in terms of new or current open vacancies), making claims about comparability or representativeness difficult.

Finally, online vacancy data provide a high-frequency indicator of vacancies, but their time evolutions should be approached with caution. The substantial rise in job postings over time poses challenges in discerning whether this increase results from a genuine surge in demand, i.e., more employers posting vacancies or an increase in vacancies posted by employers, or Lightcast increasing its scope by scraping additional job board websites. Therefore, the analyses that follow concentrate on shares of identified renewable energy vacancies rather than levels, and focus on the year 2022.

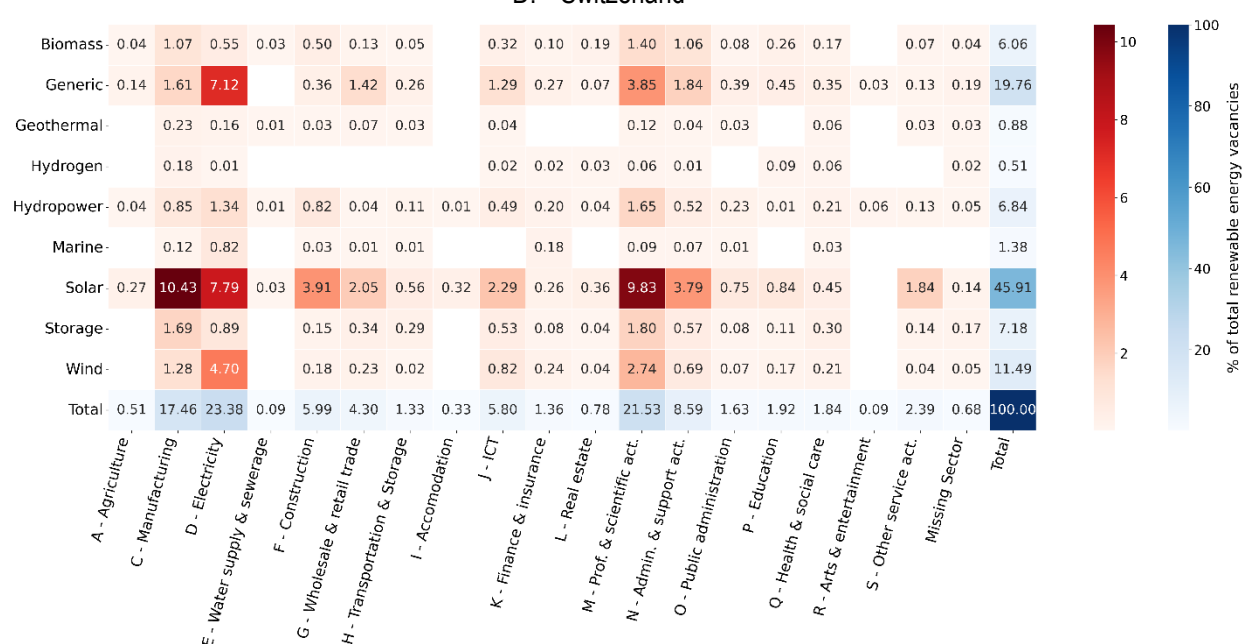
Figure A C.2. Sectoral distribution of renewable energy vacancies in European countries, 2022



C. Spain



D. Switzerland

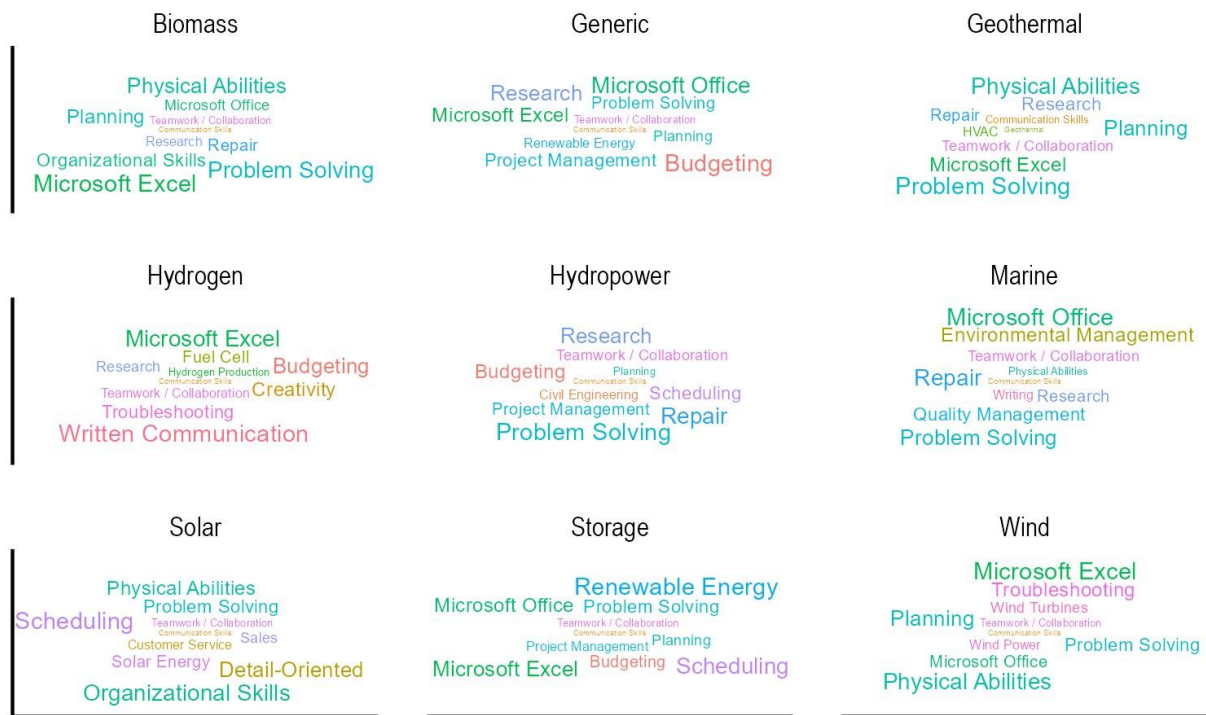


Note: The figure displays the distribution of renewable energy vacancies across sectors and technology groups in 2022 for Italy (Panel A), France (Panel B), Spain (Panel C) and Switzerland (Panel D). The intensity of red corresponds to the share of vacancies, with all red cells collectively summing up to 100%. The intensity of blue corresponds to the sum of shares either across rows or across columns. Industry information is sourced through NACE and is aggregated into one-digit sections for better comparability. Fractional counting is employed for cases involving multiple technologies. If a vacancy has been tagged through both, a generic and a specific keyword, only the specific technology is considered. Technology groups are assigned to the renewable energy vacancies based on the keywords used to identify them.

Source: Own elaboration based on Lightcast data

Figure A C.3. Top ten skills by technology group

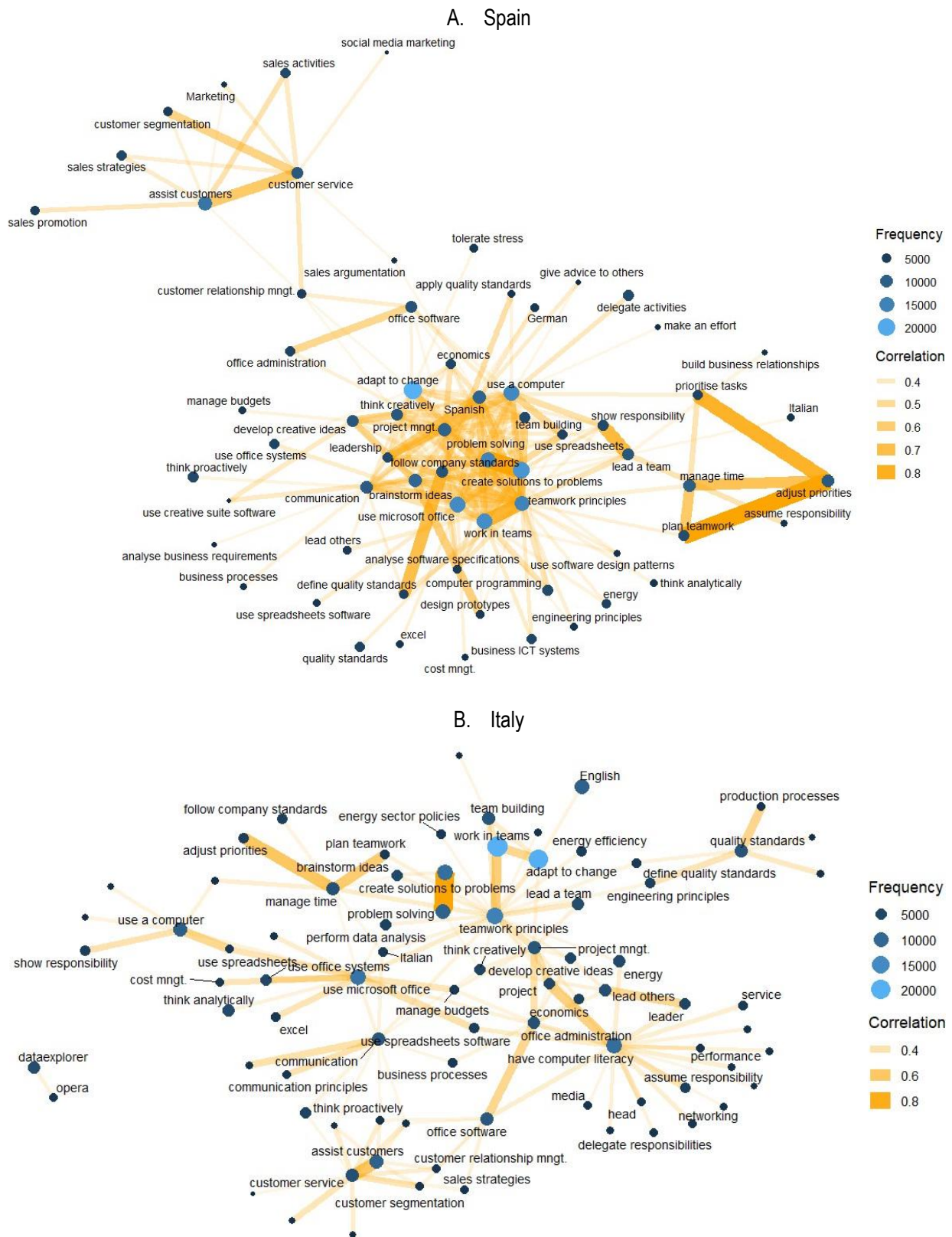
United States, 2022



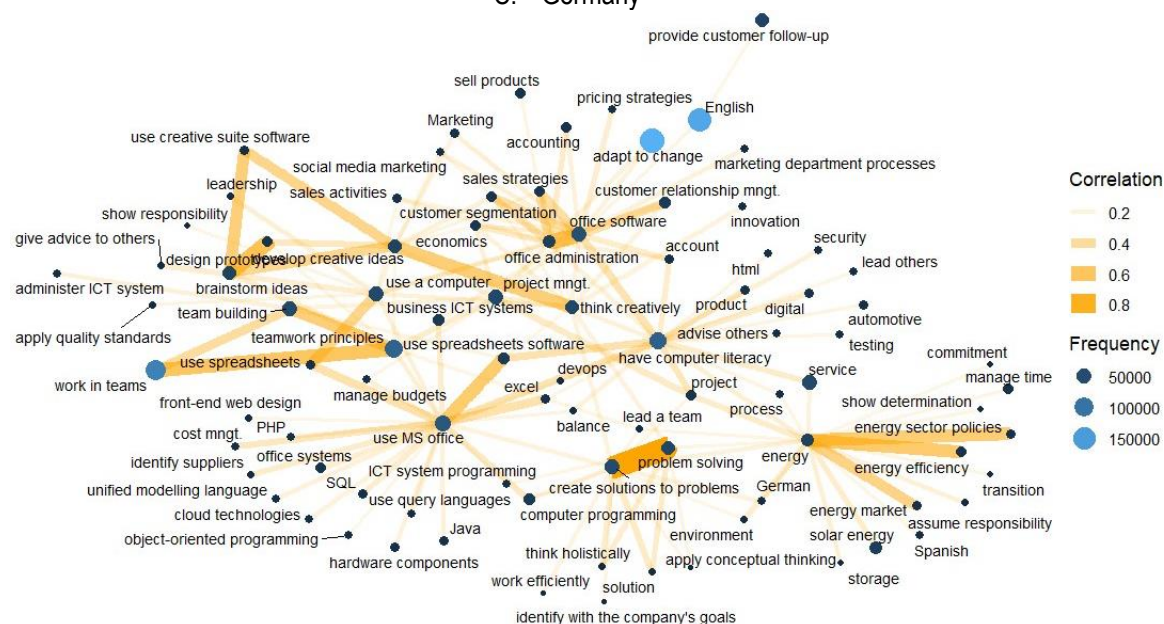
Note: Each word cloud shows the ten skills most frequently mentioned in renewable energy vacancies in the United States in 2022 that also mention keywords associated with the specific technology group, where the size of the word is representative of the skill demand. Each keyword is allocated to a specific technology group and hence vacancies can contain multiple technology groups (they are not mutually exclusive and no fractural counting was applied here).

Source: Own elaboration based on Lightcast data.

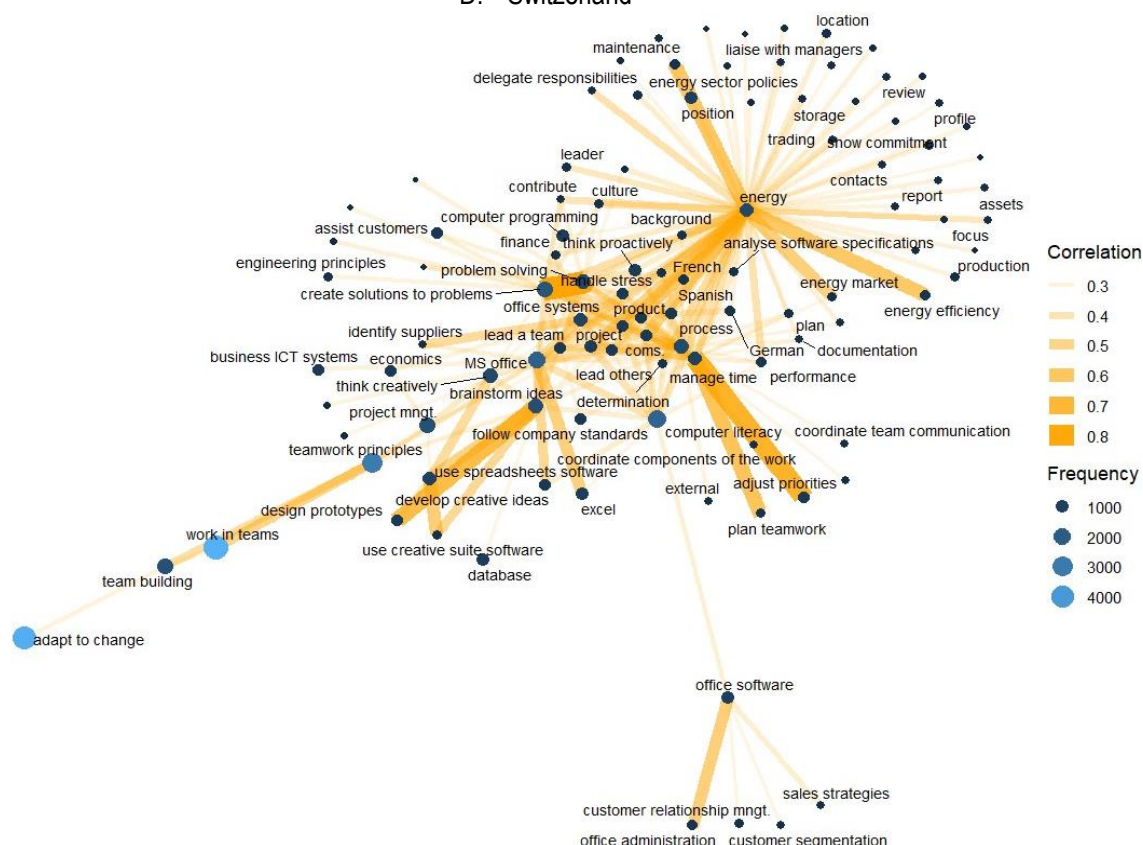
Figure A C.4. Correlation of top 20 skills and their pairs in renewable energy vacancies in European countries, 2022



C. Germany



D. Switzerland



Note: The networks show the 20 skills most frequently mentioned in renewable energy vacancies in Spain (Panel A), Italy (Panel B), Germany (Panel C) and Switzerland (Panel D) in 2022 together with skills they are correlated with. Skills in European countries utilise the ESCO taxonomy. The size of the nodes reflects the frequency with which the individual skill is mentioned in all identified renewable energy vacancies. The width of the edge between nodes shows the correlation between skill pairs. For visual presentation purposes, only edges with correlation exceeding 0.4 for Spain and Switzerland, and 0.2 for Italy and Germany and node labels for the most frequently demanded skills are displayed. Skills in European countries that were incorrectly classified as such (e.g. website features like 'menu', 'authentication' or 'upload') were dropped.

Source: Own elaboration based on Lightcast data

Endnotes

¹ The analyses utilised Python. English lemmatisation used the NLTK platform and, in particular, the WordNet lexical database (Miller, 1995^[71]; Fellbaum, 1998^[72]). For each European language, the SpaCy library and, in particular, the “core_new_md” pipeline (“de_core_news_md”, “es_core_news_md”, “fr_core_news_md”, “it_core_news_md”) were leveraged.

² The list of skills contains broader concepts, also encompassing knowledge areas (like ‘Photovoltaic’ or ‘Wind Turbines’), specific technologies and tools (like ‘Microsoft Excel’), and abilities (like ‘Physical abilities’), as reported in OECD (2022^[80]). Few vacancies associated with the renewable energy ecosystem in European countries contained skills that were misclassified as such. For example, terms related to website features like ‘menu’, ‘authentication’ or ‘upload’ were inadvertently captured by Lightcast’s algorithm as skills at the time of scraping the website, and subsequently excluded from the analysis.

³ French, German, Italian and Spanish translations were checked with native speakers to ensure that the keywords are specific to renewable energy technologies in the corresponding language.

⁴ To ensure correct fractional counting, it is important to account for the correlation between keywords belonging to the same technology group. If two keywords within a group are perfectly collinear and consistently co-occur, results are biased causing an artificial overweighting of that specific group to which the collinear keywords belong. To mitigate this bias, a correlation matrix between each keyword was calculated and perfectly collinear keywords were discarded.

⁵ For a large share of US job postings in Lightcast, Lafontaine et al. (2023^[50]) find, through vacancy text searches, that the already limited wage information in the data was estimated by intermediary or third party platforms posting the add rather than being provided by the employer directly. LinkedIn, for instance, used their LinkedIn Salary tool to impute wages temporarily.

Annex D. Policies for the renewable energy ecosystem

Box A D.1. The EU Net-Zero Industry Act

The NZIA is part of the Green Deal Industrial Plan's pillar for a predictable and simplified regulatory environment. It aims at promoting investments in the development and production of net-zero technologies in the manufacturing sector. Five of these technologies belong to the renewable energy ecosystem: Solar power (PV and thermal), wind power, electrolyzers for hydrogen, biogas/biomethane and smart grid. The Act also aims to reduce strategic dependencies that might undermine access to key technologies and components for the green transition.

The NZIA encompasses products, components and capital goods used in the manufacturing process of net-zero technologies and the innovations associated to them. It sets a benchmark for the manufacturing capacity of strategic net-zero technologies that are commercially available or close to enter the market to meet at least 40% of the EU's annual deployment needs by 2030.

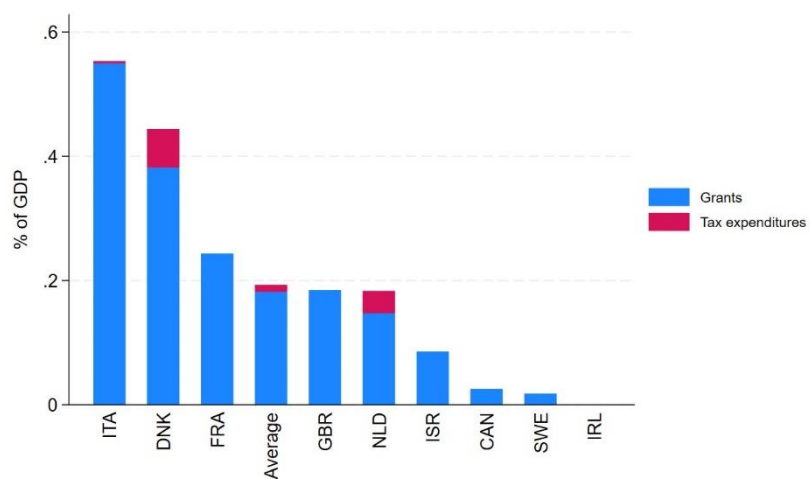
The main measures of the NZIA are:

- Streamlining administrative requirements and facilitating permitting;
- Ensuring access to information;
- Public procurement and auctions intended to facilitate access to markets;
- Schemes aimed at fostering private demand by consumers;
- Regulatory sandbox to support innovation;
- Dedicated training programmes through Net-Zero academies specialised in each technology, with the aim to train 100 000 learners in the first three years;
- Facilitating the portability of qualifications in regulated professions within and between EU countries, with the aim of enhancing knowledge spillovers in the EU industrial ecosystem through labour market pooling.

Source: NZIA press release, 2023.

Figure A D.1. Support mainly channels through grants

Business support to the renewable energy ecosystem (average 2019-2021), % of GDP



Note: Policies supporting the renewable energy ecosystem are a subset of the instruments labelled with the 'Green' eligibility criteria in QuIS. Specifically, they refer to green policies supporting renewable energy production, renewable energy purchase, adoption of renewable energy technologies, R&D and innovation in renewable energy technologies and manufacturing of goods in the renewable energy value chain.

Source: QuIS database, <http://oe.cd/quis>.