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European Commission

SCIENCE FOR POLICY BRIEF

EU competitiveness in net-zero technologies: Insights from patents and economic complexity

HIGHLIGHTS

→ The EU seeks to prioritise investments in strategic technologies where it can be competitive.

→ An approach for assessing the EU's potential competitiveness in new and established technologies is presented, applying Natural Language Processing to patent data and using the Economic Complexity framework. Technical expert knowledge is not a required input (but useful for interpretation).

→ By way of example, it is applied to 15 net-zero technologies of the Net Zero Industry Act. The results show a potentially high EU manufacturing competitiveness for wind, heat recovery and ocean technologies, and the opposite for photovoltaics and batteries.

→ The method is cross-checked by comparison with independent analysis of the JRC's *Clean Energy Technology Observatory.*

→ Detailed analyses of individual Member States' technological capabilities are also possible, to identify where specific technologies find the most fertile ground to flourish – e.g. Germany for electricity grid hardware and Italy for heat recovery technology.

→ The approach can zoom into subclasses and variants of technologies; e.g., Carbon Capture and Storage appears overall to have low prospects, but zooming in reveals that the EU could be a leader in capture technologies (but is weaker in storage and transport).

INTRODUCTION

The EU will have to take decisions on where to invest its resources to stimulate industrial growth in new strategic technologies, and to support sectors under threat by the evolving geopolitical relations. In this context, the Commission has launched new initiatives aimed at bolstering the EU's competitiveness, such as the Competitiveness Compass and the Competitiveness Coordination Tool[1], with the goal of closing the innovation gap between the EU and other areas of the world such as the US and China, while achieving climate neutrality.

To this end, it is crucial for the EU and its Member States to identify technologies and sectors that are of industrial and strategic importance *and* bear the potential for the EU to become a globally competitive player. The ability to rigorously assess existing technological capabilities is pivotal to provide industries with targeted and effective policy support through instruments such as the Important Projects

[1] https://ec.europa.eu/commission/presscorner/detail/en/ip_25_339

of Common European Interest (IPCEI)[2] or the recently announced European Competitiveness Fund[3].

History has shown that financial support alone may be insufficient to spur sustained technological and industrial development. This is illustrated by the recent bankruptcy of a former European champion in the sector of batteries for electric vehicles – the Swedish company Northvolt[4] – whose economic struggles were likely exacerbated by the lack of underlying capabilities and a missing surrounding technological ecosystem.

In this policy brief, we propose a decision support tool for policymakers to identify the most promising avenues for technological specialisation and industrial policy. It is grounded in patent data, analysed through the lens of the Economic Complexity framework (Hidalgo and Hausmann, 2009; Tacchella et al., 2012). Simply said, Economic Complexity is based on pattern recognition to identify the implicit capabilities required to specialise in a given economic activity. With the help of machine learning, it uses statistical inference from the co-occurrence of economic, or – as in the present case – patenting activities across geographical locations.

A prerequisite for applying this framework to patent data is the ability to accurately classify which and how many patents in a country are related to a given technology. Most approaches rely on available patent classifications (CPC or IPC) or on keyword searches within abstracts. In contrast, here we leverage Natural Language Processing (NLP) techniques, transforming patent abstracts and technology descriptions (generated via ChatGPT) into vectors. The similarity between these vectors indicates whether or not a patent is related to the technology (Carriagi et al. 2021). This approach offers two advantages. First, not depending on predefined classification schemes means that we can include emerging technologies or very granular subcategories that may not yet exist in patent classifications (e.g., the large language models behind many AI applications have no proper CPC code and are only included in various more general codes).

Second, NLP models interpret the context in which words appear, thereby reducing false positives arising from ambiguous keywords (e.g. the case with "X" as keyword and a patent containing the text "this patent is different from technology X").

For our computations, we use the patent database *PatStat*, considering only granted international[5] patent applications belonging to a patent family filed in at least two different patent offices, one of which must be an IP5 (EPO, JPO, KIPO, CNIPA, USPTO). This rule gives us a pool of 4.5 million worldwide patents. Once it has been determined for each patent whether or not it is related to a given technology, two indicators are computed for each country:

- **Patent Share** – the percentage within all patents (of year 2021) related to a given technology for which at least one inventor is based in the country.

- **Technology Progression Probability (TPP)** – a formal concept of the Economic Complexity framework, this metric estimates the probability that a country will be active in a given technology five years after the latest year available in the data.[6] Here, 'active' means that the country's share in that technology (as defined above) is higher than its overall share in the grand total of worldwide patents. TPP captures a country's underlying *technological capability*, a term we use as synonym of TPP.

Together, these indicators convey the country's current patenting strength, on the one hand, and its mid-term potential to develop and sustain technological leadership in a given technology, on the other.[7]

The underlying idea of the TPP is that a country is more likely to patent in a technology in the future, if it already holds patents in related fields today. For instance, a country with strong patenting activity in both computer science and quantum technologies is well positioned to also innovate in quantum computing, the intersection of the two. This reflects the notion of technological capabilities: the implicit know-

[2] https://competition-policy.ec.europa.eu/state-aid/ipcei_en

[3] https://commission.europa.eu/publications/european-competitiveness-fund_en

[4] https://www.theguardian.com/business/2025/mar/12/ev-battery-startup-northvolt-files-for-bankruptcy-in-sweden

[5] Our NLP model requires patent abstracts to be written in English. For this reason, we focus on international patents, which ensures linguistic consistency but leads to a reduction in the number of patents considered – particularly for China, where many national patents are written in Chinese characters.

[6] More details on this concept can be found in Albora et al. (2023), where the progression probability is calculated between countries and products, and in Straccamore et al. (2022), where it is computed between companies and CPC technological codes.

[7] Patent-based measures are not the only relevant indicator of competitiveness in a technological area. Indeed, our approach is meant to offer a new possibility to support expert assessments and should ideally be complemented by other approaches going beyond patent analysis.

how required to successfully develop a given technology.[8] As it is more intuitive, we will use the term *technological capability* when referring to the TPP.

The main purpose of this policy brief is to illustrate the potential of the approach for a limited number of technologies. Given their relevance in current policy discussions, 15 net-zero technologies associated with the Net Zero Industry Act (NZIA) were selected. Among them are photovoltaics, wind, heat pumps, and others (the appendix gives the full list, together with the short descriptions we used for our analysis). However, the approach can readily be employed to assess the EU's potential competitiveness for other technologies at varying levels of detail.

A weakness often encountered in forward-looking competitiveness studies is that they obtain a certain result (e.g. an indicator or ranking), but do not offer independent checks for verification or falsification. Our approach takes a step forward by proposing and passing a cross-checking exercise based on expert-vetted qualitative assessments, a key strength for an approach aiming to become a decision support tool. Specifically, we assess our results on the EU's competitiveness in 15 net-zero technologies against the benchmark of the recent report *Progress on competitiveness of clean energy technologies* (European Commission, 2025), which summarises assessments of the same technologies carried out by experts in the JRC's *Clean Energy Technology Observatory*.[9]

Finally, we provide an illustrative example of how current production trends may not be a good indicator of future technological leadership. We choose the case of one technology (solar PV) where the EU recorded growing production levels in the early 2000s, but rather stagnating technological capabilities. Using historical solar PV production data, we show that – at a time when Europe was still a leading manufacturer in this field – technological capability can provide an early signal of sectoral trends.

EU COMPETITIVENESS IN 15 NET ZERO TECHNOLOGIES

As main result, Fig. 1 depicts the two indicators *technological capability* (i.e. TPP, on the x-axis) and *patent share* (y-axis) for each of the 15 net-zero technologies, in a normalised form relative to the world's country with the highest value, based on year 2021 data. Before normalisation, the EU's technological capability is calculated as population-weighted average of the technological capabilities of its 27 Member States.[10] The EU's patent share is the simple sum of the patent shares of all Member States. Both indicators capture how close the EU is to the best-performing country. Technologies appearing towards the right of the plot are those where the EU is closer to the capabilities of the leading country in that technology. By the same token, technologies appearing towards the top of the figure are those where the EU holds a share of patents that is closer to the one of the global leader (when the EU is itself the leader, the value of patent share is equal to one). While the patent share can be interpreted as measuring current competitiveness, technological capability is a proxy for the potential to develop competitiveness, as inferred from existing technological specialisation. Along these two dimensions, the figure can be subdivided into four quadrants that offer an intuitive interpretation of the EU's position in each technology:

Leaders (upper right): Technologies where the EU shows both high patent share and high capabilities, indicating the highest potential for sustained competitiveness.

Seeds (lower right): Technologies with a relatively low patent share but strong underlying capabilities, indicating a potential for becoming competitive in the future, and thus a role for policy to provide support.

Zombies (upper left): Technologies where the EU exhibits a high patent share despite low capabilities. The elevated patent level may be supported artificially by targeted ‘wishful’ investments, but the longer-term competitiveness outlook is dubious.

Misses (lower left): Technologies for which the EU has neither a significant patent share nor strong capabilities, indicating that the EU might have missed the opportunity to become competitive.

Naturally, the choice of this classification is somewhat arbitrary, and 0.5 is just one possible threshold value. Moreover, the position of each technology in

[8] Using historical patterns to predict future developments is based on a *ceteris paribus* assumption and is less effective if structural breaks like crises or policy shocks occur.

[9] https://setis.ec.europa.eu/publications-and-documents/clean-energy-technology-observatory/ceto-reports-2024_en

[10] Other approaches to compute the EU's aggregate technological capability are possible. E.g., one could treat the EU as a single country from the beginning, but this would likely overestimate its level of integration. Or, one could compute the mean of the top-*k* performing member states, but this would introduce a free parameter and could produce inconsistent results: for instance, selecting $k = 3$ would yield very different implications if the top countries are small versus large.

the plot may vary to some extent, depending on how the set of analysed patents was selected – e.g., with or without national patents, individual applications or patent families, or the included year(s). Consequently, while the classification of batteries and wind – which are found at some distance from the threshold values – can be considered robust, those technologies located close to a dividing line (such as hydropower) could be sensitive to minor changes in the input data. For instance, a small variation could shift them from the 'Misses' to the 'Leader' quadrant.

Among the net-zero technologies, *Batteries* (here meaning Battery Energy Storage Systems – BESS, see appendix) stand out for appearing in the middle of the 'Misses' quadrant, suggesting that the EU may find it difficult to become competitive in this technology even with further investment support.[11] *Photovoltaics* appear in the 'Zombies' quadrant, which raises doubts on the likelihood that the currently high levels of patenting and research activities will translate into manufacturing competitiveness and generate economic returns. In contrast, *Nuclear Fission* falls in the 'Seeds' quadrant: despite a medium-low patent share, the EU holds relatively strong capabilities, implying that this technology might have better chances to become an area of EU competitiveness.

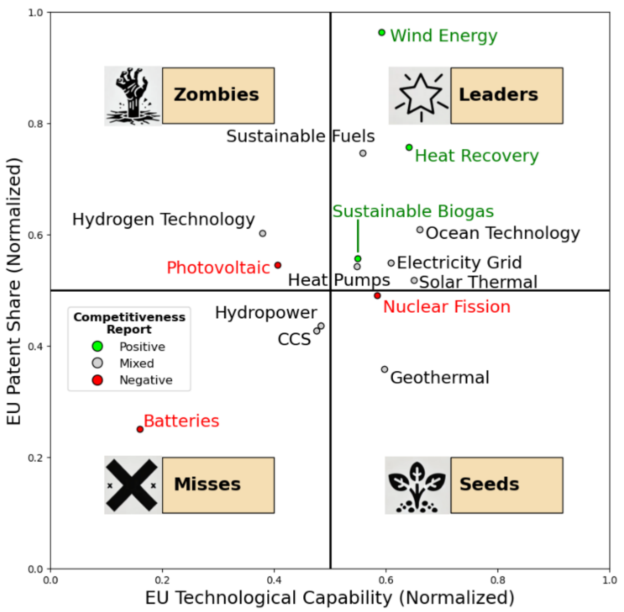

Figure 1. EU potential competitiveness in net-zero technologies in 2021, expressed as relative proximity to the country with highest technological capability (x-axis) and highest patent share (y-axis). Each point represents a technology. The colour coding of the dots indicates how EU competitiveness in each technology was assessed in European Commission (2025), as inferred by text analysis conducted using ChatGPT.

Are these results credible? We run an independent test to cross-check our results against those summarised in the European Commission (2025) *Progress Report on Clean Energy Technologies*. This report offers a specific competitiveness analysis for each of the 15 net-zero technologies, based on sectoral expertise and performance data. However, its findings are not aggregated into a single competitiveness indicator or ranking. Therefore, we used ChatGPT to infer how the report judges the EU's manufacturing competitiveness in each technology.[12]

In Fig. 1, green points denote technologies for which the report gives a rather positive outlook, grey corresponds to mixed or neutral, and red points to an overall rather negative competitiveness judgment. As visual inspection shows, there is a relatively good alignment: all green-labelled technologies are situated in our 'Leaders' quadrant, while all red ones are outside. This is a rather strong signal, considering that our analysis did not use any sector-specific data or knowledge, aside from a short description of each net-zero technology taken from ChatGPT (see appendix). Nevertheless, it can reproduce the key results of a much more comprehensive analysis.

Fig. 2 provides a more detailed view of individual EU Member States' technological capabilities (i.e. TPP), deepening the evidence presented for the whole EU. Panel (a) focuses on those technologies for which the EU was identified among the 'Leaders' in Fig. 1, while panel (b) shows those where the EU falls into any of the other three quadrants. Each technology is represented by a row, and each EU country by a dot, with the x-axis showing its technological capability level in year 2021. The top three EU countries (blue dots) are indicated by their flags. On the right end of the charts, for each technology we show the countries with the highest TPP and patent share, respectively.

As can be observed in panel (b), no EU country has particularly strong capabilities in batteries. Germany ranks highest but still trails far behind Japan, which has the highest level of battery-specific technological

[11] See also Caldarola et al. (2025), who come to the same conclusion with a similar approach based on export data.

[12] Different prompts and models have been used to achieve a sufficient stability of the results. A typical prompt was: "*Going through all the 15 net-zero technologies, analyse the document and then classify each technology in terms of how the report describes and judges the EU's competitiveness in each one, in particular whether it is rather positive, rather negative, or neutral / mixed. In this, focus on what the report says on manufacturing competitiveness, rather than just deployment levels of the technology in the EU.*"

capabilities.[13] The same is true for hydrogen technology, although in this case Germany's gap vis-à-vis Japan is notably smaller than for batteries.[14] In contrast, nuclear fission capabilities are especially high in France and Germany, the latter being the world leader. This evidence reinforces earlier findings from Fig. 1 and suggests that Italy, France, and Germany have a chance to build up and maintain a competitive position in nuclear fission technology.[15] Visually, the distribution of EU countries' capabilities in this technology most closely resembles that seen in panel (a) for technologies where the EU is in the 'Leaders' quadrant.

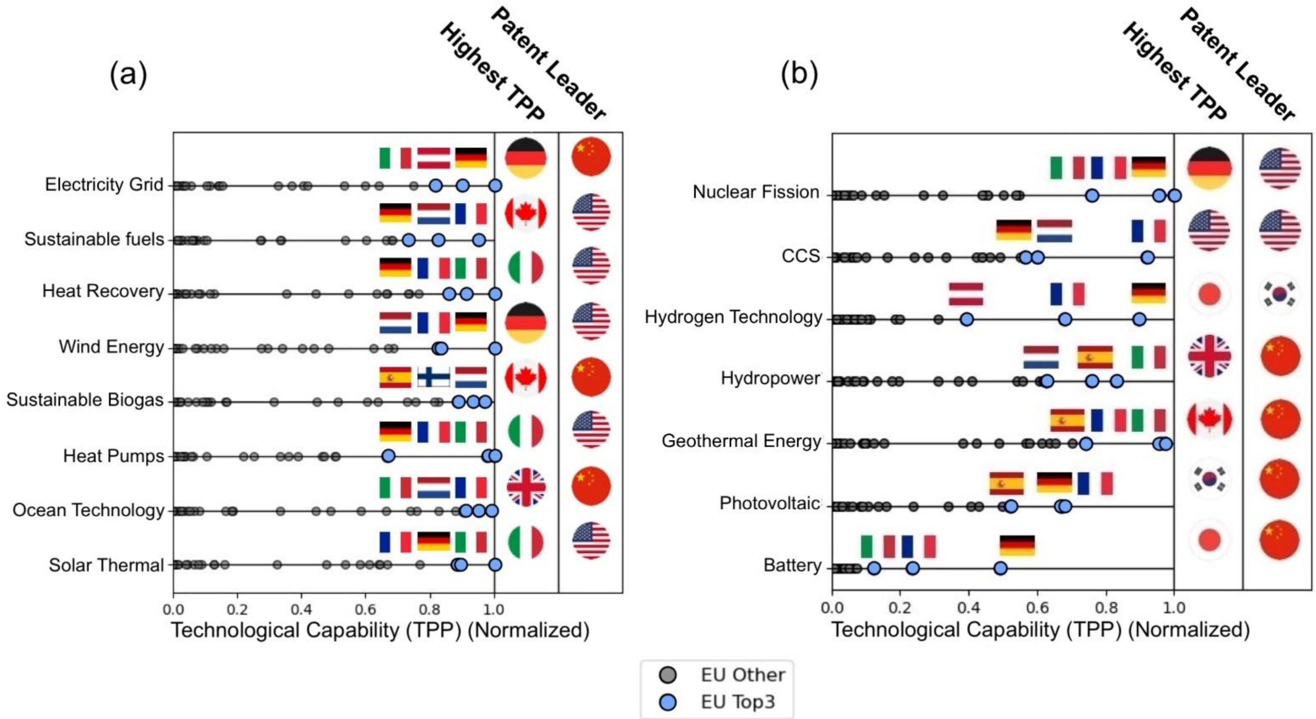

Figure 2. A close-up of individual EU Member States' technological capabilities, for technologies in which the EU was among the 'Leaders' (panel a) and all others (panel b). The horizontal axis captures the technological capability (TPP) in 2021, with respect to the global leader. EU members are shown as grey dots, except for the top three with the highest capability (blue). On the right end of each chart, for each technology, we show the country with the highest TPP and the top patent producer.

The 15 broad technology areas outlined in the NZIA provide a useful starting point for mapping competitiveness, but they may mask important differences within specific technologies. For instance, the aforementioned European Commission (2025) report on NZIA technologies distinguishes between industrial and domestic applications in heat pump technology; likewise, it distinguishes between electrolysers and fuel cells in hydrogen technology.

To analyse such differences, we employ our Natural Language Processing algorithm and identify patents related to specific sub-technologies at a more granular level. Complementary to Fig. 2, which widened our approach with a *geographical zooming* into capabilities of individual Member States, Fig. 3 offers a *technological zooming* into finer levels of technological detail. Fig. 3 uses the same type of plot as Fig. 1 but focuses on just two technologies: *Carbon Capture and Storage* (CCS, in blue), now distinguishing between *Carbon Capturing* techniques and *Carbon Storage and Transport*, and *Hydrogen* (in purple), now with a breakdown of various specific hydrogen production techniques.[16]

[13] Although Japan has slightly higher technological capability than China, patent share may better reflect which country is more competitive in this case. However, Japan's strong capabilities are not surprising, given that it pioneered the development of the first commercial lithium-ion batteries.

[14] This result is aligned with the EPO and IRENA (2022) report, where Japan ranks first in terms of international patents on hydrogen production processes, and Germany is the leading European country. It is also worth noting that Kuokkanen et al. (2023) identify Japan and South Korea as the two leaders in hydrogen technologies, while within the EU, Germany, France, and Austria rank highest, perfectly in line with Fig. 2.

[15] It is important to note that this analysis refers to nuclear fission in general. Different conclusions may emerge when focusing on specific sub-technologies, such as small nuclear reactors SMRs (see Kuokkanen et al., 2023, p. 175).

[16] Here the aim is to illustrate the potential results our approach can offer. We thus relied on a simple breakdown generated by ChatGPT, which includes both mature technologies, such as electrolysers, and emerging ones, like water splitting

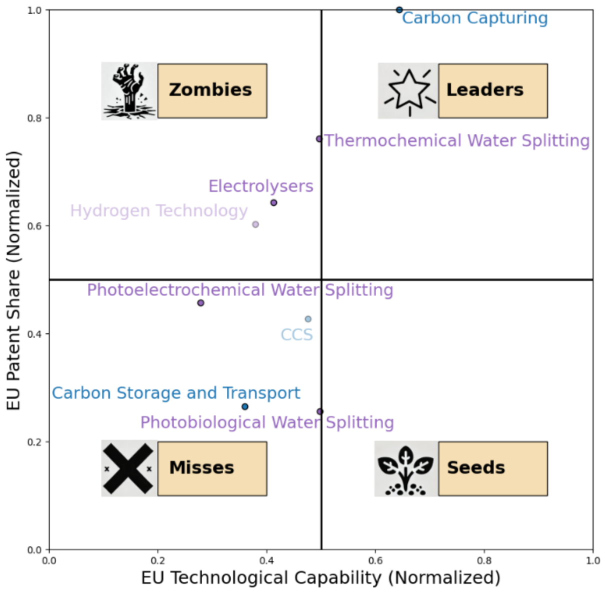

Figure 3. EU's potential competitiveness in Carbon Capture and Storage at aggregate level (CCS) and in specific techniques (in blue); likewise in Hydrogen Technology at aggregate level and in specific production technologies (in purple). Shown as relative proximity to the global leader in terms of technological capabilities (x-axis) and patent share (y-axis), based on year 2021 data.

In Fig.1, *Carbon Capture and Storage* is situated in the 'Misses' quadrant. Besides recalling this result (the blue dot 'CCS'), Fig. 3 additionally reveals that the EU's weakness is more pronounced in the storage and transport segment, while carbon capturing techniques fall into the 'Leaders' quadrant. This finding aligns well with the Competitiveness Progress Report (European Commission, 2025), which states that "*the EU is well positioned in CO2 capture technologies [...]. However, when it comes to CO2 transport, storage, and the full value chain, Europe lags behind [...].*"

A similar heterogeneity emerges for hydrogen. Recalling that at the aggregate level *Hydrogen Technology* is found in the 'Zombie' quadrant, Fig. 3 shows that two specific water splitting techniques fall into the 'Misses' quadrant, while a third one is close to the 'Leaders'. In line with the Commission's (2025) report, the figure also reveals that the subarea of *Electrolysers* has a slightly better outlook than *Hydrogen Technology* overall.

Finally, we complement the analysis with a suggestive historic example of one technology in which the EU lost a leading position, after first being overtaken in terms of technological capabilities, and then in manufacturing output. This is the case for *Photovoltaics* (PV). As can be seen in Fig. 1, the EU has a relatively high global patent share in this technology, compared to its lower capability. This might indicate a potential R&D overinvestment in an area lacking fertile ground for future growth. We use this well-known case – with its own idiosyncrasies[17] – as one example to explore how technological capabilities could be used to complement forward-looking competitiveness analysis.

Fig. 4 depicts the parallel evolution of photovoltaic technological capabilities and the production of PV cells/modules in the EU and in China. Clearly, China's rise in PV technological capability preceded its dominance in PV production. In the early 2000s, both technological capability and production were higher for the EU than for China. Yet, while the EU's capability level remained roughly constant, China experienced a steady growth. In 2004, China surpassed the EU in terms of technological capability. Four years later, in 2008, China also overtook in terms of PV cell/module production. While this analysis was not carried out systematically and thus remains illustrative, it provides evidence on how technological dominance in terms of patenting should not be interpreted as a guarantee for future competitiveness, which is better captured by the evolution of technological capabilities.

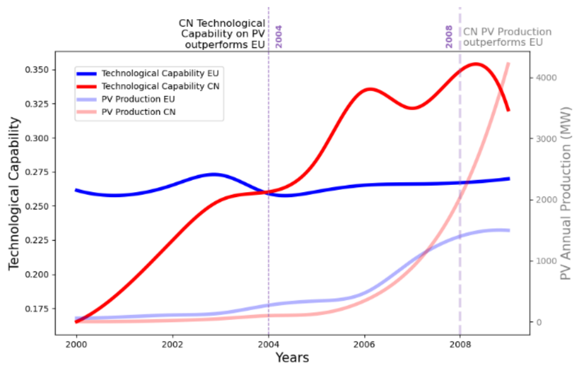

Figure 4. Evolution of photovoltaic technological capability (solid lines) and annual production of PV cells/modules for EU and China. Data from Richter et al. (2011), Fig. 4.1.1.1.

DISCUSSION

This policy brief has shown how the Economic Complexity approach can enhance the EU's analytical toolkit for competitiveness analysis, namely by identifying relevant technologies in which the EU is more likely to be naturally competitive than in others. Here, 'naturally' means that the EU already

techniques. For a more real-world assessment, a state-of-the-art list of relevant technologies provided by experts should be used.

[17] See, e.g., Zhang et al. (2014).

avails of the underlying capabilities needed for being competitive in these technologies, which the Economic Complexity approach measures by screening similar technologies and how competitive the EU is in them. The approach is quantitative and uses rigorous statistical inference. It allows to reveal hidden industrial capabilities, but also to debunk unrealistic expectations, and thus to inform EU industrial policy in a data-driven, non-prescriptive way.

A strength of the approach is that it is assumption-free with respect to the specific nature of technologies. Other than a coherent description of one or two paragraphs, it doesn't need specific information on the technologies (e.g. no CPC codes or 'correct' keywords). Moreover, it can in principle be used to analyse any technology and at different levels of granularity (Fig. 3). For instance, it would be possible to start by analysing electric vehicles (EV), then passing to EV batteries, and finally to specific battery technologies, like solid-state batteries.

To confirm the validity of the approach, we checked that our findings on net-zero technologies for which the EU was identified as a competitiveness leader or laggard (Fig. 1) are broadly consistent with benchmark results on EU manufacturing competitiveness – based on extensive sector-specific data and expertise – of the JRC's *Clean Energy Technology Observatory,* as summarised in European Commission (2025). Furthermore, selective checks showed that the approach produced meaningful results in line with other expert assessments, also at the individual country level and for more granular technology definitions, as illustrated in Fig. 2 and Fig. 3, respectively. Based on these checks, our measure of technological capabilities (i.e. TPP) turns out as a strong predictor of the EU competitiveness in manufacturing technologies.

In addition, through the example of solar PV (Fig. 4) we show the relevance of our capability metric for assessing trends in technology production and providing an early signal on the possible evolution of such trends: in year 2004 the country with the highest technological capability in solar PV technology was China, which surpassed Europe as the world's top producer four years later (Fig. 4). In spite of its mostly illustrative character, the case of solar PVs represents a good example of how a seemingly promising technological development *could* fail when adequate technological capabilities are missing. Having this said, it should be acknowledged that our analysis does not consider other potentially relevant factors – like infrastructure, investments, or scientific capabilities – that can also drive competitiveness.

Naturally, this is not the only limitation of our approach. First, the computation of technological capabilities relies on patents, which do not necessarily capture all technological knowledge and innovations (e.g. tacit or non-codified types of knowledge, or preference of firms for secrecy over patenting). Also, they suffer a time delay of about three years before being included in databases. Future work may address this drawback by going beyond patents, e.g. by integrating export data through multilayer networks (Pugliese et al., 2019).

Second, results should not be followed blindly but should be validated by technical experts. In this sense, the approach proposed here should not replace expert analysis based on specific sectoral data and knowledge. Rather, it has a complementary role, e.g. as coarse but rapid and low-effort assessment tool, or as final gateway check on technologies short-listed for policy support.

Third, in terms of informing policymaking, the signal offered by technological capabilities is just one criterion among possibly many. A low value does not mean that there might not be other valid reasons for the EU to provide policy support in a certain technology area, e.g. to ensure a minimum level of EU domestic capacity that can guarantee supply in the event of a global supply chain disruption. Hence, policymakers should use this approach in a non-prescriptive way, conscious of the fact that technological capabilities provide information on the feasibility, rather than the desirability of strategies to support technological specialisation.

To conclude, the main purpose of this contribution is to showcase the potential of the approach for a few selected technologies. However, it also provides a couple of relevant insights on the EU's current and potential competitiveness in the 15 net-zero technologies. To mention one, the results suggest that caution might be warranted on the prospects in hydrogen technology, which should not turn into the EU's next boom-and-bust industry (as solar PV manufacturing). The high number of patents in this sector may reflect a high level of targeted investments. However, in the absence of strong capabilities, long-term competitiveness remains uncertain.

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