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ORIGINAL PAPER

The EU's comparative advantage in the "clean-energy arms race"

Petter Dahlström[1] · Hans Lööf[1] · Fredrik Sjöholm[2] · Andreas Stephan[3]

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Abstract
The net-zero agreement on carbon emission from Paris 2015 gives a key role to fossil-free energy technologies with an expected multiple growth rate over the coming decades, when successively replacing oil, coal, and gas. In this paper, we examine the EU's comparative advantage in the evolving trade war in clean-energy and show that the EU excels in developing strategic net-zero technologies, but often falls short in manufacturing the final products. The EU's Net-Zero Industry Act aims to encourage investments in the production of strategic energy products and increase self-sufficiency to meet 40% of low-carbon technology needs by 2030. However, this may not fully address long-term challenges relating to growth, job creation, decarbonization, and geopolitical resilience. Supporting innovative producers could be a more effective policy to capitalize on the EU's competitive advantage in the clean-energy sector.

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✉ Hans Lööf
hans.loof@indek.kth.se

Petter Dahlström
petter.dahlstrom@riksgalden.se

Fredrik Sjöholm
fredrik.sjoholm@ifn.se

Andreas Stephan
andreas.stephan@lnu.se

1 Royal Institute of Technology, Stockholm, Sweden

2 Research Institute of Industrial Economics, Stockholm, Sweden

3 Linnaeus University, Växjö, Sweden

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1 Introduction

In 2023, the European Commission proposed the Net-Zero Industry Act (NZIA) as a part of the Green Deal strategy to promote investments in the production capacity of products that are considered to be of key importance in meeting the EU's climate neutrality goals. Similarly to the wave of low-carbon subsidies announced in the U.S. Inflation Reduction Act (IRA), the European governmental subsidy on strategic transition technologies is described as an explicit response to China's dominance in the clean-energy sector.[1] According to NZIA, manufacturing within the EU must meet at least 40% of the low-carbon technology needs by 2030. Specifically, this target applies to a list of eight "strategic net-zero technologies".[2] In this paper, we examine two aspects of clean-tech development. Firstly, we look at technology development and secondly at manufacturing production. Our results show that, while Europe has a strong international position in net- zero energy technology development, its capacity in clean-tech manufacturing is substantially weaker.

In this paper, we conjecture that patents are a key element in the supply chain and, therefore, also important for net-zero technologies. By mapping strategic net-zero technologies to patent categories in PATSTAT, we analyze if the EU currently has a competitive advantage compared to the U.S. and China. We find that the EU has a significantly higher number of patents in green tech than both China and the US. In other words, a high share of innovations and developments of new technologies, related to the ones mentioned in the net-zero industry act, is already today done in the EU.

Furthermore, we examine how patents in strategic technologies are distributed among 27 countries in the European Union. This empirical exercise sheds light on whether the efforts by the European Union may benefit the development in specific countries. There is a very large heterogeneity in innovations and technology development within the EU. More specifically, Germany dominates and accounts for around two thirds of all patents in green technology. Moreover, there are some countries with strong positions in specific industries, such as Denmark and France, Finally, Eastern- and South Europe have very limited capabilities in green tech development.

The strong position of the EU in innovation does not correspond to production. Europe is currently a net importer in the eight net-zero energy technologies, with, for example, nearly all solar PV modules and fuel cells imported from China, whose supportive industrial policies, access to low-cost energy and materials, availability of skilled and cheap workers, and trade policies largely explain its globally dominant manufacturing base.

[1] China holds at least 60% of the world's manufacturing capacity for most mass-manufactured technologies (e.g., solar photovoltaic (PV), wind systems, and batteries) and 40% of electrolyzer manufacturing.

[2] Solar photovoltaic and solar thermal; onshore wind and offshore renewable energy; batteries and storage; heat pumps and geothermal energy; electrolyzers and fuel cells; biogas/biomethane; carbon capture, utilization, and storage; grid technologies; and sustainable alternative fuels technologies.

Almost half of the world's low-carbon investments took place in China in 2022. The country spent $546 billion in 2022 on investments that included solar and wind energy, electric vehicles, and batteries. The European Union was second to China with $180 billion in clean-energy investments, followed by the U.S. with $141 billion.

The remainder of the paper is organized as follows. In the next section, we provide a brief background on recent environmental policies in the EU and the U.S., followed by a theoretical and empirical background to the research topic addressed. Section 3 presents the data, followed by the analysis of descriptive data in Sect. 4. The final section summarizes and discusses policy implications.

2 Background and motivation

2.1 The net-zero industry act

The burgeoning emphasis on green technology within Europe is prominently reflected in the net-zero industry act (NZIA). Launched by the EU in March 2023, the NZIA mandates a significant surge in the production of clean-tech within the union. Related programs such as Fit for Fifty-Five and Next Generation EU also emphasize the role of green technology, both in addressing climate change and in maintaining European competitiveness and living standards. This expansion of green technology explicitly aims to reduce the EU's dependence on foreign nations, especially China.

More exactly, the NZIA sets an ambitious objective: to ensure that by 2030, 40 percent of the union's consumption of clean-tech is produced domestically. While setting such explicit quantitative targets might be considered unorthodox in market economies, they have been recurrently integrated into German industrial strategies in recent years, as shown by Altmeier (2019), and Zettelmeyer (2019). The act also meticulously highlights the key strategic industries designated for promotion. These technologies encompass solar photovoltaic and solar thermal technologies, both onshore and offshore renewable energy, battery/storage solutions, heat pumps, geothermal energy modules, electrolyzers, fuel cells, sustainable biogas, and biomethane technologies, carbon capture and storage methods, and advanced grid systems (European Commission, 2023).

The NZIA delineates a clear strategy for amplifying production in the mentioned industries. As detailed by Tagliapietra et al. (2023), the primary methods proposed for achieving this include the acceleration of permissions and related administrative procedures. The EU has set definitive time limits for these procedures and advocates for the establishment of a singular national authority, acting as a "one-stop-shop", to oversee these projects. Furthermore, there is a significant emphasis on the coordination of private funding. The Commission's projections estimate that accomplishing the prominent target of 40 percent of green tech being produced in the EU by 2030 requires an investment of around €92 billion. A substantial majority, approximately 80 percent, is anticipated to come from the private sector. This will be streamlined through the "Net-Zero Europe Platform," which aims to enhance networking and leverage existing industry alliances. Although public subsidies will play a role, they will primarily be sourced at the national level. The NZIA notably does not introduce new EU-level funding.

Moreover, there is a push towards revising public procurement procedures and auctions to emphasize "sustainability and resilience" criteria. Simultaneously, there's a caveat: bids proposing the use of equipment mainly sourced (at least 65 percent) from non-EU countries are slated to face disadvantages. The NZIA proposal alludes to additional areas, such as regulatory sandboxes and a skills-centric agenda, but stops short of providing detailed implementation plans.

2.2 Why did the EU launch NZIA?

The NZIA, as previously discussed, is an integral component of the EU's overarching climate policy. However, it is imperative to note that the cornerstone of the climate approach of the union is the EU emissions trading system (ETS). With its anticipated expansion (ETS 2) to include emissions from construction and heating of buildings and from the transport sectors, the ETS is presumed adequately equipped to achieve emission benchmarks. Although the NZIA might streamline this pursuit, it distinctly deviates from the ETS's market-centric ethos and its emphasis on escalating carbon pricing. A more salient impetus behind the EU's drive to augment clean-tech production appears to be rooted in the shifting terrains of global geopolitics and production paradigms.

High geographical and market concentrations of minerals and manufacturing have contributed to renewed discussions on the benefits and costs of imports of net-zero energy technologies. Significant events with major global consequences, such as the COVID-19 pandemic, Russia's war against Ukraine, and increased geopolitical tensions between China and other leading industrial nations raise concerns about risks with prevailing global value chains. More rationalized production would perhaps provide greater security against disruptions that can lead to shortages in supply and uncertainty regarding net-zero energy technologies.

For example, the production of critical minerals is highly geographically concentrated. The Democratic Republic of Congo supplies 70% of cobalt today, China provides 60% of rare earth elements (REE), Australia accounts for 55% of lithium mining and Indonesia has 40% of nickel. Processing of these minerals is also highly concentrated, with China being responsible for the refining of 90% of REEs and 60–70% of lithium and cobalt. In 2021, China held 40–80% of the global mass-manufacturing capacity for producing some of the key clean-energy technologies: solar PV systems 85%, electric vehicles 71%, offshore wind 70%, onshore wind 59%, fuel cell trucks 47%, electrolyzers 41%, and heat pumps 39%.[3] Geopolitical discussions on the dominant global value chains are not only about securing access to minerals, components, and products, but also about markets and market shares. Battery cell manufacturing, for example, is expected to increase sixfold by 2030.

[3] https://www.visualcapitalist.com/where-are-clean-energy-technologies-manufactured/.

China emerges as a focal point in this discourse. The EU's reticence to rely heavily on Chinese imports subtly resonates throughout the NZIA text. Historically, China has strategically concentrated on several industries now underscored by the NZIA. For example, sectors such as these were integral to initiatives like the "Made in China" strategy unveiled in 2015 and the "Dual circulation" introduced in 2020. These prioritized sectors in China receive substantial state support, from subsidies and preferential land and capital access to protectionist measures against foreign competitors via tariffs and non-tariff barriers. Recently, the U.S. ban on high-tech exports to China has resulted in a wave of new industrial policies, aiming at self-reliance in what is perceived as vital industries.

China's support of green technology is particularly noticeable. China aims to be a world leader in the development of many green technologies and in the production of related industries. Explicit goals on production and market shares are set to guide policy makers and companies. Some of the results can already be seen, for example, in electrical vehicles and batteries. Progress so far has been more limited in other supported industries, such as high-tech chips and various types of high-tech equipment.

Accusations from the EU and the U.S. posited that China was not maintaining a level playing field. Consequently, the EU, under the stewardship of Angela Merkel, brokered an investment pact with China aimed at resolving these disparities. However, the ratification process was prolonged. By the time the EU was poised to validate the agreement in 2019, its perception of China had drastically deteriorated, due in part to events in Hong Kong, increasing tensions with Taiwan and the reported treatment of the Uighurs in Xinjiang. The resultant political climate saw the EU parliament vetoing the deal. Consequently, instead of China moderating its domestic support mechanisms, the West, including the EU and the U.S., has evolved to mirror aspects of China's industrial policies.

In a parallel development, the U.S. rolled out the Inflation Reduction Act (IRA), a formidable initiative that aims to reduce greenhouse emissions by championing green tech and renewable energy sectors. The IRA, as described by Kleimann, Poitiers, Sapir, Tagliapietra, Véron, Veugelers and Zettelmeyer (2023), adopts a carrot-focused approach, without punitive sticks. Unlike the ETS, it does not impose costs on carbon emissions but generously subsidizes a spectrum of eco-friendly production avenues, from electric vehicles and renewable energy components to carbon–neutral electricity, hydrogen, and other sustainable fuels. A salient feature of the IRA is its stipulation that subsidies are predominantly earmarked for domestically produced goods, further accentuating the "Buy American" ethos. Although the European Net-Zero Industry Act aims at reducing foreign dependence outside the Union and increasing competitiveness, stating that "any green trade is carried out under the principles of fair competition and open trade", the US Investment Reduction Act (IRA) has clear elements of "green protectionism". Some examples: The act will subsidize consumers thousands of dollars in tax credits when purchasing an electric vehicle–but only when the bulk of battery components are made or assembled in North America. In addition, tax credits for low-carbon energy technologies, such as batteries, solar panels, and wind turbines, should only apply to products made within the U.S. This provision has stoked anxieties within the EU, with speculations, such as those by Holtzhausen (2023), suggesting that the IRA could catalyze a production and export decline in the EU, due to potential relocation to the U.S. Such fears significantly contribute to the inception of the NZIA. Adding to the uncertainty is that the IRA is controversial within the U.S. With President Biden stepping down from office, the future of the IRA is unclear. However, it is probable that industrial policies and support for certain, though not necessarily all, green technologies will persist in the US, either through subsidies, protective measures, or a combination of both.

2.3 Opportunities and challenges

There is broad agreement in the literature that private sector innovation is critical to mitigating and adapting to climate change, and there is a growing body of economic research investigating how induced technological change can stimulate innovation in renewable energy (Popp 2019). There is also a consensus that market mechanisms alone cannot provide the socially optimal amount of clean innovation. The main issues are associated with factors such as technological spillovers, (Rodrik 2014; Aghion and Jaravel 2015), path dependence (Dechezleprêtre, Martin and Mohnen, 2014), and pollution as a negative externality (Gerlagh et al. 2009). Economic theories on the role of induced innovation and directed technical change have been developed to address these market failures. A seminal paper is the endogenous growth model of directed technical change proposed by Acemoglu et al. (2012). The induced innovation hypothesis, is a central building block in this two-sector model which allows profit-maximizing firms to decide whether to innovate in environmental technologies or in carbon-intensive technologies. If clean technologies are initially less developed, the potential for innovation is low because clean research requires substantial R&D investment to be competitive.

Technological progress is path dependent and builds on the accumulated knowledge from prior research. As the economy historically has accumulated a much smaller stock of knowledge for clean technologies, green innovations have a disadvantage in the market, and uncertainty about future returns of environmental R&D investment has been assessed to be particularly high (Jaffe et al. 2002).

Without public intervention to promote clean technology, the transition process towards a carbon–neutral world may be seriously delayed. Therefore, government intervention is necessary, and temporary taxes or subsidies can redirect innovation towards the clean sector. This is particularly important for renewable energy technologies, as innovators are typically younger and smaller compared to other firms, and the technology is less mature, which may imply high sunk costs. Nelson and Shrimali (2014) estimate that upfront capital costs represent 84–93% of total project costs for wind, solar, and hydro energy (compared to 66–69% and 24–37% for coal and gas, respectively).

Hence, there are compelling economic justifications, including market failures and externalities, that support the implementation of industrial policies such as NZIA. It is also true that the empirical literature on industrial policies makes it evident that crafting these policies can be challenging, with numerous documented failures (Mazzucato 2013; Pigou 1920; Rodrik 2004).

For example, the effects of Chinese industrial policies on the development trajectories of the U.S. and the EU are undeniable. However, upon delving deeper into the Chinese experience, there seems to be minimal evidence to suggest positive outcomes from the provided subsidies and support. Specifically, Branstetter et al. (2022) discovered a negative correlation between government subsidies and firm productivity. Firms that benefited from state support underperformed in comparison to their unsupported counterparts. This observation remains consistent across various forms of subsidies, including those aimed at research, innovation, and equipment upgrades. Furthermore, there is no evidence of increased expenditures on research and development, patenting, or profitability among companies that are recipients of these subsidies, as highlighted in Branstetter and Li (2022). One plausible explanation for this could be the tendency of the government to allocate support to firms with political connections, as opposed to the most efficient ones (Cheng et al. 2019).

Furthermore, there are specific elements in the design of the net-zero innovation agenda (NZIA) that could potentially hinder its influence on the advancement of clean technologies (Tagliapietra et al. 2023). For example, the European Union (EU) is currently favoring particular technologies for support, instead of adopting a technology-neutral stance that prioritizes the attainment of net-zero objectives, such as reduced emissions and heightened competitiveness. This exclusionary approach renders numerous existing clean-tech solutions ineligible for assistance, and more critically, could stifle the innovation of entirely new technologies. Other notable drawbacks include inadequate governance, insufficient attention to key areas like capital access and skilled workforce availability, and adverse impacts on the internal market's level playing field. These issues have been underscored as significant challenges that need to be addressed (Tagliapietra et al. 2023).

In summary, while there is theoretical support that government intervention is necessary to break fossil-fueled growth and achieve net-zero productivity, research has largely neglected the importance of different geopolitical centers conducting such intervention in global competition. This policy risks entailing "green protectionism" and cutting off existing value chains, while reducing a critical dependence on a few players in the global market. Our paper is an attempt to address some possible consequences of the European Net-Zero Industry Act based mainly on patent data supplemented with manufacturing data on the company level.

3 Data

We access the PATSTAT database and examine patents in so-called strategic net-zero technologies. The mapping is based on the classification of green patents, with an additional manual screening of patent codes. For example, solar photovoltaic and solar thermal technologies (hereafter solar) are mapped to patent classes Y02E 10/40 to Y02E 10/60. The full mapping of strategic technologies to PATSTAT codes is shown in Table 1. We use annual data spanning from 2016 to 2019. In addition,

Table 1 Mapping

Techology	PATSTAT
1. Solar photovoltaic and solar thermal	Y02E 10/40—10/60
2. Onshore wind and offshore renewable	Y02E 10/70
3. Battery/storage	Y02E 60/10 + Y02E 60/32
4. Heat pumps and geothermal energy	Y02E 10/10 + F24 H 4/00
5. Electrolysers and fuel cells	Y02E 60/50 + Y02E 60/36
6. Sustainable biogas/biomethane	Y02E 50/00
7. Carbon capture and storage (CCS)	Y02E 20/18
8. Grid	Y02E 40/70

Mapping is based on strategic net-zero technology and PATSTAT codes and is done by the authors

we use aggregated patent data from the OECD and miscellaneous market data fetched from Statista.

4 Descriptive statistics and analysis

In this section, we present descriptive statistics and provide an analytic interpretation based on this information. First, we show data on the number of patents in strategic net-zero industries sorted by geographic region and country. We then continue by looking at the largest manufacturers in these sectors. We restrict the subsequent analysis to the three key strategic net-zero technologies of solar energy, wind energy, and batteries.

4.1 Patent

Table 2 shows the number of patent applications over the period 2015–2019 in the eight net-zero energy technologies, that the EU has singled out to be *strategic net-zero*, distributed across Japan, EU27, U.S., China, and India. We consider patent

Table 2 Number of patents by region and strategic net-zero industry

	Solar	Wind	Battery	Heat Pump	Electrolyses	Biogas	CCS	Grid	Sum
Japan	3,503	461	12,763	149	3,163	219	44	201	20,503
EU 27	2,904	3,589	7,765	176	2,118	950	21	54	17,577
U.S	3,704	1,283	6,240	118	1,664	1,212	70	187	14,478
China	2,247	264	3,215	34	161	74	2	29	6,026
India	28	12	46	0	13	27	0	0	126
Sum	12,386	5,609	30,029	477	7,119	2,482	137	471	58,710

The table shows the number of patents in the technologies in Table 1 for different regions. Data is aggregated over the period 2016–2019 and based on PATSTAT families (a unique invention belongs to the same family regardless of whether it is protected in a single country or several countries). Several things are notable. For instance, more than half of the patents relate to battery technologies. Japan has the most patents of the five regions. But this can partly be explained by the high frequency of "patent blocking" and the number of patent applications without request for examination. More than a tenth of patent applications in Japan are withdrawn without requests for examination. With this in mind, EU27 has the most valid patent applications (as well as granted applications) of the five regions. Moreover, the EU27 has nearly three times as many patent applications in strategic net-zero technologies as China, and India have very few patents in this area. Finally, if we ignore Japan because of the patent blocking reason, EU27 is the most innovative region in the world when it comes to battery, wind, heat pump, and electrolysis technology. The table also shows that China has fewer patent applications than both the EU27 and the U.S.

Thus, our first conclusion is that the EU is a global leader with respect to innovation and the first link in the value chain for strategic net-zero energy technologies. However, we should also remember that innovation is closely associated with shared knowledge, spillovers, and collaboration. OECD statistics show that almost a tenth of the EU27 environmental related patents have a co-inventor from countries outside the union.[4] Moreover, about 5% of the EU patents belong to companies with owners outside the EU. Even taking these considerations into account, it seems fair to say that the EU has a strong position in net-zero technology development.

We continue with a more detailed description of the development of net-zero technology in Table 3, which shows the number of patents in strategic net-zero industries by the 27 EU members. When aggregating all strategic technologies, Germany has by far the most patents. We know from the global comparison, that the EU is particularly strong in wind and also in battery innovations. Patents in wind technology are mainly held by Germany and Denmark (for a graphical illustration, see Figs. 1, 2, and 3). Battery storage patents are clustered in Germany and France. In solar, the most number of patents are held in Germany, followed by France and the Netherlands. Hence, the figures reveal a great deal of country heterogeneity when it comes to technology development. There are low levels of innovation and technology development in East European countries and also in Greece. Moreover, also notable is Italy's and Spain's low level of patents compared to Germany and France.

Regarding national comparative advantages in net-zero technologies, Table 3 shows that Austria, Belgium, Germany, Finland, France, and Sweden have the largest share of their patents in batteries. Denmark, in particular, as well as Spain, exhibit a relative innovation strength in wind technology. Countries with a relative advantage in solar innovations include the Netherlands, Poland, Italy, and Ireland.

We conclude that Germany is the EU's innovation hub with almost two thirds of all patent applications in strategic energy technologies. Germany has more patents than any of the other EU countries in each of the eight technology areas. Other member countries are satellites outside the hub with a large degree of

[4] https://stats.oecd.org/index.aspx?queryid=29068.

Table 3 Number of patents by EU country and strategic net-zero industry

	Solar	Wind	Battery	Heat pump	Electrolyses	Biogas	CCS	Grid	Sum
Austria	93	43	143	3	93	26	1	1	403
Belgium	55	50	218	10	20	18	0	2	373
Germany	1,511	1,550	5,905	73	1,599	221	20	24	10,893
Denmark	35	1,348	68	7	63	162	0	4	1,687
Estonia	6	4	4	0	0	1	0	0	15
Spain	157	196	52	2	17	39	1	2	466
Finland	53	23	83	10	24	81	2	1	277
France	362	100	873	23	137	127	2	7	1,631
Greece	3	2	3	0	0	0	0	0	8
Ireland	35	9	15	0	8	6	0	7	80
Italy	182	36	138	14	27	54	1	2	454
Latvia	1	0	1	0	0	0	0	0	2
Luxemburg	15	9	16	0	0	4	1	0	45
Lithuania	0	6	2	0	0	0	0	0	8
Netherlands	203	136	106	7	94	136	1	1	684
Poland	73	17	18	1	3	17	1	0	130
Portugal	21	3	3	1	6	1	0	0	35
Sweden	93	52	117	21	25	47	1	3	359
Slovenia	2	1	2	1	2	0	0	0	8
Slovak Republic	4	4	0	3	0	8	0	0	19
Sum	2,904	3,589	7,767	176	2,118	948	31	54	17,577

The table shows the number of patents in the technologies shown in Table 1 for different European countries. Data is aggregated over the period 2016–2019 and based on PATSTAT

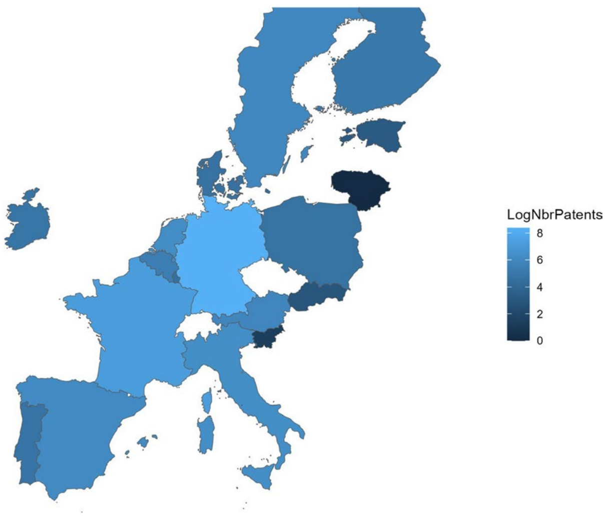

Fig. 1 Number of solar patents by country from 2016 to 2019, log-scale

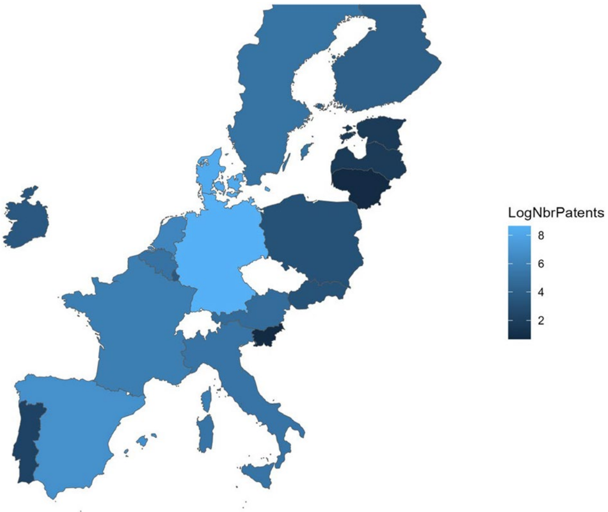

Fig. 2 Number of wind patents by country from 2016 to 2019, log-scale

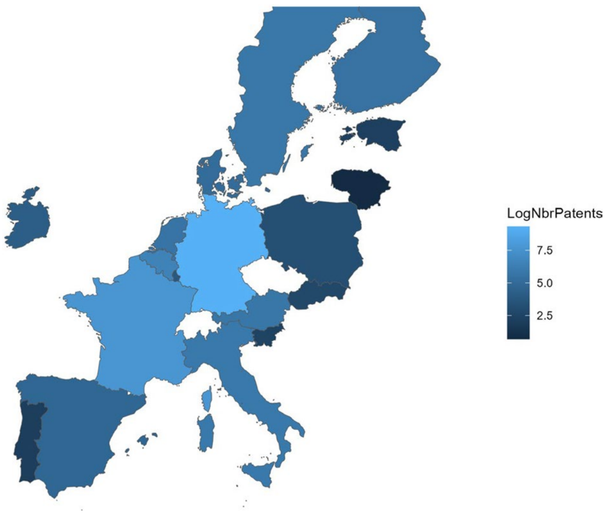

Fig. 3 Number of battery patents by country from 2016 to 2019, log-scale

heterogeneity in patent size. More than 80% of the patents are concentrated in three technologies, i.e., solar, wind, and battery, and most member countries have their relative specialization in batteries or solar technology. One notable exception is Denmark, with most of its patents in the wind sector.

4.2 Patents and government spending

We continue by examining whether the high level of net-zero technology development is related to EU subsidies. This issue is important considering the current EU policy to increase green tech development and production through various types of subsidies. In other words, past experience might give a sense of how successful the current policy can be expected to be.

More precisely, the figures in Table 4 show the number of patents in relation to the amount governments spend on R&D. It should be pointed out that the table's data, which comes from OECD statistics, does not weight the patents according to their relative importance (e.g., with the help of citations), or between radical and incremental patents, new and mature technology areas, etc. Moreover, the data are restricted to European member states of the OECD. Table 4 presents all environmental related patents (ERT) in the left column and the sub–population climate change mitigation energy patent (CCMET) in the right column. The latter mainly captures the strategic net-zero technologies.

Table 4 Green patents per unit of government spending

Country	ERT Patents/unit government R&D	CCMET patents/unit public R&D
Austria	2.72	1.14
Belgium	2.05	1.6
Denmark	3.43	5.93
Estonia	1.4	0.76
Finland	1.58	0.94
France	0.76	0.76
Germany	1.44	1.89
Greece	0.17	–
Hungary	0.51	1.2
Ireland	2.13	0.65
Italy	0.8	0.75
Latvia	0.2	–
Lithuania	0.5	–
Luxemburg	1.16	–
Netherlands	2.15	0.9
Poland	0.5	0.53
Portugal	0.39	0.57
Slovak Republic	0.93	2.97
Slovenia	0.63	–
Spain	0.45	1.31
Sweden	1.79	1.15

The table is based on OECD data. The table shows the number of patents per dollar spent in environmental related patents (ERT) and the sub-population climate change-mitigating energy patent (CCMET)

We are interested in whether government spending on research and development results in patents. Table 4 shows the number of environmental related patents (ERT) as well as climate change-mitigating energy patents (CCMET) related to energy generation, transmission, or distribution. The countries that receive the highest return on investments in CCMET are Denmark and Germany. Regarding environmental related technologies, Austria, Belgium, Denmark, the Netherlands, and Ireland have the highest R&D productivity among the EU countries. For CCMET, Denmark–with a focus on wind technology–produces the most patents per subsidized research dollar in the energy sector.

Although the comparisons in Table 4 should be interpreted with great caution, we conclude that there are significant differences in patents per subsidized monetary unit between EU member states. There is also a tendency towards systematic differences, that is, the richer EU countries have a higher return on public R&D support than the poorer member states.

4.3 Manufacturing

The explicit ambition of the EU's net-zero industry is to reduce the dependence on imports of strategic net-zero technology from China and to meet the US's in- creased protectionist policies. As previously mentioned, the Net-zero Industry Act states that at least 40% of the EU's low-carbon technologies will be made within its borders by 2030. This section examines whether current production matches this vision.

In the subsequent analysis, we focus on solar, wind, and battery, as they are the three main strategic technologies from the perspective of innovation, which is the point of departure for our paper. Our approach is to specifically examine the largest manufacturing companies in the three selected technologies.

Starting with solar technology, both photovoltaic and thermal, Table 5 presents the eight leading technology manufacturers by pipeline capacity in 2021. EU27 is the most innovative region in this technology, as shown above, but none of the top producers are European. Most of the largest companies are Chinese with a total pipeline capacity of 28 gigawatt, which is double the capacity of the leading American and Australian companies.

Table 5 Leading solar technology manufacturers 2021, by pipeline capacity

Company	GW
First Solar Inc (U.S.)	14.8
5B Australia Pty Ltd (Australia)	14.0
JinkoSolar Holding Co Ltd (China)	9.7
LONGi Green Technology Co Ltd (China)	7.4
Canadian Solar Inc (Canada)	6.8
JA Solar Technology Co Ltd (China)	5.6
Trina Solar Co Ltd (China)	2.9
Risen Energy Co Ltd (China)	2.3

Financial Times, March 2023 (via Statista id 513,150)

Table 6 Global commissioned capacity of major wind companies 2021

Company	GW
Vestas (Denmark)	15.2
Goldwind (China)	12.04
Siemens Gamesa (Spain)	8.64
Envision (China)	8.46
GE (USA)	8.30
Windey (China)	7.71
Ming Yang (China)	7.53
Nordex (Germany)	6.80
Shanghai Electric (China)	5.34
Dongfang Electric (China)	1.46

BloombergNEF, March 2022 (via Statista id 516,028)

Table 7 Largest battery manufacturers

Company	Note
CATL (China)	responsible for 96.7 GWh of the worlds's total of 296.8 GWh
LG (S. Korea)	
Panasonic (Japan)	major supplier for Tesla together with BYD (China)
Samsung SDI (S. Korea) SKI (S. Korea)	
CALB (China) Grepow (China)	
AESC (Japan)	joint venture between Nissan, NEC and Tokin Corporation
EVE (China)	

The table is based on: https://history-computer.com/ 10-largest-and-most-important-battery-companies-in-the-world/)

Next, we consider the largest companies in wind technologies. As seen above, China is lagging behind the EU and the U.S. in invention capacity in this industry. However, this is not reflected in manufacturing capacity. Table 6 shows that six out of ten leading manufacturers of wind technology are Chinese. However, Denmark, Germany, and Spain are also strong in wind energy production. All three countries have top-producing wind companies. Similar to all top producers of clean technology, the companies are global with a presence in various regions. The Danish company Vestas, for example, has most of its production sites in Europe. The manufacturing of blades, turbines, and generators is concentrated in six plants in Denmark and six plants in other European countries. But they also have 8 plants outside Europe.[5] The German company Siemens Gamesa has 6 production sites in Europe, compared to 10 in the rest of the world.[6]

Most batteries are produced in China, which has a 45% market share in the battery industry. India, and the U.S. combined have around 20% market share in the

[5] see, https://www.vestas.com/en/about/our-locations/production.

[6] see, https://www.siemensgamesa.com/about-us/location-finder.

Table 8 Projected battery cell production Europe 2030, by company

Company	GW
CATL (China)	140
Freyr (Norway)	98
Northvolt (Sweden)	94
LG Chem (South Korea)	93
Tesla (USA)	93
ACC (France)	92
Volkswagen Group (Germany)	90

Transport and Environment, March 2023, Statista id: 1,375,189)

global battery industry.[7] The importance of China is also shown in Table 7, which shows the largest batteries manufacturers in the world. The largest company on the list is the Chinese company CATL, which is responsible for one-third of the production. There are also other Chinese companies among the largest ones. The rest of the companies on the list are either South Korean or Japanese.

However, it should be noted that there is a strong increase in the global manufacturing capacity of batteries. Hence, the current pattern might change. An attempt to predict future battery production is seen in Table 8, where we look at a forecast of future battery cell production in Europe. Again, the Chinese company CATL is the largest company, but there are some European companies. For example, Northvolt was number two with planned production in Sweden and other European countries,[8] and ACC has factories in France, Germany, and Italy.[9]

Hence, a tentative conclusion is that European companies should be able to increase their market shares in the manufacturing of batteries.

Our analyses reveal that wind is a technology in which Europe is relatively strong measured in both innovation and manufacturing. Further investments in wind technology can increase innovation in countries like Denmark as there is domestic manufacturing and strong domestic research. Solar, on the other hand, is a technology where Europe is weak both in patents and manufacturing. For battery technology, we note that the EU has strong patents, but weak manufacturing. We observe that new production sites are under construction, but it is likely that China will continue to dominate manufacturing in the foreseeable future.

The overall conclusion from our research in this section is that the EU has a comparative advantage in developing strategic net-zero technologies, but often falls short in manufacturing the final products.

7 www.bolddata.nl

8 see, https://northvolt.com/manufacturing/#manufacturing-locations.

9 see, https://www.acc-emotion.com/batteries.

5 Concluding discussion

Escalating trade tension in clean-tech between the U.S. and China poses significant challenges for EU with regards to its objectives on decarbonization, geopolitical resilience, economic efficiency and anticipated growth potential. To address challenges in renewable energy technology, EU policymakers have set the goal of at least 40% strategic technologies to be produced in the union by 2030, supported by subsidies and regulations.

Although the development towards increasingly local and regional trade patterns in clean-tech can be justified by safeguarding supply links and domestic production, in the short and perhaps medium term it cannot replace the advantages of a global trade system. The general conclusion from our analysis of the proposed strategic net-zero technologies among 27 countries in the European Union is that the EU will continue to be heavily dependent on a small number of global manufacturing companies, a significant proportion of which are Chinese, to have a rapid transition to a carbon-free energy supply.

EU has its comparative advantage in the development stage of the nine renewable energy in the net-zero industrial act (NZIA), of which more than 80% are classified within the solar, wind, and battery classes. Germany is the EU's innovation hub with little less than two-third of all patent applications in the NZIA-technologies. Other member countries may be considered as satellites outside the hub with a large degree of heterogeneity in innovation performance.

The NZIA-approach follows the U.S. President's Inflation Reduction Act (IRA) from 2022 by relying heavily on import substitution, disregarding the costs of promoting self-sufficiency compared to the use of cheaper imports. However, it differs by adopting a similar benchmark value for all nine technologies despite different levels of initial comparative advantages and growth potentials.

Since the proposal fails to account for economic inefficiencies caused by increased protectionism, protecting industries dependent on subsidies, it deviates from technology-neutral industrial policy, and targets total import volumes rather than dependence on a few import suppliers, thus, the long-term and overall impact on growth and jobs, decarbonization, and geopolitical resilience may be weak, nonexistent, or even negative.

Indeed, the EU's high import dependency on China, especially for solar panels, poses significant risks due to China's dominant market position and limited supplier diversity. However, potential drawbacks must be weighed against the benefits of increasingly innovative and affordable Chinese products, which offer a cost-efficient solution to reduce the reliance of Europe on fossil fuels and transition to cleaner energy sources.

We argue that the EU should continue to prioritize innovation capability over production volume in its industrial policy. Europe has a comparative advantage in the early stages of the development of renewable energy technologies, where there is significant potential for further innovations. Supporting innovative producers aligns with the EU's Green Deal strategy to boost investment in green research and innovation, establish lead markets in clean technologies, and leverage single-market competition policy more strategically. Subsidizing producers solely to increase domestic content is unlikely to effectively address regional and subnational challenges related to growth and jobs, decarbonization, and geopolitical resilience.

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