The Role of Industrial Policy in the Renewable Energy Sector*

Todd Gerarden† Mar Reguant‡ Daniel Yi Xu§

May 16, 2025

Abstract

Renewable electricity generation technology costs have fallen dramatically, investment has grown rapidly, and renewables are now a pillar of climate and decarbonization policy. Part of the credit for these trends goes to environmental policy efforts to support renewable energy as a substitute to fossil energy. The recent rise in protectionism, industrial policy, and geopolitical tensions has the potential to either undermine or enhance these environmental policy objectives. In this paper, we provide an overview of renewable energy economics and policy, with a focus on solar and wind power. We outline theoretical rationales for industrial policy and review recent empirical research, paying particular attention to how renewable energy policies have generated spillovers across firms and countries. We close by highlighting how this recent evidence can inform ongoing industrial policy debates.

*We thank the organizers of the 7th Annual NBER Environmental and Energy Policy and the Economy Conference, supported by the Alfred P. Sloan Foundation, for the opportunity to expand our nascent project into this paper. We are grateful to Ralph Ossa, Bob Staiger, Dan Trefler, and Pinelopi Goldberg for suggesting this project. We thank our discussants Stephane Hallegatte and Joseph S. Shapiro, as well as other participants of the "Expert Dialog on Subsidy Reform" conferences in Washington, DC and Geneva, for their many constructive comments. Victor Simões Dornelas, Ha Pham, Anran Tan, and Mayra Wagner provided invaluable research assistance. This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 101001732-ENECML), and from The 2030 Project: A Cornell Climate Initiative and Cornell Atkinson Center for Sustainability.

†Cornell University

‡Northwestern University, BSE, CEPR, and NBER

§Duke University and NBER

1 Introduction

The renewable sector has been the fastest growing in the energy sector in recent years, with capacity additions in solar and wind outpacing those in any other technology (IRENA, 2024). The expansion of electricity generation capacity in these technologies was influenced by a first phase of targeted subsidies to solar and wind, which we describe in detail below, and the industry is now entering a phase in which new investments in these technologies are competitive with fossil fuel technologies in many markets (Bilicic & Scroggins, 2023). This large expansion in renewable power has also led nascent industries in wind turbine and solar panel manufacturing to become larger and more mature (IEA, 2024a). Yet, in the past decade the renewable energy sector has witnessed a rise in protectionist measures, other industrial policies intended to onshore manufacturing, and intensifying geopolitical competition between major players like China, the European Union, and the United States.

How large have subsidies been in the industry? To what extent can we associate the growth of renewable energy with subsidies versus other trends in the market? What have been the consequences of trade tensions and tariff wars in this context? What does the recent rise in industrial policy portend for renewable energy? While these are difficult questions to assess from a causal point of view, we provide descriptive evidence and review the literature documenting these effects.

While industrial policy can be controversial in many sectors, there are important features of renewable energy that deserve careful consideration. Subsidies to consumers or producers could be justified on the basis of several market failures, including environmental externalities, knowledge spillovers, Marshallian externalities, and imperfect competition, among others. The performance of past and present government interventions in the sector depends crucially on the presence and magnitude of these externalities. In some cases, such as the magnitude of environmental externalities, prior empirical evidence provides relatively clear answers. In others, such as the presence of Marshallian externalities or magnitude of knowledge spillovers, there is less prior research and very little clear guidance for policy.

We ground our assessment of the role of industrial policy in renewables by focusing on the specific cases of solar and wind electricity generation. As we will review, solar and wind technology cost decreases have consistently surprised many experts (Way et al., 2022), which has led electricity costs to fall, in many cases even when accounting for subsidy costs (Benhmad & Percebois, 2018; Mountain et al., 2018). Solar and wind are now leading new investment in the power sector in many countries (REN21, 2024b). Furthermore, these trends have generated positive spillovers for the costs of climate policies and decarbonization goals (IRENA, 2025; REN21, 2024a).

While the observed cost reductions in solar and wind technology are both success stories, their trajectories and experiences have been significantly different when it comes to protectionist measures

Table 1: Comparison between Wind and Solar

	Wind	Solar
Market structure	Concentrated	Fragmented, some leading brands
Technology	Large economies of scale Learning-by-doing (LBD) in size	More modular LBD in manufacturing, installation
Labor market	Upfront, mostly non-local	Manufacturing and installation
Trade costs	Large, produced near site	Small, global supply chain
Consumer subsidies	Utility-scale	Utility-scale and residential
Producer subsidies	Vary by country	Vary by country
Trade instruments	Limited interventions	Substantial interventions

like producer subsidies and trade policies. These two technologies offer a valuable comparative case study. Table 1 provides a summary of the main differences between the two technologies in terms of market structure, trade costs, manufacturing jobs, and trade policies.

In particular, one key difference between the two technologies is their economies of scale, and how this translates into trade costs. Technological progress in the solar industry has taken the form of incremental cost reductions through incremental improvements in energy conversion efficiency, materials, and manufacturing process improvements (IRENA, 2023b). In the wind sector, on the other hand, technological progress has primarily materialized in the form of bigger wind turbines that capture more energy from the same wind resource (IRENA, 2023b). These turbines, of massive scale, are produced by a small number of firms and are difficult to transport, making international competition harder and only focused on certain components of the supply chain. Thus, while the manufacturing of solar panels has witnessed a convergence of manufacturing to the countries with the greatest cost advantage, predominantly China, wind manufacturing exhibits somewhat less geographic concentration. On the other hand, in terms of individual firms' market shares, regional markets for wind turbines are more concentrated than for solar panels. These economic differences between the technologies imply that the rationales for, and effects of, industrial policy differ between the two contexts.

Our work contributes to a large literature on the economics of renewable electricity generation and the role of government policies in electricity markets. Borenstein (2012) provides an overview of the market and non-market value of renewable energy, and discusses the merits of several common arguments for government intervention to promote renewable electricity generation. Baker et al. (2013) provides a detailed primer on the economics of solar electricity. Other papers focus on empirically evaluating the effects of environmental policy and regulation on solar and wind generation (e.g., Aldy et al., 2023; Hitaj, 2013). Hahn et al. (2025) compare a broader range of climate policy tax instruments using the marginal value of public funds framework. They find that renewable energy subsidies deliver by far the highest returns to taxpayers across the range of climate subsidies they consider. Borenstein and Kellogg (2023) compare the performance of clean electricity subsidies, clean electricity standards, and carbon pricing. Pricing carbon using a Pigouvian tax is the textbook solution to environmental externalities created by carbon emissions, and is generally viewed as the best of the three policies on economic efficiency grounds. Borenstein and Kellogg (2023) point out an important preexisting distortion that complicates the textbook analysis: when retail electricity prices are above economically efficient levels, as is the case in many parts of the United States (Borenstein & Bushnell, 2022), carbon pricing becomes relatively less attractive. Under some scenarios, clean electricity subsidies could be more efficient than carbon pricing. Overall, this prior work emphasizes the role that subsidies to renewable energy can play as second-best environmental policies.

In contrast to this prior work, we focus on a broader set of policy tools and justifications that go beyond second-best environmental policy.[1] One notable exception is Rodrik (2014), who outlines a prospective argument in favor of green industrial policy. We retrospectively document the recent rise in protectionism and industrial policy in the renewable energy sector. We outline the canonical arguments for and against industrial policy and trade barriers, both with and without the presence of environmental externalities. Finally, we review recent empirical evidence on the performance of these different policy tools in practice to draw lessons to guide future policy development.

In section 2, we provide an overview of the cost trends, installed capacity, market structure, and sectoral employment over recent years. In section 3, we describe the evolution of consumer subsidies, producer subsidies and tariffs. We discuss economic rationales for the use of these schemes in section 4, with a special focus on spillovers between countries in section 5. Section 6 concludes.

2 Renewable sector overview

In this section, we provide an overview of developments in the renewable energy sector over the past 20 years, focusing on solar- and wind-powered electricity generation.

[1] Borenstein (2012) reviews other policy objectives such as energy security, non-appropriable intellectual property, and green jobs, and highlights a lack of empirical evidence to guide policy. We build upon and extend that survey by considering a broader set of policy tools currently in use by governments, discussing additional economic arguments such as terms of trade, and incorporating new empirical research done over the past decade. Hahn et al. (2025) account for learning-by-doing effects from renewable energy subsidies, but their policy analysis does not extend to subsidies for renewable energy techhnology manufacturers or trade barriers.

2.1 Trends in costs

The deployment of solar photovoltaics (PV) and wind turbines increased significantly starting around 2000 and accelerated in the 2010s due to technological advancements and financial support schemes for private households and manufacturers. As global competition for leading innovation and manufacturing of renewable energy technology intensified, installation and operation costs for solar and wind also decreased significantly worldwide.[2]

Figure 1 summarizes the key factors surrounding the reduction in costs of solar PV, onshore wind, and offshore wind over the past decade. The left-most panel shows the levelized cost of electricity (LCOE), defined as the average net present cost per unit of electricity generated over the lifetime of a generator. This metric captures differences in upfront costs, operations and maintenance costs, and productivity across technologies. Total installed costs, in the center panel, are comprised of hardware costs—primarily solar panels and wind turbines, but also complementary hardware inputs—as well as other installation and grid connection costs. The right-most panel displays the capacity factor, or the ratio between the electricity generated by a technology and what would have been produced if it operated continuously at its maximum capacity.

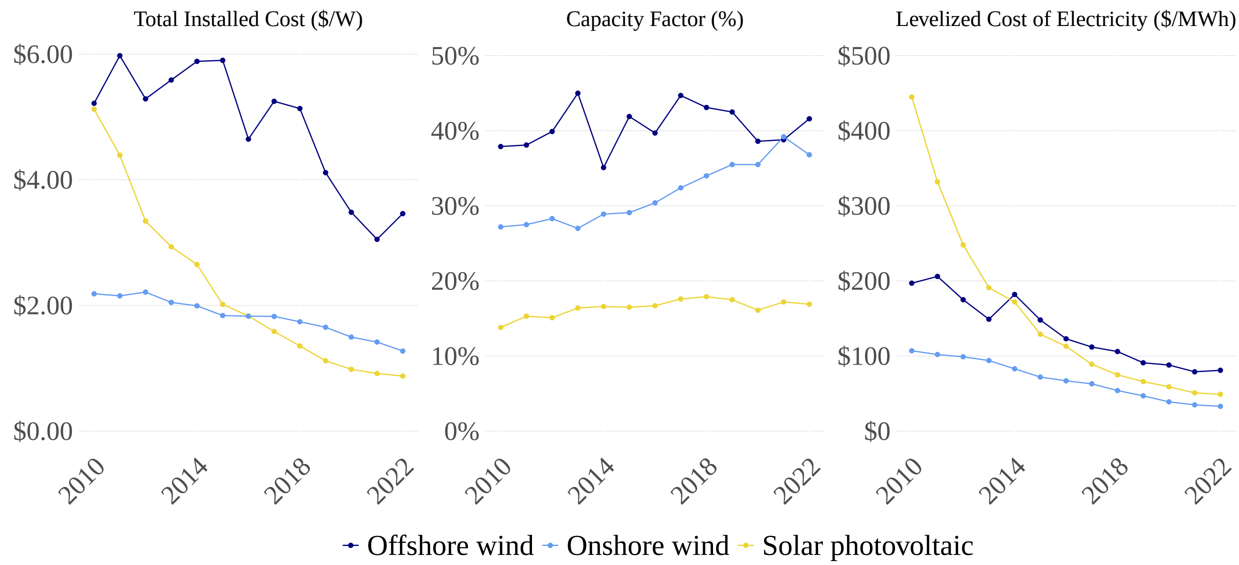
From 2010 to 2022, global average total installed cost for solar PV fell by 83% (IRENA, 2023b, p. 15). These global average figures capture secular trends but mask significant heterogeneity across countries at a given point in time. Figure A.1 shows that, in 2022, solar systems installed in China had average total costs of $0.72 per Watt, whereas systems installed in the US cost $1.12 per Watt on average. The EU countries with the lowest total installed costs for solar fell in between these two extremes, with total installed costs of roughly $0.77 per Watt in Italy and Spain.

As installed costs came down over time, the productivity of solar PV technology also increased, as summarized by the gradual increase in average capacity factor in Figure 1. Improved design and operation of solar systems, the use of solar trackers, and targeted deployment in locations with higher radiation levels are some of the factors that led to increased capacity factors. The combined effect of these changes in cost and productivity were sharp reductions the LCOE for solar technology, driven primarily by the reductions in total installed costs.

Wind power has also exhibited significant changes in cost and productivity over time. Total installed costs decreased substantially for both onshore and offshore wind, as illustrated in Figure 1. The primary driver of these cost declines was reductions in turbine prices per Watt of electricity generating capacity. For offshore wind, costs are also influenced by inherent challenges related to installing wind turbines in deep waters. As such, total installed costs for offshore wind are more

[2] In this brief overview of the evolution of costs over time, we draw heavily from analyses produced by the International Renewable Agency (IRENA, 2023b), a multilateral organization that supports the diffusion of renewable energy by facilitating cooperation between countries, compiling data, and reporting on the progress and challenges at the global and local scales.

Figure 1: Trends in costs: total installed cost, capacity factor, and levelized cost of electricity



Source: Authors' visualization based on data from IRENA (2023b, p. 42). Total installed cost accounts for all costs involved in completing a project, including hardware, installation, grid connection, engineering, permitting, etc. Capacity factor is the ratio between the electricity generated by a technology and what would have been produced if it operated continuously at its maximum capacity. Levelized cost of electricity (LCOE) is the net present cost per unit of electricity generated over the lifetime of a technology. Values are global weighted averages, with weights given by megawatts (MW) of installed capacity (IRENA, 2023b, p. 23). All dollars are 2022 USD.

subject to fluctuations associated with supply chain bottlenecks and local characteristics of wind projects, which vary based on differential deployment patterns across markets and years.

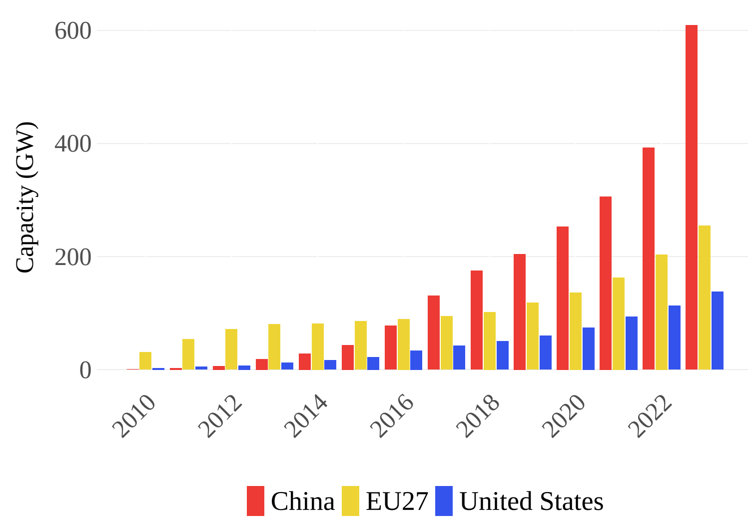
As with solar PV, the productivity of wind turbines has also increased substantially over time, particularly for onshore wind installations. Wind power capacity factors are influenced by the environmental conditions a turbine is subject to, and by how well-suited its technical features are to the environment in which it is installed. The growing deployment of taller turbines that have longer blades has been a key factor in increasing capacity factors, particularly for onshore wind farms in regions well-suited to wind generation in the United States and Latin America. By contrast, the capacity factor of offshore wind has been subject to considerably more volatility due to the varying quality of sites across regions. For example, the decline in capacity factor between 2017 and 2021 can be partly attributed to the expansion of offshore wind in China in locations with less-than-ideal conditions (e.g., too close to the shore) (IRENA, 2023b).

In total, decreases in total installed costs and increases in capacity factors combined to reduce the LCOE of wind energy substantially over time. In 2010, onshore wind had the lowest global average LCOE of the three technologies. While the LCOE of onshore wind did not fall as much in absolute or relative terms as did the LCOE of solar PV, onshore wind remained the lowest-LCOE technology (on average) by 2022. The LCOE of offshore wind also declined substantially over time, halving over roughly 10 years, though its LCOE was higher than that of both onshore wind and solar PV by 2022.

2.2 Trends in adoption

Figure 2 tells three different stories of solar PV deployment across the EU, the US, and China. The EU had a clear head start as of 2010, but its installed capacity remained in large part stagnant for the first half of decade, reflecting a retraction of subsidies in the aftermath of the 2008 financial crisis (Sendstad et al., 2022). Despite accelerating deployment after 2016, the EU still faced obstacles including high interest rates and inflation, increasing financing and equipment costs, and project cancellations and undersubscribed auctions (IEA, 2023b).

Figure 2: Cumulative deployment of solar power in China, the EU and the US



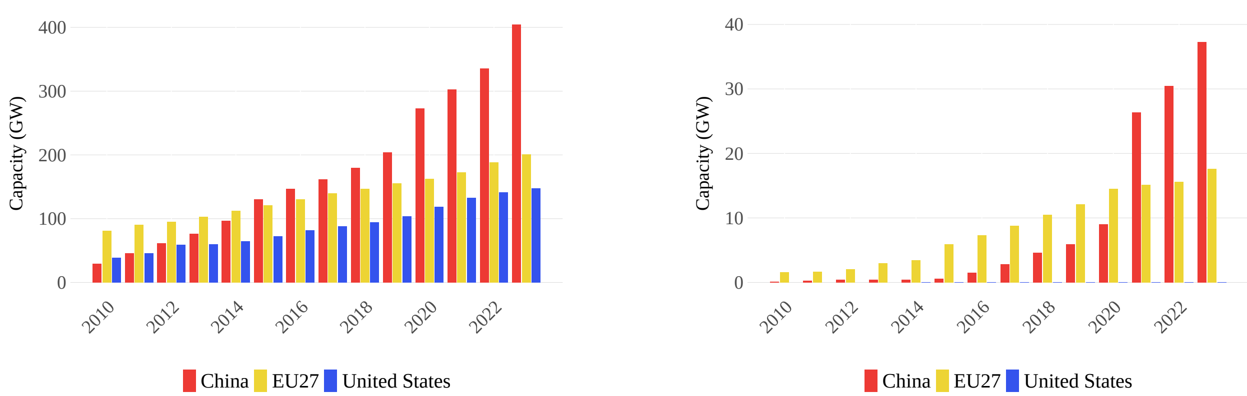
Source: Authors' visualization based on data from IRENA (2024).

Deployment has seen steady growth in the US, on par with the EU especially after 2016 in terms of capacity added. While falling costs were a major factor at play, a range of incentives targeted at consumers, discussed in more detail in section 3, also helped drive this result. In recent times, however, high interest rates, interconnection and permitting delays, supply chain issues, and policy uncertainty at the federal and state levels have led to concerns about the country's ability to sustain the trend (Davis et al., 2024).

In stark contrast, China significantly accelerated its solar PV deployment after 2012, having overtaken the EU by 2017 and reaching a record total installed capacity of over 600 GW in 2023. China's recent surge in installations, exceeding 217 GW in 2023, nearly doubled its growth rate and rivaled the combined capacity installed in the rest of the world. China has benefited from high domestic demand and significant local manufacturing. With most of the solar PV supply chain located within the country, the supply of solar panels in China has been relatively stable despite global fluctuations in raw material prices and rising interest rates. Data from IRENA (2024) reveals that, in 2021, solar PV made up 4% of all electricity generated in China. This is greater than the US's 3.4% and approaching the EU's 5.4% as a share of total electricity generation, despite the fact that it started the 2010s with negligible levels of solar PV capacity.

As with solar PV, Figure 3 shows that the EU led the US and China in both onshore and offshore wind energy generation early in the 2010s. Favorable regulatory frameworks, both at the EU and Member State levels, fostered an environment conducive to investment. In recent years, high interest rates, inflation, and project cancellations and undersubscribed auctions have become hurdles to the expansion of wind, as with solar. In addition, wind development contends with opposition from local communities, lengthy permitting processes, grid integration challenges, and site selection complexities (Costanzo et al., 2023).

Figure 3: Cumulative deployment of wind energy in China, the EU, and the US



(a) Onshore (b) Offshore

Source: Authors' visualization based on data from IRENA (2024).

Onshore wind deployment in the US largely reflects the EU trend, being subject to similar incentives and facing similar challenges (Nilson et al., 2024). On the other hand, there has been very little offshore wind deployment in the US as of 2023.[3] Part of the reason is that the US has a greater number of suitable inland sites with low population density and lower cost. In addition, issues such as the lack of installation vessels compliant with US maritime industry policy, and the necessity of floating or otherwise more expensive turbines for generation in deep water, make offshore wind relatively less attractive than onshore wind in the US (Marsh & Marcy, 2015; Powers et al., 2022).

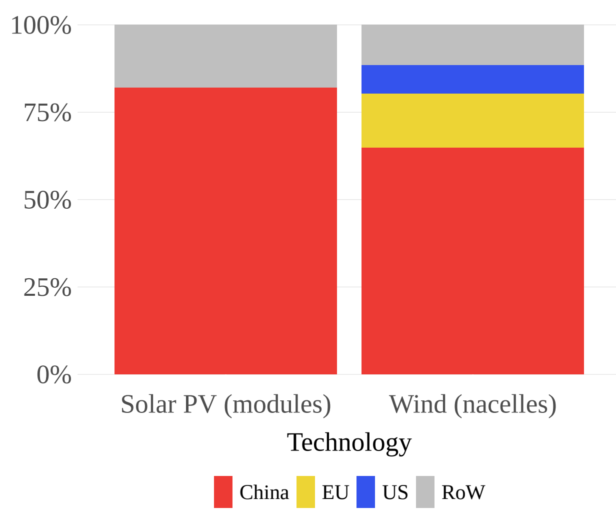
[3] In recent years, several areas have been leased for offshore wind development, and some development has started, but it is still nascent relative to onshore wind in the US and offshore wind in the EU.

In China, wind energy deployment greatly accelerated during the 2010s, mirroring the expansion of solar PV in the country. This result follows in part from an integrated policy that established "clean energy bases," expansive solar and wind parks installed in desert areas and connected to ultra-high-voltage transmission lines (IEA, 2023b). A dramatic increase in offshore wind capacity took place from 2020 to 2021. Nonetheless, deployment of offshore wind is an order of magnitude lower than onshore wind in both China and the EU.

2.3 Market structure and trade patterns

Up until the early 2000s, production of solar photovoltaics was concentrated in Japan, Europe, and the United States. Over that decade, however, firms in China rose to prominence and collectively supplied a significant share of the global market. From 2010 to 2020, this trend continued, with solar manufacturing declining in Europe and the United States in the face of competition from China. As a result, solar manufacturing has become geographically concentrated, with roughly 80% of module manufacturing capacity located in China (Figure 4). This geographic concentration is even more pronounced further up the supply chain, where China accounts for more than 95% of wafer production capacity IEA (2024a, p. 39).

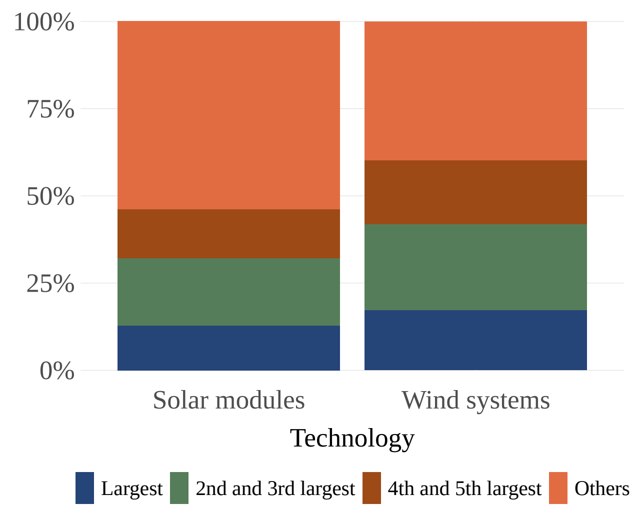
Figure 4: Geographic concentration of solar and wind manufacturing capacity (2023)



Source: Authors' visualization based on data from IEA (2024a, p. 34).

Figure 5 depicts the concentration of solar manufacturing by firms rather than geography. The three largest solar manufacturers account for roughly one-third of all output. The five largest firms account for almost half. The other half of solar panels are produced by a large number of smaller firms. These market shares are global rather than local, and local markets are somewhat more concentrated. However, the low cost of transportation for solar panels means that manufacturers compete across many local product markets, so that they are not significantly more concentrated than the global market.

Figure 5: Concentration of solar and wind manufacturing across firms (2021)

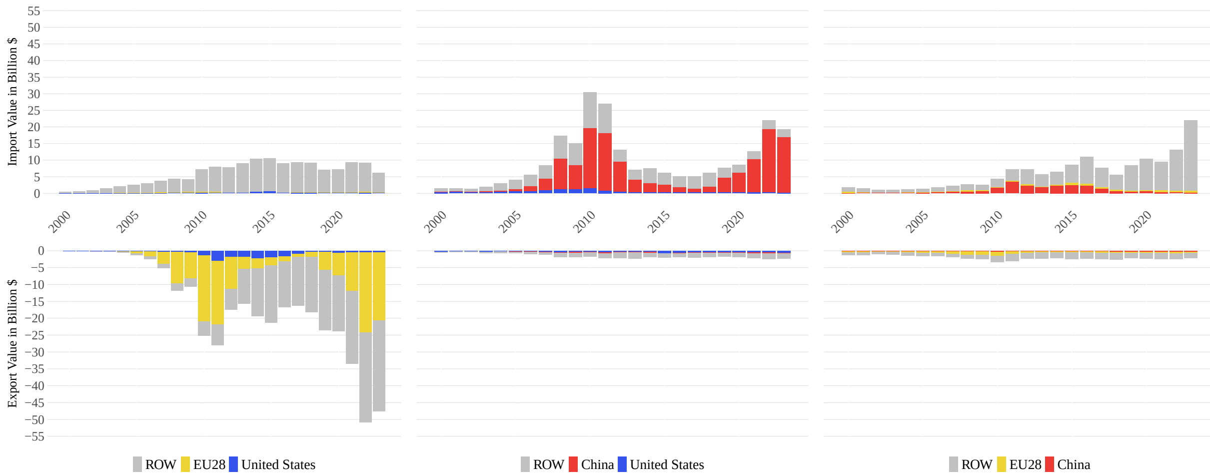


Source: Authors' visualization based on data from IEA (2023a).

Figure 6 summarizes trade in solar products across China, the EU, and the US. China is a major exporter of solar products, consistent with its share of manufacturing capacity. A large fraction of those exports have gone to the EU and other markets, with a smaller fraction destined for the US. By contrast, the US and EU were net importers over the past 20 years.

The first hubs of wind energy manufacturing developed in Europe, with Denmark, Germany, and Spain emerging as key centers prior to the 2000s. European wind turbine manufacturers benefited from domestic demand, long-term relationships with developers, and limited international competition due to high transportation costs and logistical challenges (Gasperin & Emden, 2024). However, the wind supply chain gradually became more globalized over time. One driver of this trend was increases in demand in other geographic markets in which it was attractive to manufacture locally due to high transportation costs. A second driver was cost advantages that led some suppliers to shift production of components to low-cost countries (Lee & Zhao, 2024). Countries without an existing wind industry tended to develop suppliers for low-complexity components such as towers and generators, whereas countries with an established wind industry were generally less likely to experience shifts in suppliers for high-complexity components like blades and gearboxes (Surana et al., 2020). While European firms continue to play a major role in the global market, their dominance has declined as Chinese manufacturers have expanded. Roughly two-thirds of wind turbine nacelles

Figure 6: Total Imports and Exports from 2000-2023 of solar PV manufacturing products



(a) China (b) European Union (c) United States

Source: Authors' visualization based on data from UN Comtrade Database. The graph depicts the total value of imported and exported photovoltaic products with the HS Code 854140 (854141, 854142, 854143, 854149 after 2022) by the EU, the United States and China from the years 2000 to 2023. Each bar represents the yearly total value, with colors indicating the region of origin.

are now manufactured in China (Figure 4).[4] Similarly, manufacturers headquartered in China supplied roughly two-thirds of the global market in 2023 (Figure 7). Manufacturers headquartered in Europe were the next largest set of suppliers, followed by manufacturers headquartered in the US.[5] Despite these shifts, the global market remains relatively concentrated, with the five largest companies controlling almost two-thirds of global orders in 2021 (Figure 5).

Local markets are even more concentrated due to preferences and technology that create significant regional variation in manufacturing patterns. Figure 7 summarizes the total market share of firms in each regional market, categorized according to their headquarters location.[6] In Europe, most wind turbines are produced by domestic manufacturers, reflecting transportation and trade costs at both the regional and national levels.[7] This pattern is also apparent at the country level, as shown in Appendix Figure A.2.

The experience of the European wind manufacturing industry contrasts with that of the US.

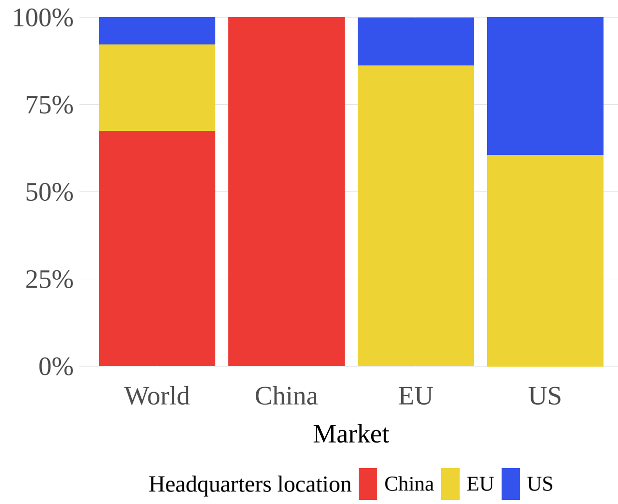
[4]The nacelle of a wind turbine is the box-like structure on top of the tower that contains the equipment that controls the wind turbine and transforms the mechanical energy from the spinning rotor into into electricity.

[5]Manufacturers headquartered in other locations supplied a trivial fraction of the global market in 2023 (IEA, 2024b, p. 97).

[6]A manufacturer's home country does not necessarily indicate the origin of its individual wind turbine components installed in a given market. For example, European manufacturers produce turbine components in multiple locations, including in the US.

[7]Home bias due to consumer preferences for products made by domestic firms may also explain some of these patterns, though this is likely to play a small role in the wind industry relative to consumer goods industries (Coşar et al., 2015).

Figure 7: Onshore wind turbine market share by location of manufacturers headquarters

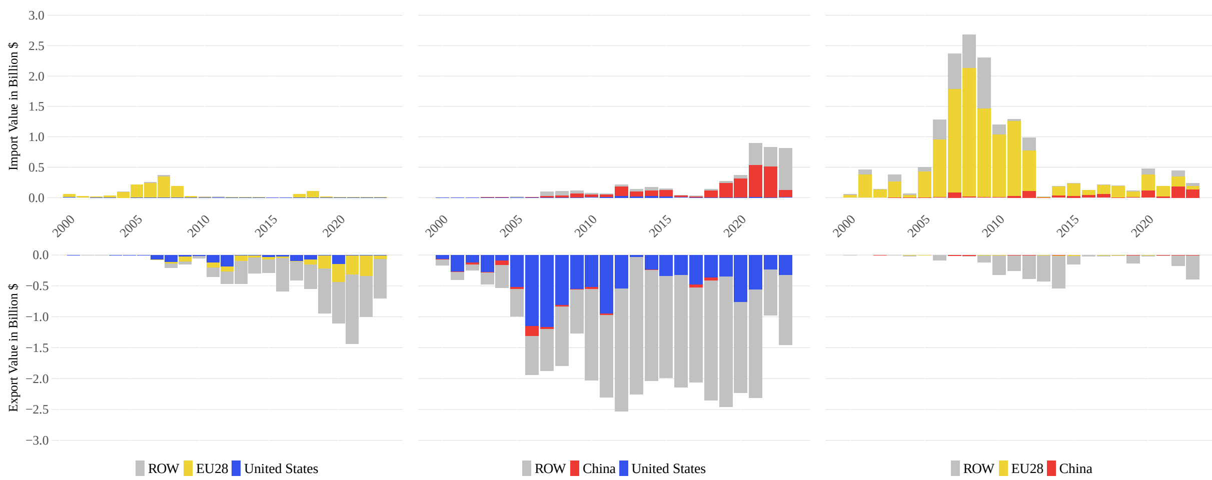


Source: Authors' visualization based on data from IEA (2024b, p. 97). Data for the EU and US markets are approximated by Europe and North America.

Roughly half of wind turbines installed in the US from 2021 to 2023 were produced by US manufacturers (IEA, 2024b, p. 97). The rest of the market is supplied by foreign firms, almost all of which are European manufacturers that produce wind turbine components in North America in addition to Europe. In China, on the other hand, almost all wind turbines installed in recent years were manufactured by firms headquartered in China.

Figure 8 shows the total value of wind manufacturing products imported and exported by China, the European Union, and the United States. The European Union stands out with the highest export volumes, also playing a significant role as a trading partner for the United States. Although China's trade volumes are relatively lower, its strong domestic demand, as discussed in section 2, has allowed Chinese manufacturers to maintain a dominant position in the market. International trade in wind products is much smaller than for solar products: the value of solar product trade flows (Figure 6) have been an order of magnitude larger than wind product trade flows (Figure 8).

Figure 8: Total Imports and Exports from 2000-2023 of wind manufacturing products



(a) China (b) European Union (c) United States

Source: Authors' visualization based on data from UN Comtrade Database. The graph depicts the total value of imported and exported wind products with the HS Code 850231 by the EU, the United States and China from the years 2000 to 2023. Each bar represents the yearly total value, with colors indicating the region of origin.

2.4 Employment in the renewable energy sector

The renewable energy industry employed about 6 million workers as of 2021-2022 (IRENA, 2023a). The solar industry accounted for 4.9 million jobs globally, and the wind industry accounted for 1.4 million. These figures include both direct and indirect jobs. Direct jobs encompass roles in renewable energy systems manufacturing, onsite installation, and operation and maintenance. Indirect jobs are further up the supply chain, such as equipment supply and the extraction and processing of raw materials. Additionally, other associated roles revolve around marketing and selling renewable energy products, along with responsibilities carried out by regulatory bodies, consultancy firms, and research organizations (Fragkos & Paroussos, 2018). Around half of all jobs in solar and wind were located in China, reflecting in part its specialization in manufacturing due to low labor costs, infrastructure provision, and targeted industrial policy. The EU is the second largest global employer in these industries, trailed by the US (IRENA, 2023a).

3 Industrial policies in use for renewable energy

In this section, we summarize the wide array of industrial policies employed in the renewable energy sectors globally. We categorize these policies into three main groups: consumer subsidies, which are designed to encourage consumers to adopt renewable energy; producer subsidies, which directly compensate manufacturers for producing specific products or for their R&D activities; and trade barriers, which have indirect effects on consumers and producers.

3.1 Consumer subsidies

Consumer subsidies to spur adoption of renewable energy technology are used throughout the world. Some subsidies are directed at firms such as utility-scale renewable energy developers, whereas others are available to individual households. One of the most prominent type of consumer subsidies is known as feed-in tariffs. In this scheme, governments offer a fixed rebate for each unit of renewable electricity generated and fed into the grid. These feed-in tariffs are granted in lieu of conventional payments for energy fed into the grid. The tariff rates vary significantly over time and across different countries, as shown in Figure 9. Some governments subsidize electricity generation from renewable energy by providing compensation that is additional to the market value of electricity (rather than in lieu of). Implicit subsidies for output, such as net metering, are a second class of consumer subsidies. A third common type of subsidy is direct payments or tax credits for a portion of upfront investment costs. Finally, some jurisdictions use procurement auctions to determine the subsidy needed to encourage more investment and production of renewable energy. The rest of this section summarizes prevailing policies in the EU, the US, and China to provide more detailed examples of these policies.

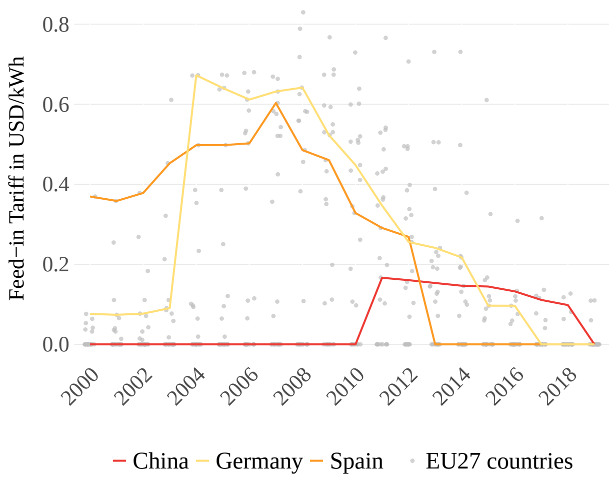
3.1.1 Consumer subsidies in the European Union

Figure 10a summarizes renewable energy subsidies in the EU by policy instrument. The EU primarily utilized feed-in tariffs to subsidize renewable energy sources. Several European countries like Germany and Spain were the pioneers of feed-in tariffs policy in the early 2000s, as is evident in Figure 9a. Their historical feed-in tariff rates were as high as 40-60 cents per kWh for solar, much higher than the wholesale prices received by other forms of electricity generation. Meanwhile, the tariff rate for wind has been stable at around 10 cents per kWh in most EU countries (Figure 9b).

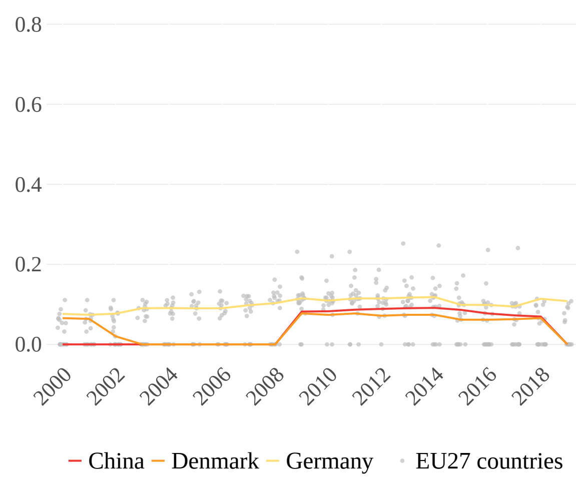
Germany, in particular, used feed-in tariffs to great effect throughout the 2000s and early 2010s, making it the largest onshore wind market in Europe with nearly 61 GW of installed capacity by the end of 2023. The peak expansion year was 2017, with almost 5 GW added. After that, the switch to an auction-based support system in 2018 caused the onshore wind market to collapse with insufficient permitting, unsubscribed auctions, and investor uncertainty being significant barriers until 2022 (Wehrmann, 2024).[8]

[8]While uncertainty in the industry and macroeconomic challenges such as inflation, high interest rates, and limited raw materials arose during the COVID-19 pandemic and following Russia's invasion of Ukraine (IEA, 2023b), regulatory changes in licensing and land use, along with new political ambitions, accelerated expansion and led to oversubscribed auctions in 2023. Remaining barriers include limited construction space, investor uncertainty, and slow licensing

Figure 9: Feed-in tariffs for solar and wind power by country



(a) Solar Photovoltaics



(b) Wind Power

Source: Authors' visualization based on data from OECD. The graph displays the weighted average feed-in tariff for China and selected European countries in photovoltaic (a) and wind power (b) for the years spanning from 2000 to 2019. The overall distribution of feed-in tariffs in the EU27 is depicted as a gray scatter plot. Feed-in tariffs were initially introduced in Europe, followed by adoption in the United States and China in subsequent years.

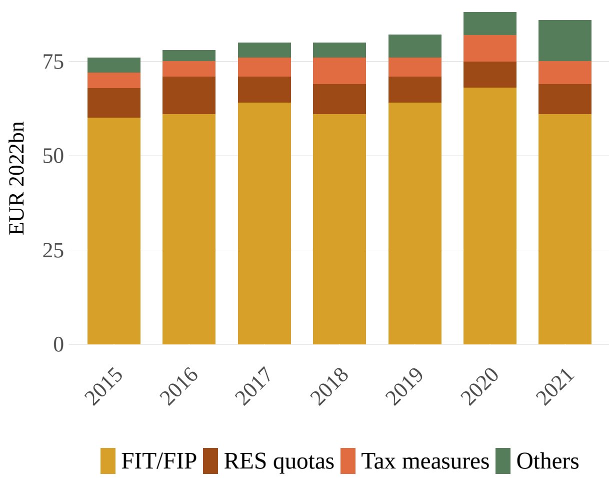
In terms of the subsidy amounts allocated to different technologies, both the level and composition has been quite stable in the past decade (Figure 10b). Overall, solar received the largest amount of subsidies, followed by wind, both of which were primarily supported by feed-in tariffs. Additional subsidies went to biomass, hydroelectricity, and other technologies.

Subsidy policies vary significantly across EU Member States. For instance, in 2021, Greece and Malta allocated over 90% of their subsidies to solar energy, while Ireland predominantly supported wind technologies (European Commission et al., 2023). Germany and France offered more balanced subsidies across various technologies, reflecting their larger geographic sizes. In terms of spending, Germany led the EU both in absolute terms, with 35 billion EUR, and relative terms, at 0.9% of GDP. Italy followed with 16 billion EUR (0.84% of GDP). In contrast, France's spending was considerably lower at 8.8 billion EUR, representing 0.33% of GDP (European Commission et al., 2023).

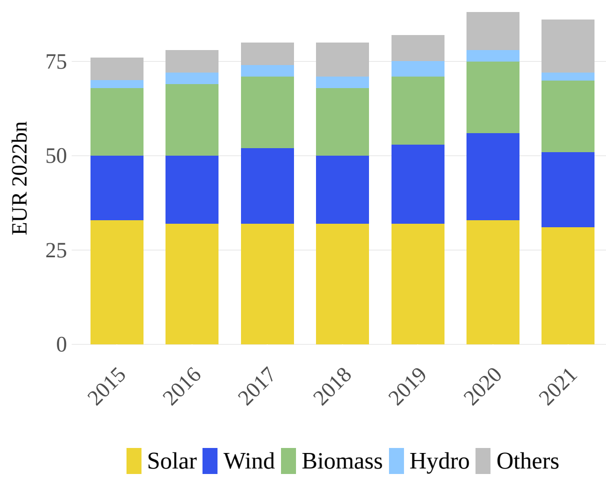
In 2024, the EU adopted the Net-Zero Industry Act. The Act proposed the Strategic Technologies for Europe Platform (STEP), which focuses on developing specific technologies to enhance the competitiveness of European industry. This approach includes reallocating existing funds towards clean technology and attracting further private and public investments. In 2023, the European

procedures (Wehrmann, 2024).

Figure 10: Renewable energy subsidies in the EU27



(a) Renewable energy subsidies by instrument



(b) Renewable energy subsidies by technology

Source: Both graphs show the total amount of subsidies in EUR 2022 bn across all EU Member States. Panel a contains a breakdown of subsidies by policy instrument based on data from Figure 6, Enerdata and Trinomics. "FIT/FIP" refers to feed-in tariffs, also sometimes referred to as feed-in payments. "RES quotas" are renewable energy source quotas. The category "Others" also includes subsidies through direct investment. Panel b contains a breakdown of subsidies by technology based on data from Figure 11, Enerdata and Trinomics.

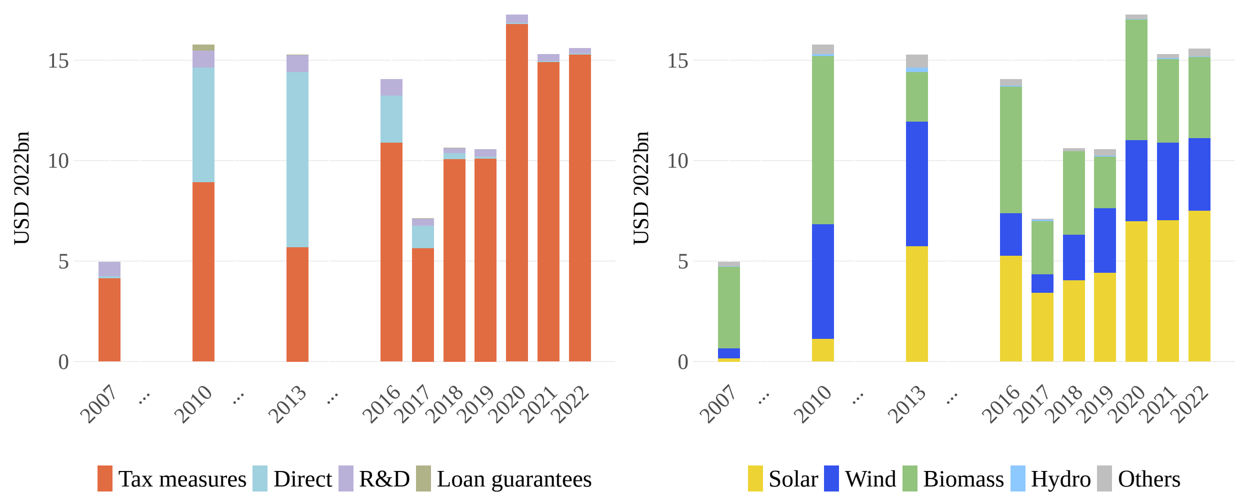
Commission revised its State Aid framework to allow Member States to support the green transition and prevent companies from relocating outside the EU. Recent approvals under the Temporary Crisis and Transition Framework for state aid include a 3 billion EUR support package for the construction and operation of new solar PV and onshore wind farms in Romania (European Commission, 2024a), and 2.2 billion EUR in direct grants for the decarbonization of production processes in the German industrial sector (European Commission, 2024b).

3.1.2 Consumer subsidies in the United States

Figure 11a summarizes how the US federal government has subsidized renewable energy technology over the past two decades. Historically, the US government has played a significant role in subsidizing the investment costs and electricity generation for renewable energy sources, primarily through provisions in the tax code. These tax subsidies take multiple forms, aiming to either reduce the financial burden of investing in renewable energy projects or increase the return to generating electricity using renewable technology. A third important category of federal subsidies are direct expenditures by the federal government to encourage renewables adoption. Finally, the government provides subsidies for research and development (R&D), which we will return to in section 3.2.

Taken together, these federal subsidies have primarily gone to investments in wind, solar, and biofuels over the past two decades (Figure 11b). Finally, states and local governments also provide a range of smaller-scale subsidies in the US. Figure 11 understates subsidies for renewable energy in the US because it does not account for these state and local subsidies. It also omits state policies such as Renewable Portfolio Standards and net metering, which create implicit subsidies for renewable energy but do not directly affect public finances. The remainder of this section summarizes each of these policy instruments.

Figure 11: Renewable energy subsidies in the United States



(a) Renewable energy subsidies by instrument (b) Renewable energy subsidies by technology

Source: Both graphs show the total amount of subsidies in USD 2022 bn from the US federal government. Panel a contains a breakdown of subsidies by policy instrument. Panel b contains a breakdown of subsidies by technology. Both visualizations are based on data from the US Energy Information Administration. Missing bars indicate missing data for 2008, 2009, 2011, 2012, 2014, and 2015, not an absence of subsidies.

Investment Tax Credit (ITC) The Investment Tax Credit (ITC) is one of the primary mechanisms through which the US government provides upfront financial incentives for renewable energy projects. The ITC allows taxpayers to deduct a percentage of the cost of installing a solar energy system from their federal taxes. The ITC is available to both businesses and individuals, though the specific benefits vary slightly between these groups. The goal of the ITC is to lower the initial capital expenditure required for renewable energy projects, thereby encouraging more widespread adoption.

From 2006 to 2019, the ITC offered a 30% subsidy on the upfront cost of constructing a qualifying facility, such as solar farms. The subsidy rate was then reduced to 26% for the years 2020 and 2021. Under current law, the subsidy rate has returned to 30% for the period 2023-2032, after which it will phase out. Cost estimates for the Inflation Reduction Act indicate that this subsidy extension is a major financial commitment, costing over $100 billion over five years between the individual and corporate ITC provisions, most of which will go to solar energy investments (Congressional Research Service, 2024).

Production Tax Credit (PTC) The Production Tax Credit (PTC) offers a performance-based incentive, providing payments per unit of electricity generated by renewable energy projects. This credit is available for the first 10 years of a facility's operation. The initial value of the PTC was $0.015 per kWh in 1992 dollars, adjusted annually for inflation. By 2022, the value had increased to $0.0275 per kWh (in 2022 dollars).

Historically, wind farms have been the primary beneficiaries of the PTC. Solar energy was not eligible for the PTC until the passage of the Inflation Reduction Act of 2022. The PTC provides additional financial support on top of the private market value of renewable electricity, differing from the feed-in tariffs used in other markets. Thus, the PTC is similar to a second-best emissions abatement subsidy, where the value of electricity is determined by the market, and renewable electricity generators receive payments in addition to that market value to reflect the external benefits of the renewable electricity they generate. However, since the PTC is a flat rate that does not vary with the emissions that wind farms offset, the subsidy is not well targeted (Novan, 2015a). This policy design places more risk on renewable project developers than feed-in tariffs do, since PTC recipients are exposed to wholesale electricity price risk.[9] On the other hand, the PTC has the advantages of retaining the market signal of the value of electricity, which varies considerably depending on when and where it is produced. Furthermore, this approach imposes less of a fiscal burden than an equivalent feed-in tariff scheme.

Section 1603 Grant Program Between 2009 and 2012, the US government offered eligible renewable energy projects to receive direct payments in lieu of of tax credits through the Section 1603 grant program. The Section 1603 grants accounted for the majority of direct expenditures for renewable energy between fiscal years 2010 and 2016. Direct expenditures have played a more minor role in recent years, as evidenced by the shift back towards tax-based incentives shown in Figure 11a.

State and Local Policies In addition to national policies, many states and local governments in the US offer a variety of explicit and implicit subsidies that encourage investment in renewable energy, particularly solar. For example, residential solar electricity is eligible for net metering in many states. In these programs, households are billed based on their net electricity consumption, so that excess

[9] Renewable energy developers often hedge this price risk by signing long-term contracts with utilities or corporations.

Table 2: US state and local renewable energy subsidies by type

Program Type	2010	2020
Loan Program	76	109
Grant Program	84	102
Rebate Program	82	98
Property Tax Incentive	51	65
Net Metering	53	60
Interconnection	56	59
Renewables Portfolio Standard	45	51
Sales Tax Incentive	32	40
Industry Recruitment/Support	38	37
Other	183	253

(a) Solar

Program Type	2010	2020
Grant Program	67	82
Loan Program	58	73
Net Metering	53	60
Interconnection	54	57
Property Tax Incentive	47	57
Renewables Portfolio Standard	46	52
Industry Recruitment/Support	40	40
Sales Tax Incentive	27	30
Rebate Program	27	27
Other	123	155

(b) Wind

Source: Own summary based on the Database of State Incentives for Renewables and Efficiency (DSIRE) from https://www.dsireusa.org. The tables show the number of state and local policies by program type in the years 2010 and 2020. The program types are sorted by their frequency in 2020.

electricity exported to the grid is reimbursed at a rate higher than the wholesale price of electricity. Borenstein (2017) uses data from California to quantify the range of subsidies to residential solar from a combination of the federal ITC, rebates from the California Solar Initiative (CSI), accelerated depreciation, and net metering. In that context, the combination of increasing-block pricing for electricity with net metering yielded a subsidy larger than the rebates from the CSI and almost as large as the 30% ITC from the federal government.

The scope and economic importance of these programs vary widely. Table 2 summarizes the most common policy types in terms of their raw frequency in 2010 and 2020. In both cases, grant and loan programs are the most common policy instruments used to subsidize renewable energy at the state and local level. For solar, rebate programs and property tax incentives are also commonly used. Net metering, discussed above, is the next most common policy instrument, followed by policies related to grid interconnection and Renewable Portfolio Standards.

3.1.3 Consumer subsidies in China

China launched the "Golden Sun Program" in 2009 to accelerate the development of solar PV power plants. The program subsidized up to 50% of investment costs—including solar panels, inverters, balance-of-system components, and installation—for grid-connected systems. For off-grid PV systems in remote or rural areas, the subsidy reached up to 70% of total investment costs. By 2013, the program was phased out as other policies took its place.

China also implemented feed-in tariffs starting in 2010, with rates comparable to those offered in the EU27 countries at the time (Figure 9). The feed-in tariff rates in China also varied regionally, reflecting differences in solar potential and economic conditions. A primary goal of the Chinese government was to achieve "grid parity," where the cost of solar-generated electricity, after accounting for rebates, is equal to or lower than that of conventional grid power. In recent years, as many regions have reached grid parity, China has gradually phased out its feed-in tariff model.

Another key initiative was the "Top Runner Program," introduced in 2015 to drive technological innovation and improve quality within the industry. While this policy was primarily designed to influence manufacturers, it provided a consumer subsidy by mandating a certain amount of solar investment that met certain standards. The program did this using procurement auctions: the National Energy Administration designated specific regions for utility-scale solar development and awarded projects through competitive bidding. Bidders are evaluated not only on price but also on the efficiency of their technology. Many observers argue that this program helped leading Chinese solar firms expand their domestic dominance while fostering innovation and economies of scale.

In 2021, China launched its "Whole Country PV program" which aims to expand distributed rooftop solar. Through tenders or auctions, a single supplier is selected for each region to install all rooftop installations, specifically to lower the soft costs of customer acquisition and contracting (Hove, 2023).

3.2 Producer subsidies

Direct producer subsidies to manufacturers are prevalent in many emerging economies, particularly in China, but systematic data on their quantitative impact remains scarce. Recent research by Juhász et al. (2022). utilizes textual analysis, basing estimates of policy intensity on the frequency of relevant policy documents across countries. While this method provides a viable workaround for data limitations, its precision still requires validation in specialized sectors like the solar and wind industries. An alternative strategy involves analyzing detailed firm-level production and investment data to deduce subsidy levels from the 'wedges' in firms' optimization decisions. This approach, as applied by Barwick et al. (2021) to the Chinese shipbuilding industry, presupposes that deviations from optimal strategic responses are primarily due to industrial subsidies—a significant assumption.

3.2.1 Producer subsidies in the European Union

Historically, solar panel and wind turbine manufacturers operating in the European Union have received limited direct government support in the form of producer subsidies. Some EU-based manufacturers have benefited from targeted subsidies, such as a European Investment Bank green R&D loan to wind turbine manufacturer Vestas (Vestas Wind Systems A/S, 2022). On the whole, though, producer subsidies in the EU remain relatively small and fragmented when compared to other countries (OECD, 2025).

In recent years, the EU has taken on a more active role in directly subsidizing renewable energy technology manufacturing. A prominent example is the Net Zero Industry Act, part of the Green Deal Industrial Plan. This aims for the EU to produce at least 40% of the clean technologies it needs by 2030, including solar panels, wind turbines, batteries, heat pumps, and electrolyzers. The law aims to simplify permitting procedures, boost investment, and strengthen the EU's strategic manufacturing capacity (European Commission, 2023a). In parallel, the EU has approved direct state aid under its Temporary Crisis and Transition Framework as a reaction to increased energy costs in the context of Russia's war against Ukraine. For example, in October 2023, the European Commission approved €1.2 billion in Polish state aid to support a large-scale offshore wind component production facility (European Commission, 2023b). However, such measures fall short of the scale seen in China or even the US.

3.2.2 Producer subsidies in the United States

In the United States, policies to promote renewable energy have historically focused on consumer subsidies to encourage adoption of renewable energy technology by firms and individuals. One important exception to this is the provision of R&D funding to renewable energy. However, this funding is primarily focused on basic and applied research rather than commercial technologies, and is small in magnitude compared to the consumer subsidies outlined above (Figure 11a).

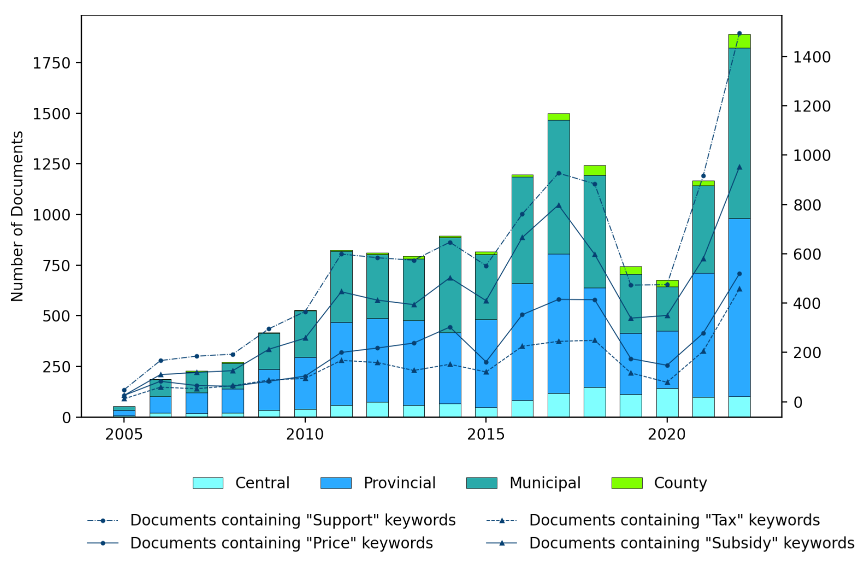
In recent years, new policies to encourage manufacturing activity have been enacted. Most notably, the IRA included a provision to subsidize clean energy manufacturing through the Advanced Manufacturing Production Tax Credit ("45X MPTC"). According to the Congressional Research Service (2024), this policy is projected to be roughly one-third of all the renewable energy tax provisions under the IRA over fiscal years 2023-2027. This projection puts the government commitment to producer subsidies on the same order of magnitude as consumer subsidies for the first time for the US renewable energy sector. However, it is too early to determine what the full impacts of these policies will be.

Like past federal policies, most state and local policies in the US are designed to encourage adoption rather than production of renewable energy technology. While it is difficult to quantify the exact scale of state and local subsidies to manufacturing activity in terms of direct expenditures or tax expenditures, the number of producer subsidies to manufacturers tracked in the Database of State Incentives for Renewables and Efficiency is small relative to the number of consumer subsidies and other policies. For example, the most common type of program in the database that includes references to "manufacturing" is Industry Recruitment/Support, but programs of that type are employed less frequently than the consumer subsidies summarized based on the frequency counts in Table 2.

3.2.3 Producer subsidies in China

Figures 12 and 13 visualize the total counts of policy documents of Chinese central, provincial, municipal, and county level governments classified as producer subsidies. We can further classify these subsidy documents based on their keywords. These policy counts are derived from the PKULaw database, which contains over two million government policy documents from China. A key advantage of this database is its ability to distinguish the issuing authority of each document—whether at the central, provincial, municipal, or county level. We conduct a comprehensive textual analysis to identify documents that prominently feature keywords related to "solar energy" and "wind power." As shown in Figures 12 and 13, there has been a steady increase in subsidy-related policies in China beginning around 2006–2008. Policies issued at the provincial and municipal levels make up the majority of these documents, consistent with the top-down policy experimentation model documented by Wang and Yang (2024). We further classify these policies by specific types of support using keyword-based textual analysis. Most documents include the term "support" (dashed circle line), while more specific terms such as "tax" (dashed triangle line), "price" (solid circle line), and "subsidy" (solid triangle line) appear less frequently. Still, over half of the policy documents in our sample reference "subsidy" for both solar and wind energy.

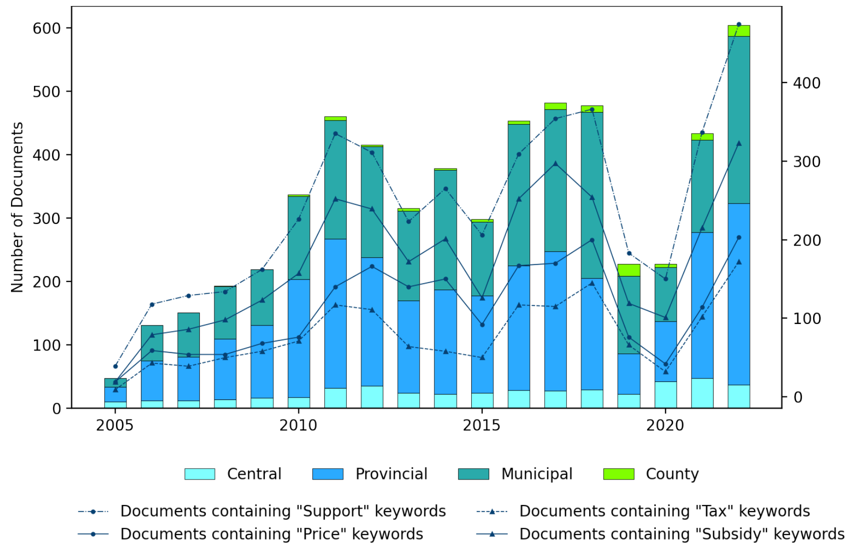
Figure 12: Renewable Energy Subsidy Policy Documents in China: Solar



Source: Authors' visualization based on data from PKULaw.

The Top Runner Program, mentioned above in our discussion of consumer subsidies, is an example of a unique national program that served as both a consumer subsidy and a producer

Figure 13: Renewable Energy Subsidy Policy Documents in China: Wind



Source: Authors' visualization based on data from PKULaw.

subsidy. The program was designed to improve the quality of solar panels manufactured in China. To encourage manufacturers to do this, it specified certain efficiency standards and provided consumer subsidies that were only available to projects that used solar panels that met the standards. This provided implicit producer subsidies, and directed production activity toward higher quality products.

3.3 Trade barriers

3.3.1 Solar

Despite the dominance of European, Japanese, and US photovoltaic producers in the early 2000s, Chinese firms rapidly closed the gap, leveraging their cost advantage to collectively surpass firms from other countries in market share before 2010. In response, both the US and the EU initiated several anti-dumping investigations targeting Chinese manufacturers. However, the protective measures diverged significantly between these two major economies after 2017.

The first round of US anti-dumping and countervailing duties was enacted in 2012. These tariffs were directed at solar cells produced in China, whether these cells were imported individually or as components of assembled solar panels. The duties varied by manufacturer, reflecting their pricing strategies and the level of subsidies they received from the Chinese government. The anti-dumping margins for large Chinese manufacturers who participated in the investigations ranged from 18.3% to 31.7%. All other Chinese manufacturers were subjected to a "PRC-Wide Entity" rate of 249.96%.

In 2014, the US implemented a second round of tariffs to close loopholes in the 2012 measures. These tariffs, initiated in June 2014, extended to solar panels assembled using solar cells from China or Taiwan, and to all solar panels assembled in China, regardless of the origin of the cells. This expansion significantly broadened the scope, compelling Chinese manufacturers to adjust their operations to circumvent the tariffs.

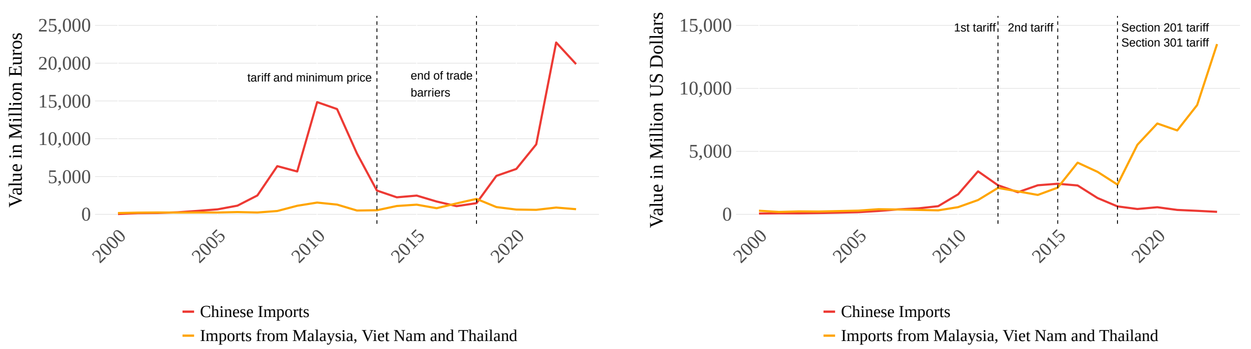
For comparison, the EU began its own anti-dumping investigation of Chinese solar manufacturers around the same time. The EU's anti-dumping duties for large cooperating Chinese producers ranged from 27.3% to 64.9%. A more lenient "PRC-Wide" duty of 53.4% was applied to all others. Initially, the EU's anti-dumping measures were set to last two years, until the end of 2015, but were subsequently extended in March 2017 for another 18 months. In December 2013, the EU and China reached an agreement on a minimum import price scheme, which set a price floor for Chinese exports to the EU. Under this arrangement, manufacturers selling photovoltaic products above the minimum import price and within an annual quota were exempt from anti-dumping tariffs.

Despite adopting similar protectionist stances in the early phases of trade restrictions, the US and EU diverged significantly after 2017. Following the insolvency of SolarWorld, the last major EU manufacturer, the European Commission decided in 2018 to remove both the anti-dumping tariffs and the minimum import price restrictions on Chinese producers.

In contrast, the Trump administration broadened the scope of tariffs to include many more countries, utilizing Section 201 of the Trade Act of 1974. It imposed a 30% tariff on cell and panel imports in February 2018. These "Section 201 tariffs" targeted crystalline silicon products from all major solar product exporters to the US. The tariffs were scheduled to decrease by 5% annually until their expiration in 2022. A fourth round of tariffs implemented by the US also affected the solar market. In 2018, the Trump administration imposed tariffs of up to 25% on imports from China under Section 301 of the Trade Act of 1974. These "Section 301 tariffs" encompassed a broad range of products, including solar cells and panels. Both the Section 201 and Section 301 tariffs were applied in addition to the pre-existing anti-dumping and countervailing duties established in 2012 and 2014. All of the tariffs have been reviewed and adjusted over time. In 2022, President Biden modified and extended the Section 201 tariffs through 2026. In 2024, the Biden administration increased the ad valorem duty rate for the Section 301 tariffs from 25% to 50%.

The changing anti-dumping regulations significantly impacted the primary sources of solar products for both the EU and the US. As illustrated in Figure 14a, products manufactured in China saw rapid growth in the EU market from 2005 to 2011. This growth was markedly curtailed in in 2012 and 2013, around the time of the introduction of the EU's anti-dumping tariffs and the Minimum Import Price. However, the reduction in Chinese imports began prior to the trade actions, likely because this time period also saw a major contraction in consumer subsidies like feed-in tariffs (Figure 9a). The net effects of these policies was a significant decline in EU imports from all countries, not just China (Figure 6b). Despite the trade actions, imports from China still comprised a non-trivial share of all EU imports, though less than in prior years. Later, after the tariffs and minimum import price were removed in 2018, and the costs of solar technology had come down over time, the European market expanded again and imports from China increased in both relative and absolute terms (Figure 6b).

Figure 14: Solar product imports from China and Southeast Asia



(a) European Union (b) United States

Source: Own elaboration based on data from UN Comtrade Database and The World Bank. The figure shows the evolution of Chinese imports in the EU in Panel (a) and USA in Panel (b) for solar photovoltaic products from 2000-2023, overlapped with the main trade policies affecting these products. HS Codes used: 854140, 854141, 854143, 854149. HS Code 854149 excludes photovoltaic products, but we include it to maintain consistency in the definition of products over time as the HS Codes changed.

The situation in the US stands in stark contrast. The US not only maintained its 2014 anti-dumping and countervailing tariffs, but further escalated these measures with two additional rounds of tariffs during the Trump administration. Consequently, direct imports from China have gradually declined since 2014 and have yet to recover. Meanwhile, imports from Malaysia, Vietnam, and Thailand have dramatically increased over the past decade and now dominate the US solar import market, as shown in Figure 14b. As documented by Bollinger et al. (2024), this development was driven by Chinese companies that expanded their manufacturing capabilities in these Southeast Asian countries, effectively circumventing the US tariffs on Chinese products by relocating their production facilities.

3.3.2 Wind

As in the case for the solar market, the US has actively implemented trade barriers to protect its wind turbine industry. In 2013, the United States imposed countervailing duties on utility-scale wind towers from China and anti-dumping duties on utility-scale wind towers from both China and Vietnam. These protective measures were expanded to imports from Canada, Indonesia, and South

Korea in 2020, and to Spain in 2021. Perhaps in part due to these trade barriers, the majority of US imports of wind products over the period 2000-2023 came from the EU (Figure 8). Only a small fraction came from China and other countries.

In contrast to the US approach, the EU did not impose systematic trade barriers on wind turbines until more recently. In December 2021, the EU implemented anti-dumping measures on imports of steel wind towers from China. These measures include duties ranging from 7.2% to 19.2%. Wind product imports from China fell in both absolute and relative terms in the ensuing years (Figure 8). Overall, the value of wind product imports to the EU over the period 2000-2023 was small relative to its exports, even before accounting for EU production for EU consumption.

4 The economic rationales for industrial policy

In this section, we briefly outline the economic justifications for industrial policy in the renewable energy sector. We then take a policy-focused approach to reviewing theoretical arguments and empirical evidence for specific policy instruments, discussing consumer subsidies, producer subsidies, and trade barriers in turn. Each of these forms of industrial policy can be justified on the basis of several distinct economic rationales. Table 3 summarizes the relationship between economic rationales and policy instruments.

Table 3: Economic rationales for industrial policy instruments

	Policy Instrument		
Economic Rationale	**Consumer Subsidies**	**Producer Subsidies**	**Trade Barriers**
Environmental Externalities	Price emissions	Price emissions	
Knowledge Spillovers	Amplify peer effects Induce innovation Induce LBD	Subsidize innovation Induce innovation Induce LBD	
Marshallian Externalities		Protect infant industry	Protect infant industry
Strategic Motives		Improve terms of trade	Improve terms of trade
National Security		Secure energy supply	Secure energy supply

The most salient justification for government intervention in the renewable energy sector is to address environmental externalities including greenhouse gas emissions and local air pollution. As a form of second-best environmental policy, subsidies to renewable power provide a substitute to a Pigouvian tax by providing incentives to reduce the environmental footprint of the electricity sector. Under some assumptions, these Pigouvian subsidies can be quite effective, even if they do not perform as well as a Pigouvian tax (see, e.g., Borenstein & Kellogg, 2023).[10]

The existence of knowledge spillovers provides a second economic rationale for government intervention. Knowledge spillovers can stem from social interactions (i.e., peer effects), innovation, and learning-by-doing. We distinguish between general knowledge spillovers and Marshallian externalities since they have different implications for industrial policy.[11] Both are externalities that tend to grow with the size of an industry. The defining feature of Marshallian externalities is that they are local, rather than global, in scope. We also consider strategic trade considerations that lead the incentives of a national actor to diverge from that of a global social planner, even in the absence of any market failures. Finally, we discuss national security as a potential justification for industrial policy.

4.1 Consumer subsidies

The primary purpose of most consumption subsidies, such as feed-in tariffs and subsidies for technology adoption, is to address the unpriced environmental externalities associated with conventional fossil fuel-based energy sources. While consumer subsidies are not equivalent to a Pigouvian tax, since they indirectly subsidize electricity consumption, they can serve as a second-best policy instrument by lowering the cost of renewables relative to fossil fuels. A large body of empirical work has studied how renewable electricity generation substitutes for conventional forms of electricity generation, and the implications of this substitution for emission of local and global air pollutants (e.g., Callaway et al., 2018; Cullen, 2013; Dorsey-Palmateer, 2019; Graff Zivin et al., 2014; Gutierrez-Martin et al., 2013; Kaffine et al., 2013, 2020; Novan, 2015b; Sexton et al., 2021; Siler-Evans et al., 2012). One consistent conclusion that has emerged from these papers is that emissions impacts vary over space and time due to variation in the generation mix and operation of the electric grid. Most of the subsidies reviewed in this article are more coarse and are not designed to account for granular spatial and temporal variation.

Further research has studied the direct effects of consumption subsidies on the adoption of renewable energy technology. For solar, extensive research has been conducted on residential consumers' adoption of this technology (e.g., Bollinger & Gillingham, 2012; De Groote & Verboven, 2019; Gillingham & Tsvetanov, 2019; Hughes & Podolefsky, 2015; Langer & Lemoine, 2022). For wind, work has focused on utility-scale adoption since it constitutes almost the entire market for wind power (e.g., Aldy et al., 2023; Hitaj, 2013; Johnston, 2019). In many cases, this research builds on the prior work discussed in the preceding paragraph to estimate the net benefits of subsidies

[10] See Ricks and Kay (2025) for a recent analysis of Pigouvian subsidy design under political constraints.

[11] Harrison and Rodríguez-Clare (2010) provides an excellent survey of the theoretical literature on Marshallian externalities and industrial policy more generally.

with a narrow focus on environmental benefits. Evidence from this literature on the net benefits of subsidies are mixed. On the one hand, early papers often found the implicit marginal abatement cost for carbon emissions to be higher than estimates of the social cost of carbon (see, e.g., Gillingham & Tsvetanov, 2019; van Benthem et al., 2008). However, estimates of the social cost of carbon have increased significantly over the past decade, to the point that more studies find the policies to be net beneficial on environmental grounds. Several papers in the European context find positive welfare effects for reasonable costs of carbon for solar (Abrell et al., 2019) and wind (Abrell et al., 2019; Liski & Vehviläinen, 2020; Petersen et al., 2024), also finding that consumers can be better off in the presence of subsidies despite its costs, due to the reduction in market prices, with the largest negative impacts being endured by traditional power producers.

There are also other industrial policies that affect demand for renewable energy, and therefore serve as implicit consumer subsidies, even if they are not direct subsidies to adoption. For example, Gonzales et al. (2023) study transmission expansion, which led to significant investment in solar electricity by increasing market access and, therefore, the profitability of new solar farms. Thus, transmission expansion and other policy interventions could be justified by the same economic rationales as consumer subsidies, and potentially others.

Knowledge spillovers such as non-appropriable innovation, learning-by-doing, or social interaction effects can provide additional justifications for consumer subsidies. This rationale is strongest in cases where consumer subsidies are well-targeted. This is most likely to be the case when the spillovers are a direct effect of consumption, such as in peer effects in technology adoption (Bollinger & Gillingham, 2012).

Learning-by-doing by renewable energy installers is another example. The idea that learning could lead free markets to inefficient equilibria has been recognized since Arrow (1962). To the extent that this market failure is present in renewable energy, consumption subsidies provide one policy instrument to correct it. Several recent studies have investigated how consumption subsidies affect learning in the solar industry, and what the policy implications of this learning are (Anderson et al., 2019; Bollinger & Gillingham, 2019; Bradt, 2024; Myojo & Ohashi, 2018; van Benthem et al., 2008).

In general, consumer subsidies can also correct knowledge spillovers further up the supply chain. Gerarden (2023) makes this point in the context of the solar industry, focusing on how solar panel manufacturers improve their technology and thereby lower their costs in response to variation in consumer subsidies. Gao and Rai (2019) analyze the effect of consumer subsidies for solar adoption on patenting related to balance-of-system components in China. Covert and Sweeney (2024) study similar economic forces in wind turbine manufacturing. While they do not focus on the role of consumer subsidies *per se*, Covert and Sweeney (2024) identify spillovers across firms that could provide a justification for consumption subsidies. However, this body of research has not fully addressed the questions of when and how consumer subsidies are more effective economic tools than subsidies to producers or subsidies specific to innovation in addressing knowledge spillovers.

Hahn et al. (2025) applies the marginal value of public funds framework to assess the welfare impact of consumer subsidies for renewable energy in the US. Their approach accounts for environmental impacts, learning-by-doing effects, and fiscal externalities in a unified framework. They find that renewable energy subsidies provide the highest return to the government of the different climate policy spending programs they consider. For both solar and wind, learning-by-doing effects play a quantitatively important role in their estimates of the subsidies' total effects.

The case for using consumer subsidies as tools to address Marshallian externalities, strategic trade considerations, or national security is weaker and more context-dependent. The historical experiences of the European solar and wind industries outlined in sections 2 and 3 provide informative case studies to understand why.[12] Consumer subsidies were the dominant form of industrial policy for both sectors from before 2000 through 2020. These policies helped European solar and wind manufacturers succeed in both domestic and foreign markets, but their nondiscriminatory nature meant that they also benefited foreign producers. Over time, competition from aboard eroded the market shares of European manufacturers to different degrees in the two industries. In the solar industry, where trade costs are low, foreign manufacturers came to dominate the supply of solar panels. Any beneficial effects of consumer subsidies that were specific to European solar manufacturers—due to, for example, Marshallian externalities—were outweighed by the comparative advantage of foreign manufacturing. In the wind industry, by contrast, European manufacturers remain significant global players. This is in part due to high transport costs that make it more difficult for foreign manufacturing to substitute for domestic manufacturing, as highlighted by the differences in market shares across regions in Figure 7. It may also be a result of differences in the ability of firms to appropriate the knowledge they create, or the extent of Marshallian externalities, in the wind industry relative to solar.[13] But to the extent that Marshallian externalities, strategic trade considerations, or national security provide justifications for government intervention, other industrial policies such as producer subsidies or trade policy would be better targeted than consumer subsidies.

[12] Pegels and Lütkenhorst (2014) provide a more detailed assessment of the impact of Germany's energy transition policies on both solar and wind.

[13] Hansen et al. (2003) study how subsidies for wind-powered electricity influenced the development of the Danish wind industry. They conclude that the success of Danish wind turbine manufacturers was because of learning-by-doing that was induced by the subsidies. They further conclude that the development of this infant industry created more benefits than costs.

4.2 Producer subsidies

Many of the rationales for supply-side subsidies overlap with those for consumption subsidies, particularly in a perfectly competitive market. To the extent that subsidies to solar panel and wind turbine manufacturers lower the price of renewable energy relative to fossil fuels, and there are unpriced environmental externalities, those producer subsidies could be justified as an indirect Pigouvian subsidy. In general, this rationale is weaker for producer subsidies than for consumer subsidies. This is because consumer subsidies can directly correct preexisting distortions in consumption due to environmental externalities, whereas producer subsidies introduce new distortions in production in the process of influencing consumption decisions.

Subsidies to R&D or production of renewable energy technology could also address knowledge spillovers that lead to socially inefficient investment in knowledge creation. There is a large theoretical literature on the economics of innovation that considers the implications of knowledge spillovers across firms that dates at least back to Arrow (1962). Likewise, empirical research seeks to understand the drivers of innovation, and to obtain causal estimates of the magnitude of spillovers (e.g., Bloom et al., 2013). Much of this research focuses on patents as a measure of innovative activity. Prior work as shown that renewable energy technology patenting responds to market forces (e.g., Dugoua & Gerarden, 2025; Popp, 2002) and to environmental policy (e.g., Dechezleprêtre & Glachant, 2014; Johnstone et al., 2010). There is relatively less work that directly quantifies the magnitude of R&D spillovers. One exception to this is Myers and Lanahan (2022), who study grant funding from the Department of Energy and find evidence of substantial spillovers from grant recipients to other firms. Furthermore, the literature on directed technical change highlights the importance of subsidizing research activity in addition to addressing environmental externalities (Acemoglu et al., 2012, 2016; Fried, 2018). Taken together, this research suggests the social returns to subsidizing renewable energy R&D are high. However, we know relatively less about the effect of other types of producer subsidies—such as subsidies for investment or output from manufacturing facilities—on knowledge creation and spillovers in the renewable energy industry.[14] This economic rationale provides the strongest support for policies that directly encourage innovation, relative to indirect policies like consumer and producer subsidies.

Marshallian externalities are a third economic rationale for producer subsidies. These local externalities from industrial activity are widely considered to be the textbook justification for industrial policy (Harrison & Rodríguez-Clare, 2010). A particularly relevant concept for industrial policy is "infant industry protection," where a developing economy might specialize in a less

[14] A notable exception to this is Banares-Sanchez et al. (2023), who provide evidence that subsidies for solar production in China led to increases in output, innovation, and productivity over time. On the other hand, Banares-Sanchez et al. (2023) find that local consumer subsidies have very little impact on production and innovation. The main reason for the modest impact of consumer subsidies is that new installations adopted by consumers were not required to be produced by local firms.

competitive sector, such as agriculture, even when it has a latent comparative advantage in a more advanced sector like manufacturing. Since sectors like manufacturing require coordination to fully exploit Marshallian externalities and development often takes time, an argument for infant-industry protection can be substantiated. Such an argument is a highly relevant theoretical possibility for many countries that aim to promote their own renewable energy sectors. However, providing empirical evidence to understand the relevance of this theoretical possibility is no small task.

International competition and market structure can introduce strategic interactions between producers that justify an additional set of policies rooted in the strategic trade policy literature. In their classic work, Brander and Spencer (1985) illustrated that when a domestic manufacturer and a foreign manufacturer engage in Cournot competition, the home government could subsidize domestic production to reduce the foreign firm's market share and shift profit to domestic producers. This prediction depends heavily on the market conduct of oligopolistic firms (Eaton & Grossman, 1986), but when domestic consumer welfare is taken into account, production subsidies can be further justified. Finally, national security is often cited as a policy objective that could justify producer subsidies.

While it is difficult to quantify the extent and magnitude of producer subsidies for manufacturing renewable energy technology, let alone determine whether and to what extent these subsidies are justified by the economic rationales we have outlined, the role of China in the global renewables industry provides suggestive evidence regarding the impact of supply-side policies. China has specified multiple goals for the solar industry through its Five-Year Plan. Groba and Cao (2015) outline various supply-side policies, such as increasing R&D spending on clean energy technology at the local and central government levels. Government supports are shown to help Chinese solar firms (Lin & Luan, 2020). Zhi et al. (2014) show that policies gradually move from the producer subsidies to consumer subsidies in later years. Banares-Sanchez et al. (2023) provide evidence of the impacts of production and innovation subsidies from different cities in China.

India provides another example of the impacts of producer subsidies. Recently, the Indian government has used a combination of import tariffs and production subsidies to support manufacturers. Garg and Saxena (2023) estimate a structural model of the Indian solar industry, with a focus on imperfect competition among solar manufacturers. Their results suggest that combining these two policy tools could do better than either one in isolation in terms of addressing the distortions created by imperfect competition.

4.3 Trade barriers

While many countries have applied import tariffs to renewable energy products over the past decade, their traditional economic rationale rests on strategic motives—specifically influencing terms of trade—rather than addressing market failures such as environmental externalities or knowledge spillovers. If foreign supply is relatively inelastic, import tariffs imposed by a large country could reduce the world price for subject renewable energy products. As a result, the incomplete pass-through of tariffs into consumer prices could improve domestic welfare if the gain in tariff revenue more than compensates for the loss in domestic consumer surplus.

Recent research casts doubt on the strength of this justification for trade barriers in the renewable energy sector. Houde and Wang (2024) focus on the residential solar market and study the incidence of US import tariffs on Chinese solar products from 2012 through 2018. They find that tariff pass-through exceeded one.[15] Furthermore, the benefits to domestic manufacturers were negligible relative to the harms to domestic consumers. As a result, Houde and Wang conclude that the tariffs were not justified on the basis of strategic trade motives, since they reduced both US and global welfare.

Environmental externalities do not justify trade barriers: their presence makes the case for trade barriers in renewable energy even weaker. Houde and Wang extend their analysis to account for environmental externalities, and find that it increases the aggregate welfare loss from tariffs by an order of magnitude. Similarly, knowledge spillovers do not provide an economic rationale for trade barriers. Limiting trade has the potential to reduce these spillovers directly since it may disrupt international collaborations and information flows. Furthermore, since trade barriers tend to reduce the size of the market for renewable energy overall, they are likely to reduce the extent of knowledge creation and knowledge spillovers indirectly.

Overall, the case for substantial import tariffs on renewable energy products is weak unless one believes there are large Marshallian externalities or important national security considerations. There is very little credible or comprehensive evidence on the extent of Marshallian externalities in the renewable energy sector. An exception to this is Bollinger et al. (2024), who study solar product tariffs in the US. Bollinger et al. develop a model of solar panel supply by manufacturers that allows for Marshallian externalities for solar manufacturing activity within the US. Based on preliminary estimates, though, the externalities are modest and are insufficient to justify historical import tariffs, particularly after accounting for unpriced environmental externalities.

We are not aware of research that incorporates and quantifies national security outcomes in the renewable energy sector that would enable policymakers to weigh their costs and benefits along with the other considerations we have discussed when evaluating tariffs. Renewable energy trade is in the stock of energy-producing capital such as wind turbines and solar panels, rather than in the flow of energy materials as in the case of global oil markets. For that reason, the traditional national security arguments in the energy sector are somewhat less persuasive in the context of renewable

[15] Tariff pass-through, and cost pass-through more generally, can exceed one in certain cases depending on both the demand function and the nature of competition among firms.

energy. The possibility of recycling and reprocessing for solar panels and other clean technology in the future lessen may also help to lessen national security risks. Despite these measurement challenges, we can learn about the effects of trade barriers on national security from past experience. Trade barriers in the EU and US failed to foster secure domestic supply chains in the solar industry. While the US import tariffs led to a resurgence in solar panel assembly starting in 2018, the country still relies heavily on imports of solar cells and other intermediate inputs from foreign countries. In fact, the growth in manufacturing was largely driven by foreign direct investment (Bollinger et al., 2024). While these facts do not rule out the possibility that more stringent trade barriers—or trade barriers paired with other domestic support such as producer subsidies—could have had more effect, it does highlight their limitations.

In summary, while there is theoretical support for trade barriers to address terms of trade, Marshallian externalities, and national security, there is little empirical evidence to support their application in the renewable energy sector. A key reason for this is the countervailing effects of environmental externalities and knowledge spillovers, which lead the market to provide too little renewable energy absent any intervention, are a key reason for this. In combination, these economic rationales provide stronger support for producer subsidies than for trade barriers, or for a combination of different policies that address each market failure more directly.

5 Recent evidence on industrial policy in renewable energy

In this section, we provide a detailed summary of several recent papers that seek to identify the precise sources of spillovers across firms and over international borders in order to further our understanding of the cases for and against industrial policy.

5.1 Consumer subsidies

Spillovers from innovation Gerarden (2023) develops and estimates a dynamic model of competition among firms to study the impact of consumer subsidies on innovation by solar panel manufacturers. The results suggest that if governments had not offered consumer subsidies, cumulative global solar adoption would have grown linearly from 2010 to 2015. This is in stark contrast to the rapid exponential growth of cumulative solar adoption observed in the data. A key driver of this finding is the effect of consumer subsidies on innovation by firms. These results suggest that dynamic effects of consumer subsidies and other industrial policy can have first-order impacts on the overall evolution of the industry.

These dynamic effects can also produce international spillovers. Since the market for solar panels is globally interconnected, the effects of subsidies in one country can spill over to other countries through innovation responses by firms. Germany is a prime candidate for such an effect. Germany was a pioneer in providing substantial feed-in tariffs when the solar market was in its infancy (Figure 9a), and it was the largest market in the world in the early 2010s (Figure 2). At the same time, a majority of solar panels in Germany were imported from abroad. These facts, when taken together with the global induced innovation impacts described above, highlight the potential for Germany's consumer subsidies to yield positive international spillovers through innovation by firms.

Gerarden (2023) analyzes the potential importance of this channel by simulating the model with and without German feed-in tariffs to isolate their effects from the effects of other consumer subsidies. Gerarden then quantifies how the innovation induced by these subsidies affected the quantity of solar technology adopted over time and space. In total from 2010 to 2015, 88% of the solar panel adoption due to innovation induced by German subsidies occurred in markets other than Germany. While this is not a direct welfare measure, this induced innovation generated welfare-relevant spillovers across countries in the form of consumer surplus gains and improved environmental quality.

Spillovers from learning-by-doing Another potential way in which consumer subsidies could have third-party effects is through learning-by-doing. If feed-in tariffs or investment subsidies cause solar panel manufacturers and installers to learn and lower their costs faster than they would without subsidies, it could generate social surplus by bringing future benefits from solar adoption closer to the present. Furthermore, if learning spills over across firms, these consumer subsidies could increase the total amount of solar adoption and potentially serve as a second-best instrument to address the market failure of non-appropriable learning.

Bollinger and Gillingham (2019) and Bradt (2024) study this phenomenon in the California solar market. Both papers formulate models of solar installer competition that allow for appropriable and non-appropriable learning-by-doing by installers. The papers find evidence of both forms of learning. However, these two analyses come to somewhat different conclusions regarding the welfare impacts of consumer subsidies. Bollinger and Gillingham (2019) find that the costs of the California Solar Initiative are higher than the benefits from consumer surplus and avoided environmental damages. By contrast, preliminary results from Bradt (2024) suggest that the consumer subsidies provided under the California Solar Initiative increased welfare in California, though this conclusion may be sensitive to assumptions about the marginal cost of public funds.

This research on solar installers does not provide direct evidence of international spillovers since it focuses on one sub-national market. However, some of the learning that occurred in the California solar market could have spilled over to installers in other markets in principle. There may also be international spillovers if learning-by-doing is present in upstream solar panel manufacturing.[16]

In the wind industry, Anderson et al. (2019) find that knowledge spillovers among wind farm developers are highly localized, decreasing in the physical distance between firms. However, the magnitudes of the spillovers are small enough that they may not be economically important. Both findings cast doubt on the likelihood that government policy causes learning among developers that spills over across borders.[17]

On the other hand, Covert and Sweeney (2024) study the global market for wind turbines and find evidence of learning-by-doing spillovers among wind turbine manufacturers, who are upstream of the developers studied by Anderson et al. (2019). These spillovers are not restricted to one country: the authors show that Chinese firms entering the market in the late 2000s benefited from the prior manufacturing experience of non-Chinese firms. This provides a clear exposition of how government policies could have positive effects on third parties.[18]

5.2 Producer subsidies

Spillovers from production and innovation Banares-Sanchez et al. (2023) study the effect of Chinese industrial policy on solar panel manufacturing and innovation. They use a synthetic-difference-in-differences approach to compare outcomes in locations that were eligible for city-level production and innovation subsidies to other locations that were not. They find that production subsidies caused increases in production, innovation, and productivity for firms in treated cities relative to firms in matched control cities. Effects were larger for cities that offered both production and innovation subsidies. Since solar panels are globally traded, any effects of government intervention on production are likely to cause static third-party effects that spill over to other countries. These static spillovers would presumably be positive for consumers and the environment, and negative for competing firms (putting aside any dynamic countervailing effects such as Marshallian externalities). Similarly, government support for innovation could have spillovers to other countries over time, as in Gerarden (2023). However, more evidence is needed to confirm these hypotheses because the analysis in Banares-Sanchez et al. (2023) draws comparisons between treated and control cities, and thus cannot determine whether the policies had any effect on the aggregate level of production

[16]Myojo and Ohashi (2018) estimate small learning-by-doing effects and spillovers across firm in the Japanese solar panel manufacturing over the period 1997-2007. On that basis, they conclude that the Japanese policy they study cannot be justified purely on the basis of knowledge spillovers in the absence of unpriced environmental externalities. However, the paper does not fully account for the dynamic nature of the firm's problem.

[17]Wind farm developers, like solar system installers, tend to operate in local geographic markets rather than in multiple countries.

[18]In principle, government policies that affect learning-by-doing may have positive or negative spillovers that go beyond the analysis of Covert and Sweeney (2024). For example, it may affect entry and exit decisions and lead to changes in market structure relative to a world without government intervention, which are beyond the scope of their study.

and innovation in equilibrium.

Bollinger et al. (2024) use a structural model to provide some prospective estimates of the static third-party effects of producer subsidies. According to model estimates, a subsidy for solar manufacturing in the US would increase domestic manufacturing and decrease foreign manufacturing. Impacts on producer surplus of foreign firms depend on the scale of the subsidy and the extent to which it induces foreign firms to enter into US manufacturing. If entry is inelastic, the subsidy would increase domestic profits at the expense of lower profits for foreign firms. If entry is sufficiently elastic, the subsidy could increase profits for both domestic and foreign firms due to its overall effect on expanding market size.

5.3 Trade barriers

Spillovers from production Bollinger et al. (2024) analyze Chinese firms' response to US import tariffs and provide evidence that solar panel manufacturers shifted production to other countries to avoid paying tariffs. Thus, the tariffs appear to have had third-party effects based purely on raw data and descriptive evidence: for Chinese firms, their production share in China declined while their production share outside China increased. Furthermore, individual firms' market shares changes over time as tariffs affected the extent of their comparative advantage over one another. Bollinger et al. formulate and estimate a structural model to quantify the impacts of tariffs taking these responses into account. The results confirm that tariffs affected third parties beyond the US border. Despite Chinese firms' ability to relocate production to avoid tariffs, the imposition of tariffs made Chinese firms worse off because they incurred higher costs and lost market share to their competitors. US firms were the primary beneficiaries. Firms from other countries benefited initially, but then later suffered from broad-based tariffs imposed on imports from all countries (not just China). Finally, the tariffs suppressed adoption of solar panels in the US, which meant foregone environmental benefits that were both local and global in scope. The results on producer surplus and environmental impacts are broadly in line with Houde and Wang (2024), who study the impacts of tariffs on the US residential solar market from 2012 and 2018.

Coşar et al. (2015) analyze the impact of borders and geography on the Danish and German wind markets, though they do not focus on specific unilaterally-imposed trade barriers. They find that eliminating frictions at the border between Denmark and Germany would increase total welfare in both markets on net. However, it would decrease profits for Danish firms and increase profits for German firms relative to baseline. This provides an upper-bound estimate of the effects of removing trade barriers, since the frictions at national borders are comprised of many factors that may be beyond the control of specific policy initiatives.

6 Conclusion

Supporters of industrial policy have traditionally highlighted industry-level scale economies and Marshallian externalities as key justifications for government intervention. These technological features likely apply to both the solar and wind industries, with the EU's subsidies for wind power and China's subsidies for solar manufacturers frequently cited as major factors behind their industrial "success." However, disentangling localized externalities from other determinants of comparative advantage remains difficult—in part because the industrial policies themselves are endogenous—and therefore the social returns generated by such policies are as yet unknown. In our analysis, we outline the key economic rationales for industrial policy and discuss the extent to which different policy instruments are supported by those rationales. We summarize several recent papers that aim to identify the precise sources of these externalities in the renewable energy industry in order to further our understanding of the case for industrial policy.

As we highlighted above, additional considerations have entered the industrial policy debate in recent years. First, many industries—such as solar—are increasingly dominated by large multinational firms whose production and sales span multiple countries. Governments have increasingly relied on trade instruments, either independently or in conjunction with domestic policies, to influence trade flows and shape the global production strategies of these firms. In this context, industrial policy must account for more factors, including market power and cross-country terms-of-trade effects.

Second, solar and wind have become emblematic of the "green industries" leading the fight against global warming and domestic pollution. While first-best solutions—such as a carbon tax—continue to encounter significant political resistance in some countries, industrial policies may offer a more feasible alternative, given these political economy constraints. The research community is still in the early stage of formally modeling and quantifying the role of industrial policies in these types of second-best environments, particularly when it comes to weighing the relative performance of different policies against their political feasibility. But the evidence we have so far suggests that the benefits associated with mitigating unpriced environmental externalities can far exceed those stemming from traditional channels, such as scale economies or standard terms-of-trade gains.

Finally, several manufacturing industries—solar in particular—have become increasingly concentrated in China as a dominant production hub. This geographic concentration has heightened concerns over national security and industrial overcapacity, further strengthening the case made by proponents of industrial policy in other countries. While more research is clearly needed in this area, we suspect that the relatively low entry barriers in solar manufacturing and the durable nature of its products may make it a less compelling case for intervention on national security grounds compared to other critical industrial inputs, such as semiconductor chips.

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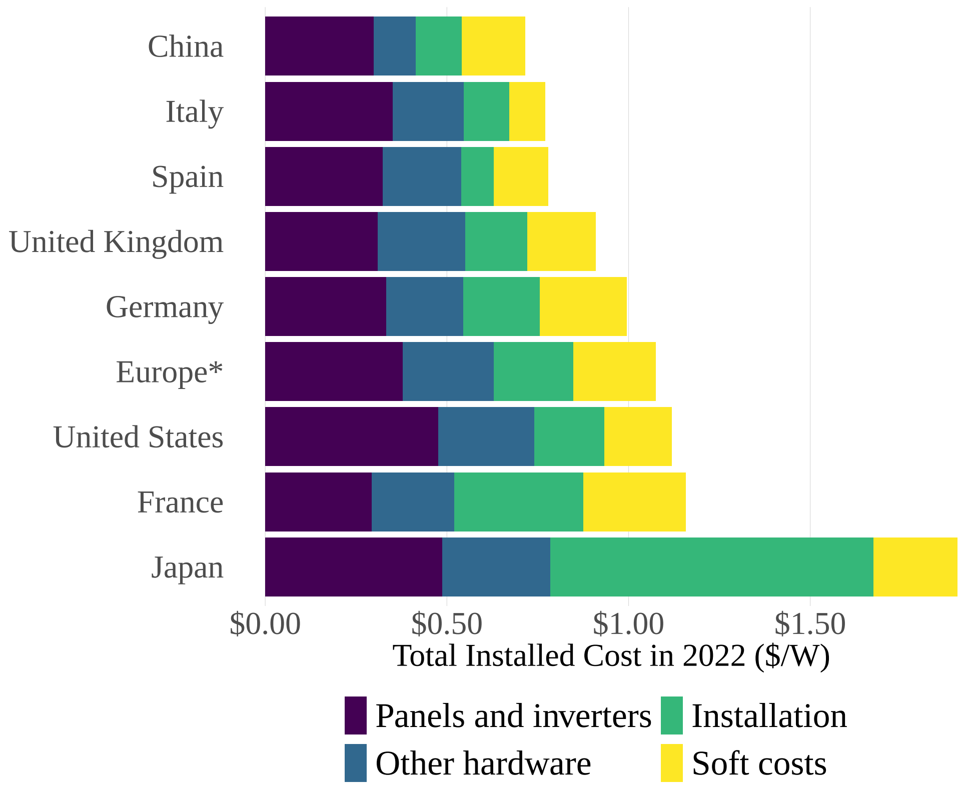
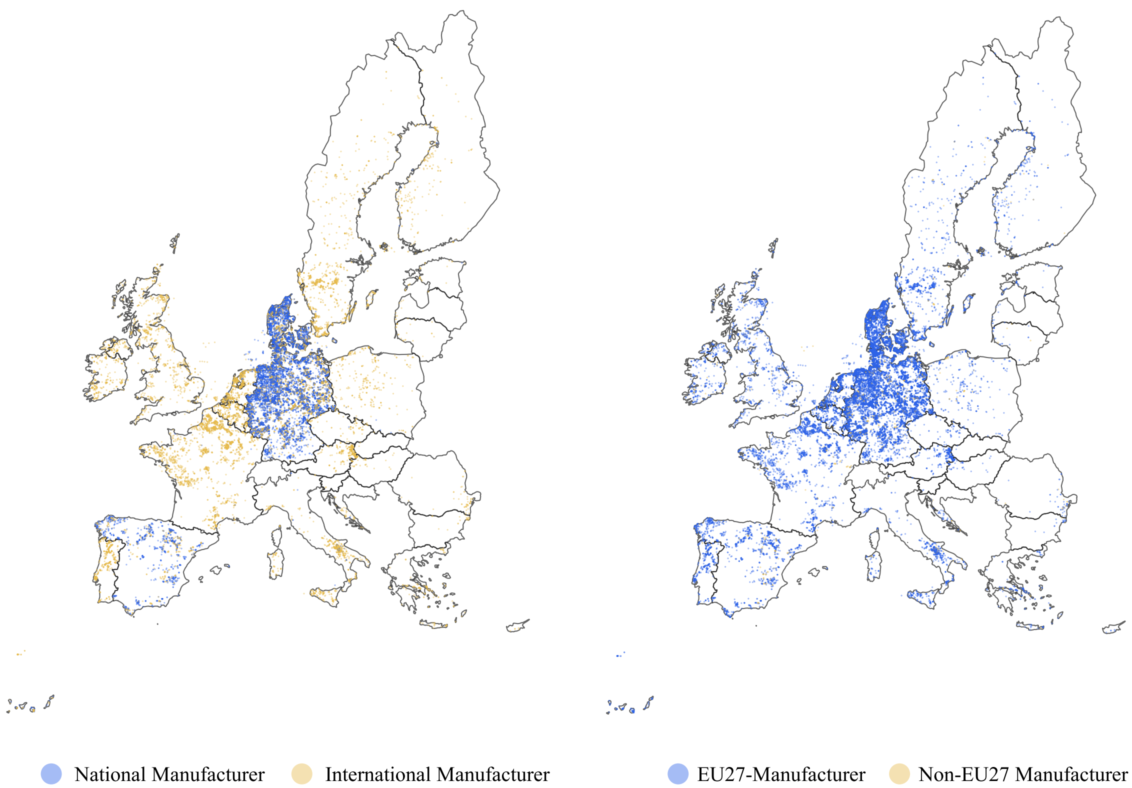
A Appendix: Additional Figures

Figure A.1: Breakdown of utility-scale solar PV total installed costs by country in 2022



Source: Authors' visualization based on data from IRENA (2023b, p. 101). Europe shows the average of Bulgaria, Denmark, Croatia, Cyprus, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Romania, Slovenia, Spain. Solar panels are also referred to as solar modules. All dollars are 2022 USD.

Figure A.2: Location of installed wind turbines by manufacturing location, 2000-2022



Source: Authors' visualization based on data from Wind Power Database. The maps show the locations of wind turbines installed between 2000 and 2022. The colors indicate whether they were produced by domestic manufacturer or not (left side) or whether they were produced by a EU27 manufacturer or not (right side).