The Role of Industrial Policy in the Renewable Energy Sector*

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PRELIMINARY AND INCOMPLETE

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 wind and solar power. We outline theoretical rationales for industrial policy and review recent empirical research, paying particular attention to policy spillovers. We close by providing policy recommendations from the perspective of individual governments and the world trading system.

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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. The expansion of electricity generation capacity in these technologies was influenced by a first phase of targeted subsidies to wind and solar, 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. This large expansion in renewable power has also led nascent industries in wind turbine and solar panel manufacturing to become larger and more mature. 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, external economies of scale, knowledge spillovers, 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 external economies of scale 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, wind and solar technology cost decreases have consistently surprised many experts, which has led electricity costs to fall in many countries even accounting for subsidy costs. Wind and solar are now leading new investment in the power sector in many countries. Furthermore, these trends have generated positive spillovers for the costs of climate policies and decarbonization goals.

While the observed cost reductions in wind and solar technology are both success stories, their trajectories and experiences have been significantly different when it comes to protectionist measures like producer subsidies and trade policies. These two technologies offer a valuable comparison of case studies due to substantial variations in their trade costs. 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. [TBC]

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. 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. These turbines,

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		
Trade instruments	Limited interventions	Substantial interventions

Notes: To be completed and refined with references to links sections.

of massive scale, are produced by a handful of concentrated 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 boom and bust of many small and medium-sized companies and a convergence of manufacturing to the countries with the greatest cost advantage, wind manufacturing exhibits substantial concentration and home bias. These economic differences between the technologies imply that the rationales for, and effects of, industrial policy differ between the two contexts.

The differences in the two technologies have also impacted their popularity and the public support towards subsidy policies. [TBC: we plan to summarize differences in labor market impacts, domestic or in-state requirements (e.g., RPS), point out that solar is adopted adopted by individual consumers in residential settings whereas wind is only utility-scale, etc.]

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). Overall, prior work emphasizes the role that renewable energy policies 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. In doing so, we 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. We provide a summary and policy recommendations in Section 6.

2 Renewable sector overview

2.1 Trends in costs

The deployment of solar photovoltaic (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 wind and solar also decreased significantly worldwide.[1]

Figure 1 summarizes the key factors surrounding the reduction in costs of solar PV and wind (onshore and offshore) 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, maintenance, and productivity across technologies. Total installed costs, in the center panel, comprise hardware such as solar modules, inverters, and turbines, as well as installation, equipment for racking, mounting, and grid connectivity. The last 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.

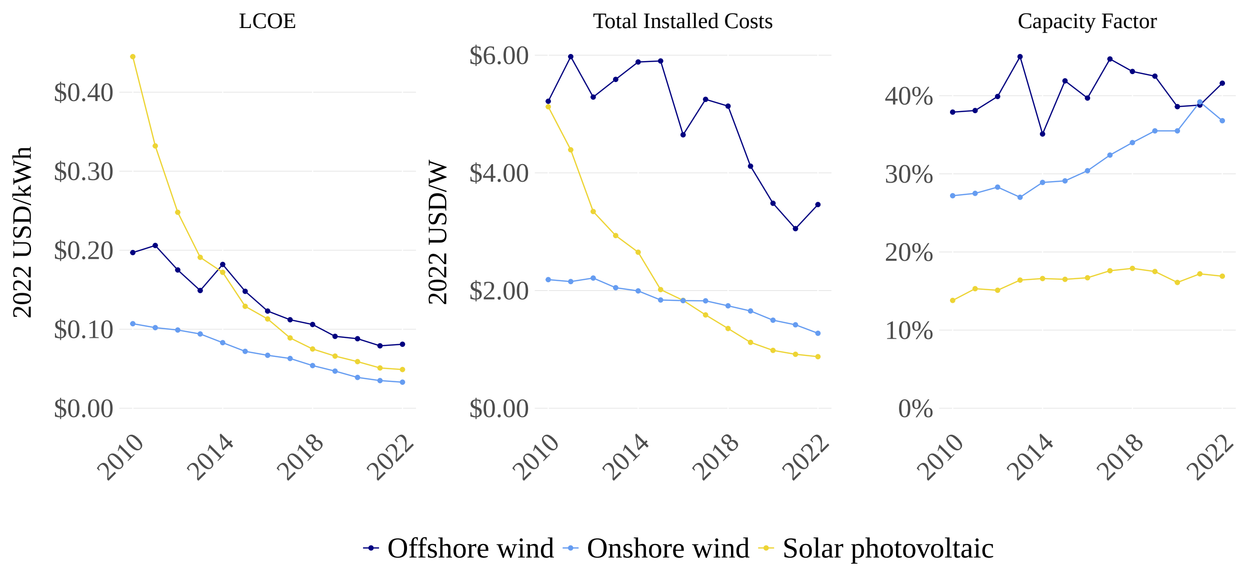
From 2010 to 2022, the global average solar PV total installed costs fell by 83% (IRENA, 2023b, p. 15), result achieved amid extensive Chinese production subsidies and trade tensions between the US, Europe and China. Taking into account deployment over time, the industry displayed experience curves consistent with Wright's law.[2] China compared favorably with the US throughout the whole period and, in 2022, had average total costs at 715 US$/kW against the US's $1,119, also less than that of Italy ($771) and Spain ($778), countries among those with the lowest costs in the EU.

The total installed costs trend explains the sharp reduction in solar PV's LCOE observed in the Figure 1. Pillai (2015) investigate the factors that have contributed to the decline in the cost of producing solar panels, finds that learning-by-doing and economies of scale don't have a significant effect when taken into account: reduction in the cost of a principal raw material, increasing presence of solar panel manufacturers from China, technological innovations and increase in investment at the industry level. Concomitantly with cost reduction, the productivity of solar PV also increased during the period, as evidenced by the upward capacity factor trend. Improved design and operation of solar systems, the use of solar trackers, and targeted deployment in locations with higher radiation levels are believed to have been driving this trend.

[1]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.

[2]Wright's law posits that an industry's costs fall at a constant rate as its output level increases. It has emerged in the context of solar PV as the observed experience curve approximately describes a straight line when plotted against the log of cumulative deployment (Roser, 2023).

Figure 1: Global weighted averages of LCOE, capacity factor and total installed costs



Source: IRENA (2023b, p. 42). The levelized cost of electricity (LCOE) is the net present cost per unit of electricity generated over the lifetime of a technology. Capacity factor is the annual energy output produced by installed power. Total installed costs account for all costs involved in completing a project, including hardware, installation, grid connection, engineering, permitting, etc. Values are global weighted averages, with weights given by installed MWs (IRENA, 2023b, p. 23).

In terms of wind generation, the main component of total installed costs is the construction and installation of wind turbines. Overall, these costs decreased significantly for both onshore and offshore wind, as illustrated in Figure 1. For onshore wind, the price of turbines also makes up for most of the LCOE, producing a trend similar to that of installed costs during the period. As turbine prices stabilize, however, operational and maintenance tend to become increasingly important in further reducing the LCOE. Offshore wind, on the other hand, additionally faces inherent challenges related to installing and operating wind turbines in deep waters. As such, total installed costs are subject to yearly fluctuations associated with supply chain bottlenecks and local characteristics of wind projects, which vary based on differential deployment patterns across markets and years. Major drivers for cost reductions for wind technologies were lower commodity prices and stable national politics, alongside financial support schemes and clustered projects in Europe. An important factor of these cost reductions was an industry-level experience effect, whereby processes are optimized and costs decrease as the industry gains more experience manufacturing and deploying the technology.[3]

The capacity factor of wind generation is influenced not only by the environmental conditions a turbine is subject to, but also its technical features. The growing deployment of onshore wind farms with higher heights and longer blades has been a key factor in increasing its capacity factor, particularly in regions well-suited to wind generation in the United States and Latin America. In contrast, the capacity factor of offshore wind has

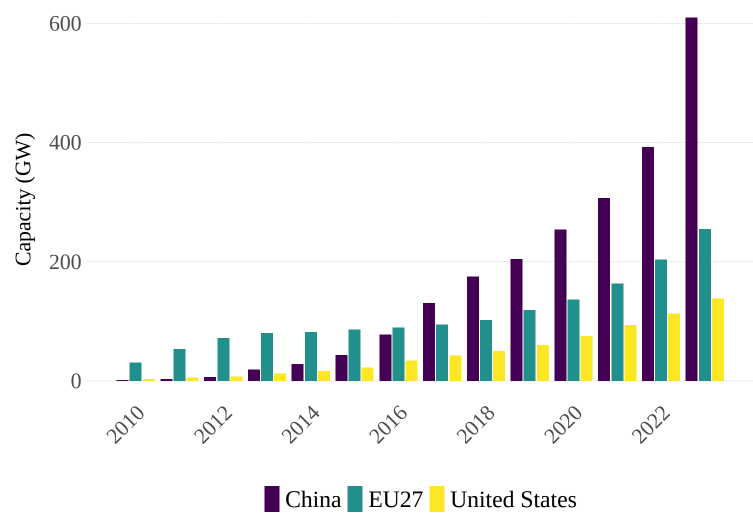
[3]This industry-level effect could be due to a combination of mechanisms including not just learning-by-doing by individual agents but also innovative activities, economies of scale, spillovers across firms, etc.

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).

2.2 Trends in adoption

Figure 2 tells three different stories of solar PV deployment across China, the EU, and the US. 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, 2023).

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



Source: Own 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 raised concerns about the country's ability to sustain the trend (Davis et al., 2024).

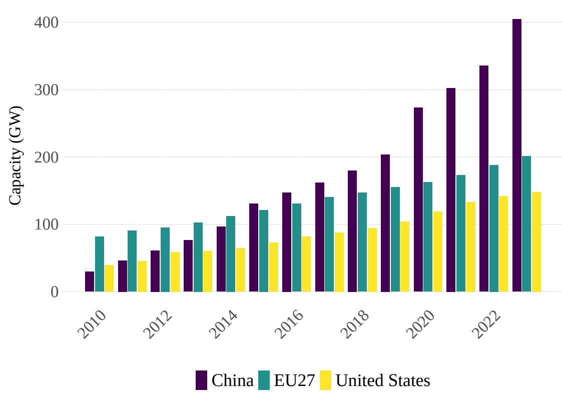
In stark contrast, China significantly accelerated its solar PV deployment after 2012, having overtaken the EU by 2017 and reaching a record total installed capacity of over 600 GW in 2023. China's recent surge in installations, exceeding 217 GW in 2023, nearly doubled its growth rate and rivaled the combined capacity installed in the rest of the world. China has benefited from high domestic demand[4] and strong,

[4] 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 installation, to specifically lower the soft costs of customer acquisition and contracting (Hove, 2023).

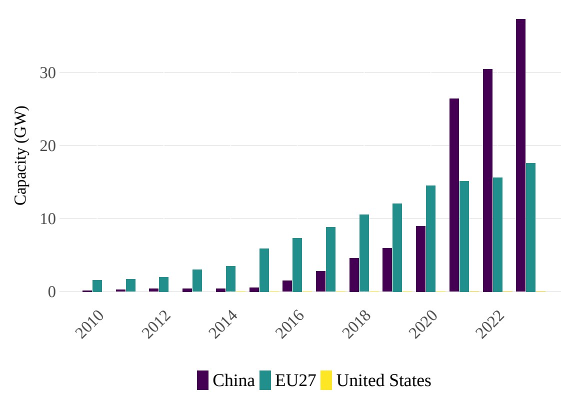
vertically integrated manufacturing. With most of the solar PV supply chain located within the country, it was able to maintain supply relatively stable despite global fluctuations in prices of raw material and rising interest rates. Data from IRENA (2024) reveals that, in 2021, solar PV made up for 4% (327,651 GWh) of all electricity generated in China, effort that placed it in between the EU's 5.4% (144,777 GWh) and the US's 3.4% (148,153 GWh) in relative terms only a decade after starting at negligible levels.

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. Technological advances and economies of scale have driven down costs, enhancing the competitiveness of onshore wind. Favorable regulatory frameworks, both at the EU and Member State levels, have fostered an environment conducive to investment. In recent years, challenges similar to those faced by solar PV deployment are also hurdles to the expansion of wind generation. In addition, it contends with opposition from local communities, lengthy permitting processes, grid integration challenges, and site selection complexities (Costanzo et al., 2023).

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



(a) Onshore



(b) Offshore

Source: Own 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 (BerkeleyLab, 2024). On the other hand, offshore wind remains unexplored as of 2023 largely because, compared to the EU, the US had a greater number of suitable inland sites with low population density that, combined with the lower operational and maintenance costs of onshore wind farms, steered the country away from offshore generation (Marsh & Marcy, 2015).

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 wind and solar parks installed in desert areas and connected to ultra-high-voltage transmission lines IEA (2023). A dramatic increase in offshore wind capacity took place from 2020 to 2021, despite that year marking the end of the country's preferential Feed-in Tariff (FiT) program (Dedene, 2023).[5]

In terms of labor, solar accounted for 4.9 million jobs globally and wind, 1.4 million as of 2021-2022

[5]A feed-in tariff is a contract establishing a fixed rate that remunerates a generator for renewable electricity fed into the grid. More details in section 3.1.1.

(IRENA, 2023a). These figures include both direct and indirect jobs; direct jobs encompass roles in renewable energy systems (RES) manufacturing, onsite installation, and operation and maintenance, whereas 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 RES 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 (56% and 49%, respectively), reflecting its low labor costs, infrastructure provision and targeted industrial policy. The EU is the second largest global employer in these industries (10% and 23%), trailed by the US (5% and 9%) (IRENA, 2023a).

2.3 Market structure and trade patterns

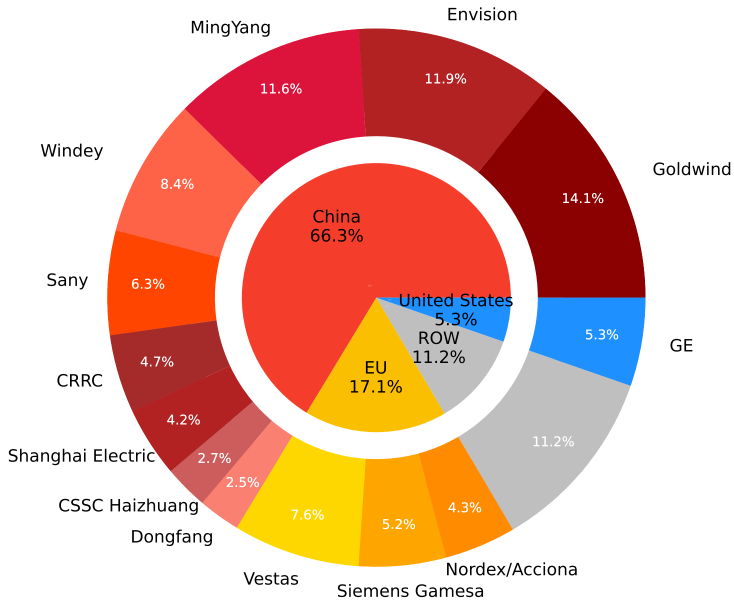
This section explores the development and current state of solar and wind product manufacturing in China, the EU, and the US, while also highlighting key manufacturing locations outside these regions. It begins with an overview of major manufacturing hubs for solar and wind technologies and analyzes trade behaviors based on the status of each national manufacturing sector.

The first hubs of wind energy manufacturing developed in Europe, with Denmark, Germany, and Spain emerging as key centers in the early 2010s. European Original Equipment Manufacturers (OEMs), companies that both design and produce wind turbines, benefited from strong domestic demand, long-term relationships with developers, and limited international competition due to high transportation costs and logistical challenges (Gasperin & Emden, 2024). Unlike the solar industry, where Chinese firms rapidly gained market share, European wind manufacturers maintained a dominant position for years. However, the wind supply chain has since become highly globalized. In the early 2010s, supply chain proximity was a priority, but cost advantages have since led some suppliers to shift production lines to low-cost countries (Lee & Zhao, 2024). At the same time, 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, their dominance has declined as Chinese manufacturers have gained market share (Lee & Zhao, 2024). In terms of take-in-orders as of 2022, Chinese firms account for 66% of global wind turbine market share, while European firms hold 22% (see Figure 4). Despite these shifts, the market power remains concentrated, with the seven largest companies controlling two-thirds of global take-in orders in 2022.

Manufacturing patterns show regional biases. In Europe, wind turbines are predominantly produced by domestic manufacturers, reflecting a strong home bias at both the regional and national levels. Figure 5 shows the country of origin for the manufacturers of wind turbines in Europe and the US. As Figure 5a makes clear, most wind turbines in Europe are manufactured by European companies. This home bias is also acute at the country level, as shown in Appendix Figure A.1, which has been used to estimate home bias and trade frictions in this sector (Coşar et al., 2015). The successful development of a domestic industry in the EU can be seen in the limited role that imports play in the wind sector when compared to exports (see Figure 6b).

The successful development of an European wind manufacturing industry is apparent when we compare

Figure 4: Market Shares of Wind Manufacturers in terms of take-in-orders (2022)

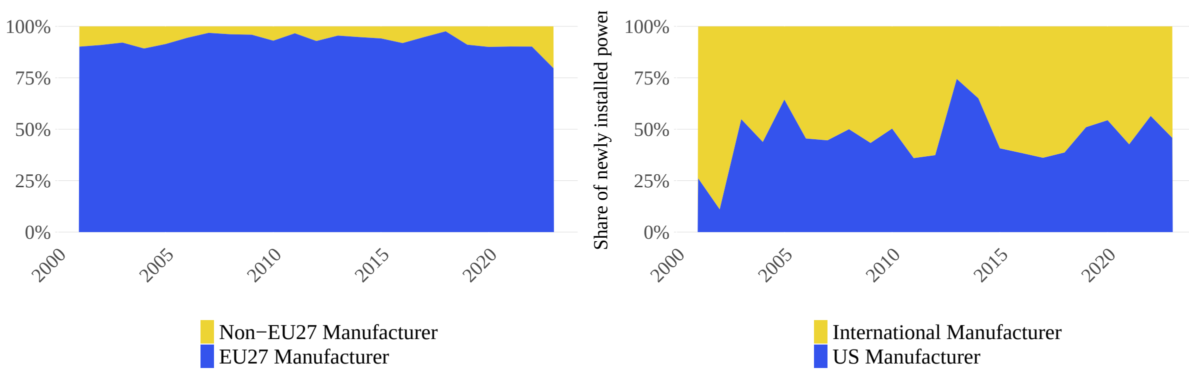


Source: Own visualization based on data from Enerdata. The graph shows the market share of wind manufacturers based on take-in-orders from 2022.

the same patterns in the US. As seen in Figure 5b, wind manufacturing does not exhibit as strong home bias in the US. Although manufacturing locations are mostly located in the US or Canada due to the large transportation cost, the parent companies are often European-based, as shown also in the patterns of imported wind goods (see Figure A.3b and Figure 6c). Figure 6 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.

[TBC]

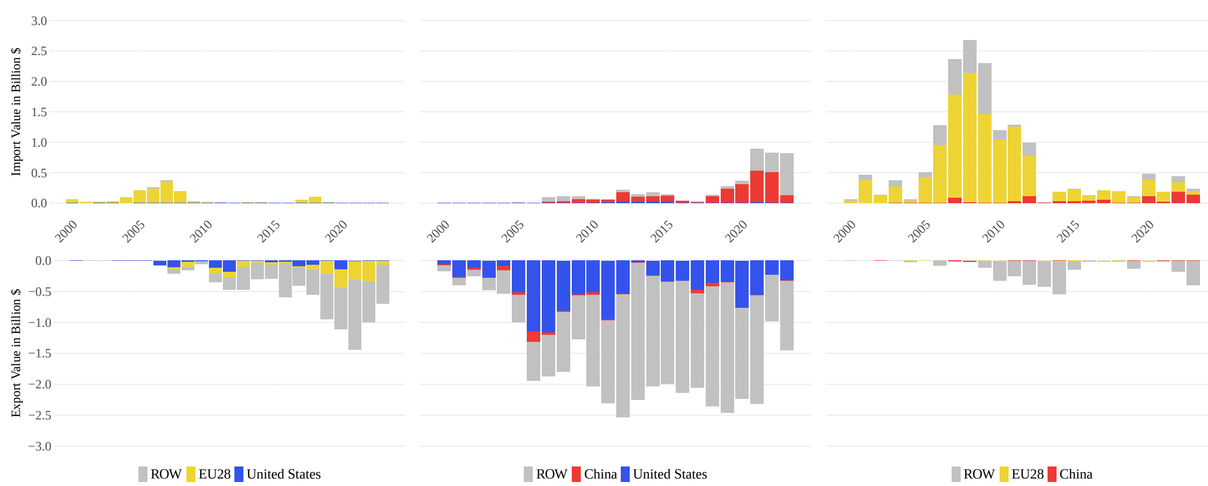
Figure 5: Comparison of country of origin for wind turbines in the EU and United States



(a) European Union (b) United States

Source: Own visualization based on data from WindPower. The graph shows the share of newly installed wind turbines which were manufactured by a domestic or by an international manufacturer for each year from 2000 to 2020. In Panel (a), "International Manufacturer" refers to turbines produced by manufacturers from countries other than the one where the turbine is installed (e.g., other EU countries, US, China, etc.). "National Manufacturer" refers to turbines manufactured by a manufacturer with the same origin country as the country of the turbines installation. Following a similar logic, "EU27 Manufacturer" refers to all turbine manufactured by a manufacturer with its origins in one of the EU27 countries. In Panel (b), concerning the US, "International Manufacturers" includes all non-US manufacturers. By definition, each panel legend is a complementary pair.

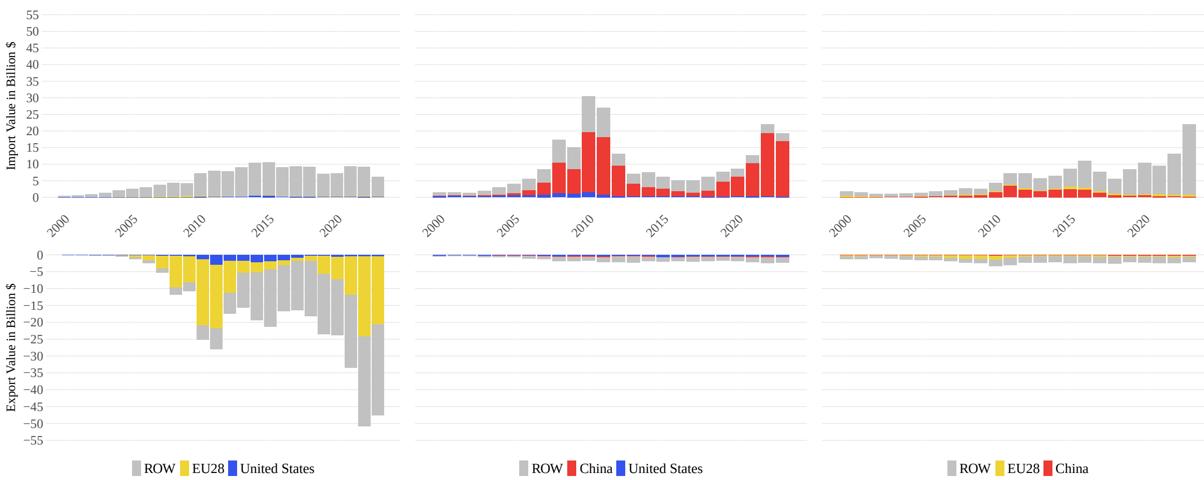
Figure 6: Total Imports and Exports from 2000-2023 of wind manufacturing products



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

Source: Own 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.

Figure 7: Total Imports and Exports from 2000-2023 of solar PV manufacturing products



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

Source: Own 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.

3 Industrial policies in use for renewable energy

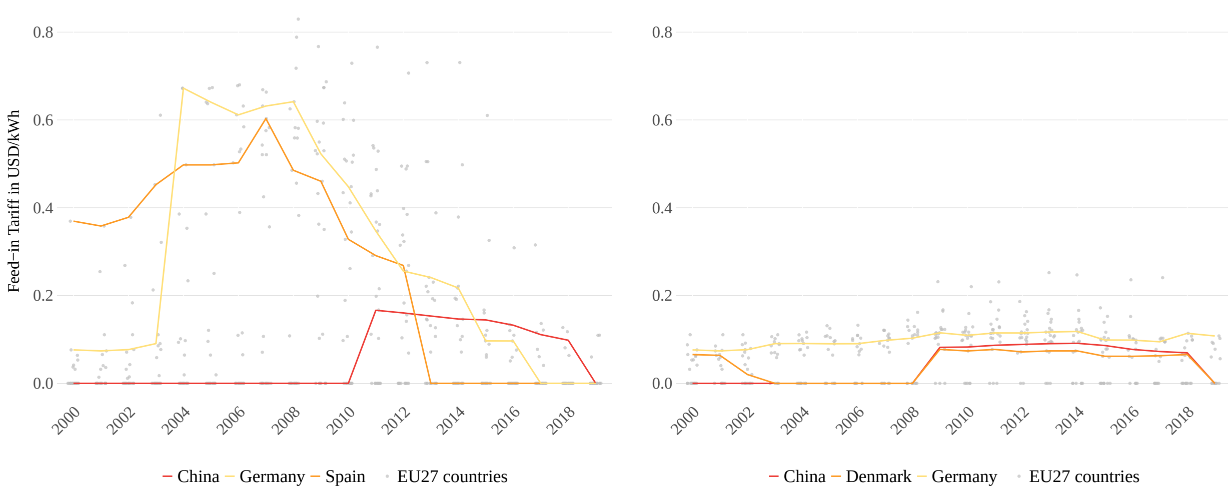
In this section, we summarize the wide array of industrial policies employed in the renewable energy sectors globally. We categorize these policies into three main groups: consumer subsidies, which are designed to encourage consumers to adopt renewable energy; producer subsidies, which directly compensate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

3.1 Consumer subsidies

3.1.1 Feed-in Tariffs

Feed-in tariffs (FiTs), or Feed-in payments (FiPs), are a policy tool used by many major world economies to support renewable energy producers. Governments offer a rebate for each unit of electricity generated and fed into the grid. These tariff rates vary significantly over time and across different countries. As we show in Figure 8a, several European countries like Germany and Spain were the pioneers of this policy in the early 2000s. Their historical tariff rates were as high as 0.4-0.6USD per kWh for Solar but those declined rapidly over time. Meanwhile, the tariff rate for wind has been stable at around 0.1USD/kWh in most EU27 countries as in Figure 8b.

Figure 8: Feed-in tariffs for photovoltaic and wind power by country



(a) Photovoltaic (b) Wind Power

Source: Own visualization based on data from OECD. The graph displays the weighted average feed-in tariff for China, the United States, and selected leading 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.

Germany, in particular, used FiTs 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, but 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).[6]

The United States has made more limited use of feed-in tariffs (FiTs). There is no nationwide FiT policy, but some states have implemented their own FiTs to encourage the development of renewable energy. These typically operated at relatively low rates, around 0.10USD per kWh, and for shorter durations. Overall, the popularity of these tariff schemes declined after 2014 and they did not gain widespread acceptance.

China implemented its own feed-in tariffs (FiTs) starting in 2010, with rates comparable to those offered in the EU27 countries. The FiT 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 FiT model.

3.1.2 Investment Schemes: United States

Historically, the U.S. 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 subsidies aim to reduce the financial burden on individuals and businesses investing in renewable energy projects, thereby promoting the adoption and expansion of renewable energy infrastructure across the country.

Over the past two decades, these national subsidies have primarily gone to investments in wind, solar, and biofuels (Figure 9). The

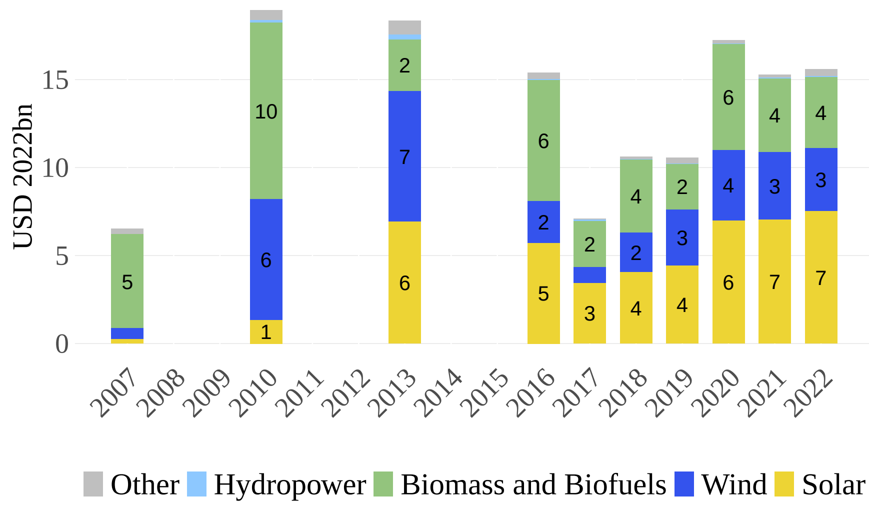
been split between

Investment Tax Credit (ITC) The Investment Tax Credit (ITC) is one of the primary mechanisms through which the U.S. 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).

[6] 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, 2023), 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 procedures (Wehrmann, 2024).

Figure 9: Renewable energy subsidies by technology for the United States



Source: Own visualization based on data from the U.S. Energy Information Administration. The graph shows the total amount of subsidies from the U.S. Federal Government by renewable energy technology.

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. The PTC is essentially a second-best emissions abatement subsidy, where the value of electricity is determined by the market, and the external benefits of renewable electricity are paid in addition to that market value. This places more risk on renewable project developers than feed-in tariffs do, since PTC recipients are exposed to wholesale electricity price risk.[7] 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 U.S. government offered eligible renewable energy projects to receive direct payments instead 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 10.

[7] In practice, renewable energy developers often hedge this price risk by signing long-term contracts with utilities or corporations.

Figure 10: Renewable energy subsidies by instrument for the United States

Source: Own visualization based on data from the U.S. Energy Information Administration. The graph shows the total amount of subsidies from the U.S. Federal Government to renewable energy technologies by instrument.

State and Local Policies In addition to national policies, many states and local governments in the U.S. 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 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.

Table 2: U.S. 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.

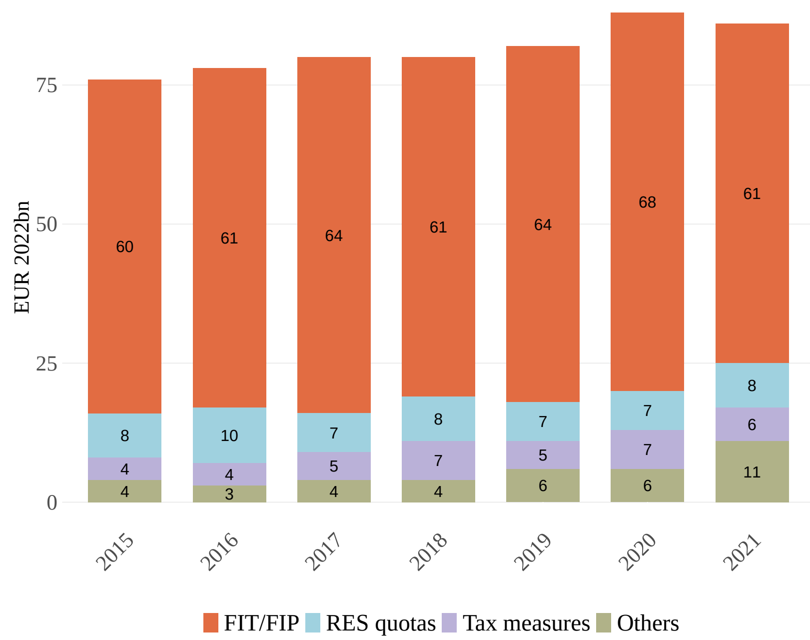
3.1.3 Investment Schemes: European Union

Unlike in the United States, subsidies for renewable energy sources in the European Union primarily utilized feed-in tariffs/payments (FiT/FiP) or renewable energy source (RES) quotas with tradable certificates. As illustrated in Figure 11, tax measures represent a relatively small proportion of the total subsidies in the EU, while the majority is allocated to FiT/FiP.

In terms of the technologies subsidized, both the level and composition has been quite stable in the past decade for Solar and Wind. For instance, in 2021, solar received the largest amount of subsidies (EUR 31 bn) followed by wind, both technologies are most supported by FiT/FiP. Figure 12 also shows that in 2021, subsidies for renewable energies decreased for the first time since 2015, possibly due to an increase of wholesale electricity market prices. Additionally, 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. 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.

Net metering, in combination with stable auction schemes, proved effective in the Netherlands, which leads overall with the highest solar capacity per capita. However, in recent years, the country has faced political uncertainties due to ongoing negotiations about the net metering scheme and significant changes in the Dutch government. The newly formed government essentially agreed on phasing out net-metering and focusing on grid congestion issues Schmela et al. (2023). In Spain, the second largest solar market in the

Figure 11: Renewable energy subsidies by instrument of EU27



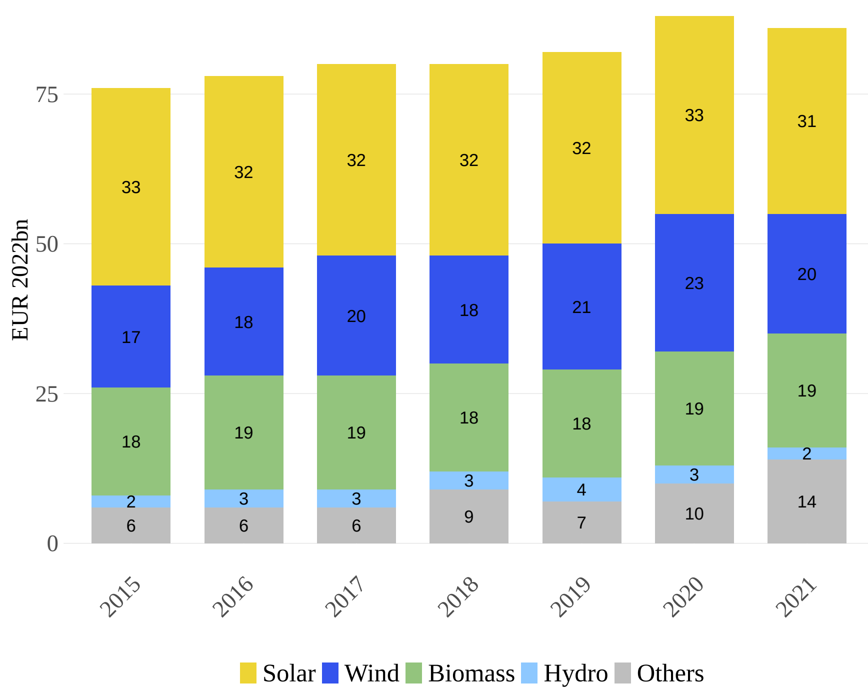
Source: Own visualization based on data from Figure 6, Enerdata and Trinomics. The graph shows the total amount of subsidies in EUR 2022 bn by instrument across all EU Member States. The category "Others" also includes subsidies through direct investment.

EU, the end of the sun tax in 2018[8], high electricity prices, and governmental support with stable regulations have attracted national and foreign international investments in the solar sector through, for example, Power Purchasing Agreements (PPAs) Schmela et al. (2023).

Finally, following the US Inflation Reduction Act, the EU introduced its own Net-Zero Industry Act. Instead of offering intensive subsidies like those in the IRA, the EU proposed the Strategic Technologies for Europe Platform (STEP), which primarily reallocates existing funds towards clean technology. The Commission suggested an additional allocation of 10 billion Euros and anticipates that STEP will attract further private and public investments. In 2023, the European Commission also 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, and 2.2 billion EUR in direct grants for the decarbonization of production processes in the German industrial sector.

[8]The Spanish "sun tax", in place from 2015 to 2018, was a charge on the consumption of the electricity generated by one's own solar PV installation (Tomasi, 2022).

Figure 12: Renewable energy subsidies by technology for EU27



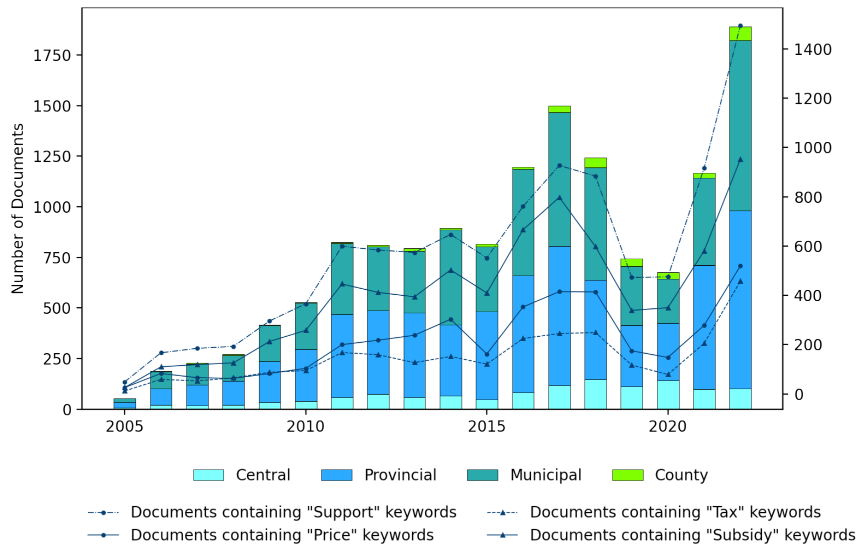
Source: Own visualization based on data from Figure 11, Enerdata and Trinomics. The graph shows the total amount of subsidies in EUR 2022 bn by technology across all EU Member States.

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, notably 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. We propose that integrating this firm-level data approach with textual analysis could significantly enhance the reliability and measurability of both methodologies.

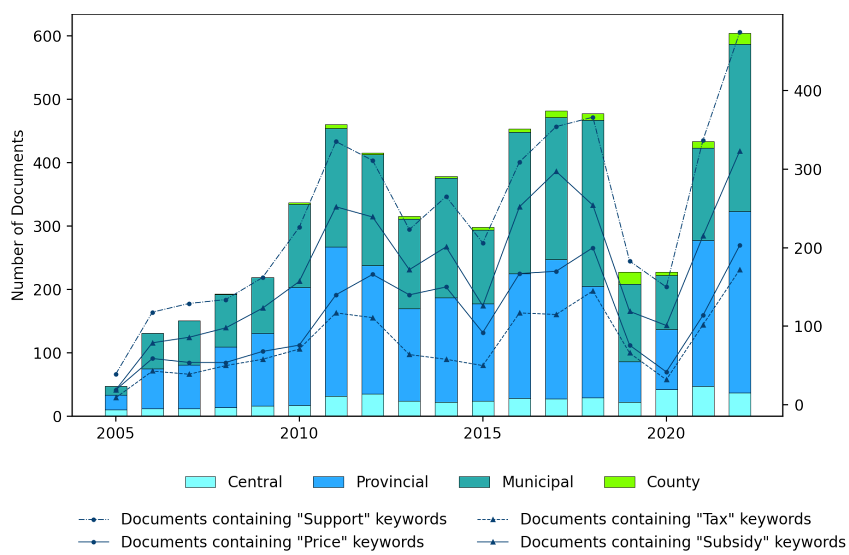
In the United States, policies to promote renewable energy have primarily focused on consumer subsidies to encourage adoption of renewable energy technology by firms and individuals. One important exception to this is the provision of R&D funding to renewable energy. However, this funding is primarily focused on basic and applied research rather than commercial technologies, and is small in magnitude compared to the consumer subsidies outlined above (Figure 10). In recent years, new policies to encourage manufacturing activity have been enacted. Most notably, the IRA included a provision to subsidize clean energy manufacturing

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



Source: Own visualization based on data from PKULaw.

Figure 14: Renewable Energy Subsidy Policy Documents in China: Wind



Source: Own visualization based on data from PKULaw.

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 U.S. renewable energy sector. However, it is too early to determine what the impacts of these policies will be.

Like past Federal policies, most state and local policies in the U.S. 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.

In Figures 13 and 14, we have provided preliminary analysis of the total counts of policy documents of Chinese central, provincial, municipal, and county level governments that can be classified as supply side subsidies. We can further classify these subsidy documents based on their keywords. Future work is needed to construct a comprehensive understanding of the producer subsidies used to promote renewable energy manufacturing activity and how they vary over space and time.

3.3 Barriers to trade

3.3.1 Solar

Despite the dominance of European, Japanese, and U.S. photovoltaic producers in the early 2000s, China rapidly closed the gap, leveraging its competitive cost advantage to eventually surpass these nations in market leadership before 2010. In response, both the United States 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 initial round of U.S. 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 U.S. 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. These measures remained effective until the onset of the Trump administration's tariff policies.

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 (MIP) 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 U.S. and EU diverged significantly after 2017. Following the insolvency of SolarWorld, the last major EU manufacturer, in 2017, the European Commission decided in 2018 to remove both the anti-dumping tariffs and the Minimum Import Price (MIP) 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. "Section 201 tariffs" targeted crystalline silicon products from all major solar product exporters to the U.S. The tariffs were scheduled to decrease by 5% annually until their expiration in 2022. However, President Biden extended these tariffs through 2026, albeit with some modifications. A final round of tariffs implemented by the U.S. did not specifically target solar panels. Instead, utilizing Section 301 of the Trade Act of 1974, the U.S. Trade Representative imposed tariffs of up to 25% on imports from China. 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 conjunction with the pre-existing anti-dumping and countervailing duties established in 2012 and 2014.

The changing anti-dumping regulations significantly impact the primary sources of Photovoltaic products for both the EU and the United States. As illustrated in Figure 15a, products manufactured in China saw rapid growth in the EU market from 2005 to 2012. However, the introduction of the EU's anti-dumping tariffs and the Minimum Import Price in 2013 markedly curtailed this growth. While imports from Malaysia, Vietnam, and Thailand – countries in Southeast Asia – did increase from 2013 to 2017, they were not sufficient to offset the decline in imports from China. Once the tariffs and MIP were removed in 2018, the Chinese producers again took over the whole market.

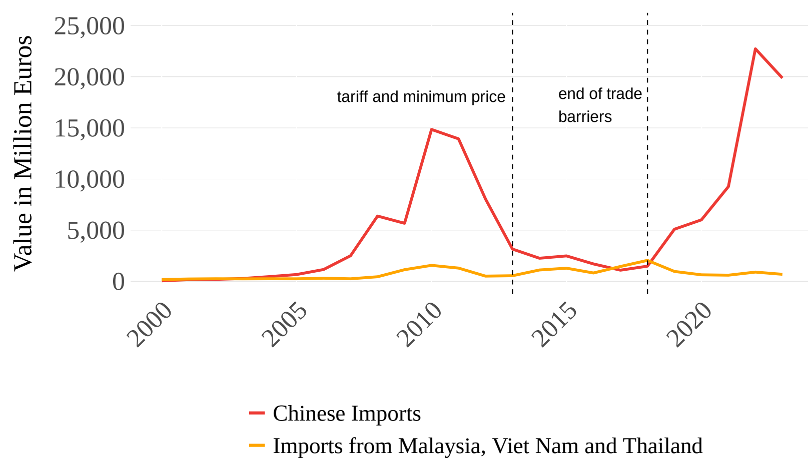
The situation in the United States stands in stark contrast. The U.S. not only maintained its 2014 anti-dumping and countervailing tariffs but further escalated these measures with two additional rounds of tariffs under Sections 201 and 301 during the Trump administration. Consequently, direct imports 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 U.S. solar import market. As documented by Bollinger et al. (2024), Chinese companies have aggressively expanded their manufacturing capabilities in these Southeast Asian countries, effectively circumventing the U.S. tariffs on Chinese products by relocating their production facilities. Such a pattern is evident in Figure 15b.

3.3.2 Wind

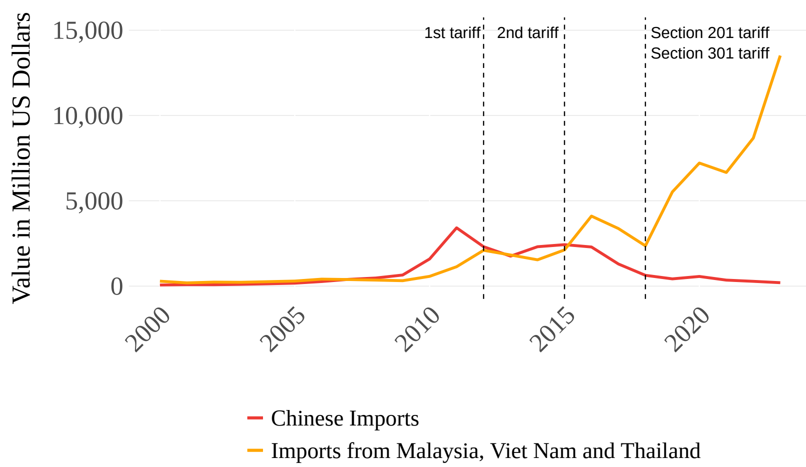
The United States has actively implemented trade barriers to protect its wind turbine industry. In 2013, the United States imposed countervailing duties (CVD) on utility-scale wind towers from China and anti-dumping duties (AD) on utility-scale wind towers from both China and Vietnam. These CVD and AD measures were renewed by the Department of Commerce in 2019. These protective measures were further expanded to imports from Canada, Indonesia, and South Korea in 2020 and to Spain in 2021.

In contrast, the European Union did not systematically impose trade barriers on wind turbine until more recently. In December 2021, the European Union implemented definitive anti-dumping measures on imports of steel wind towers from China. These measures, which include duties ranging from 7.2% to 19.2%, were established following an investigation that determined Chinese producers were selling these wind towers at unfairly low prices. These investigations were continued in April 2024. That said, imports from China in 2020 remained relatively small, although increasing, as seen in Appendix Figure A.4b. [TBA: re-do non-2020 data]

Figure 15: Photovoltaic manufacturing products 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 (Panel (a)) and USA (Panel (b)) for photovoltaic products from 2000-2023 overlapped with the main trade tariff policies affecting these products. HS Codes used: 854140, 854141, 854143, 854149.

4 Economic rationale and impacts of subsidies and tariffs

Subsidies to renewable power, either demand- or supply-focused, can be justified with a variety of arguments, static and dynamic. A main driver of their justification is focused on achieving climate goals and decarbonizing the economy, although recently issues such as security of supply and diversification of the energy portfolio have gained prominence.

In the absence of global carbon taxes or low carbon taxes, subsidies to renewable power can provide incentives to reduce the environmental footprint of the electricity sector, as a substitute for a Pigouvian tax. Under some assumptions, these subsidies can be quite efficient at delivering the desired outcome of decarbonization, even if not as efficient as a carbon tax (Borenstein & Kellogg, 2023).

Also, their effects may be distributional rather than efficiency-reducing e.g., they may effectively subsidize consumers worldwide at the expense of the subsidizing government's coffers and non-subsidized producers.

4.1 Static arguments

4.1.1 Consumer subsidies

Consumer subsidies as second-best environmental policy The primary purpose of most consumption subsidies, such as feed-in tariffs, is to address the price disparity between fossil fuel energy sources and green energy, especially when environmental costs are not properly accounted for. 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 emissions 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, 2015; 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.

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 (Bollinger & Gillingham, 2012; De Groote & Verboven, 2019; Gillingham & Tsvetanov, 2019; Hughes & Podolefsky, 2015; Langer & Lemoine, 2022). For wind, by contrast, work has focused on utility scale adoption since it constitutes almost the entire market (e.g., Aldy et al., 2023; Cullen, 2013; 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 with a narrow focus on static 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 static 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), 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.

Other motivations for consumer subsidies In addition, the substantial adoption costs and experience curve associated with clean energy can justify the use of additional one-time investment tax credits (ITCs), such as those employed in the United States (Bollinger & Gillingham, 2012; De Groote & Verboven, 2019; Langer & Lemoine, 2022; van Benthem et al., 2008). A separate body of literature highlights the existence of information asymmetry or inattention regarding the long-term benefits of green energy investments. Subsidies are argued to reduce these frictions and encourage consumers to switch to renewable energy sources (Allcott (2016)).

An additional argument for consumption subsidies often focuses on their market equilibrium effects on the supply side. Several studies have investigated how consumption subsidies enhance technological learning (Bollinger and Gillingham (2019), Bradt (2024), and Myojo and Ohashi (2018)) and innovation (Gerarden (2023), Gao and Rai (2019)) among solar installers and manufacturers. Covert and Sweeney (2024) and Anderson et al. (2019) study similar economic forces in the wind industry. While they do not focus on the role of consumer subsidies *per se*, Covert and Sweeney (2024) find spillovers across firms that could provide a justification for consumption subsidies. However, this line of argument has not fully addressed the question of when and how consumption subsidies are more effective economic tools than supply or innovation subsidies in achieving these policy goals.

There are also other policies that affect demand for renewable energy, 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.

Pegels and Lütkenhorst (2014) assess the impact of Germany's energy transition policies on both wind and solar. Both technologies received subsidies which affected investment in electricity generation capacity. The wind turbine manufacturing industry also seems to have benefited from these policies. The solar manufacturing industry, by contrast, was less successful in the face of competition from abroad.

4.1.2 Producer subsidies

Many of the rationales for supply-side subsidies overlap with those for consumption subsidies, particularly in a perfectly competitive market. However, the nature of international competition and market structure can introduce strategic interactions between producers that justify an additional set of policy rationales rooted in the strategic trade policy literature.

In their classical 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 and Grossman (1986)), but when domestic consumer welfare is taken into account, production subsidies can be further justified.

While it is difficult to quantify the extent and magnitude of producer subsidies for manufacturing renewable energy technology, 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 supply-side subsidy to the demand side in later years. Banares-Sanchez et al. (2023) provide evidence of the large impact of production and innovation subsidies from different cities in China. On the other hand, they find that local consumer subsidies have very little impact on production and innovation. The main reason for the modest impact of demand subsidy is that new installations were not required to be from local firms.

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 rather than environmental externalities. Their results suggest that combining these two policy tools could do better than either one in isolation in addressing imperfect competition.

4.1.3 Barriers to trade

While import tariffs and countervailing duties have been prevalent trade policy instruments for many countries, their traditional economic rationale often relies on the "terms-of-trade" argument. When foreign supply is elastic, an import tariff can reduce the world price of renewable manufacturing products in the solar and wind sectors. As a result, the incomplete pass-through of tariffs into consumer prices could improve domestic welfare if the tariff revenue more than compensates for the domestic consumer welfare loss. However, the substantial environmental cost associated with the reduction in consumption often dominates the welfare effect in the specific case of renewable energy products (Bollinger et al. (2024) and Houde and Wang (2023)). Overall, the theoretical underpinning for a substantial import tariff is thin unless one believes there is an extremely dynamic scale economies for domestic production (as we will discuss below).

[TBD: Where should we put security and energy independence concerns? We think the point is that these concerns are overstated, given the nature of renewable power – trade is in the stock of energy-producing capital, not the flow of energy materials as in oil/gas/coal – and the possibility of recycling.]

4.2 Dynamic arguments/externalities

Industrial policy can also be justified by the theoretical possibility of Marshallian externalities, the benefits an industry yields from the geographic concentration of firms acting in the same sector. Harrison and Rodríguez-Clare (2009) provides an excellent survey of the theoretical literature underlying these mechanisms. A particularly relevant concept for trade policy is "infant industry protection," where a developing economy might specialize in a less competitive sector, such as agriculture, even when it has a latent comparative advantage in a more advanced sector like manufacturing. This can occur in one of the multiple equilibria. 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 obviously still a highly relevant theoretical possibility for many countries that aim to promote their own renewable energy sectors.

Harrison and Rodríguez-Clare (2009) also pointed to a particularly relevant case study by Hansen et al. (2003) which examines the welfare effects of Danish subsidies to its wind power industry. The study argues that government subsidies helped cultivate a strong Danish windmill industry, now dominant in the global export market. The success of this policy is attributed to significant learning-by-doing effects. Similar empirical findings were supported by Qiu and Anadon (2012) and Nemet (2012), who studied the analogous industry development process in China and the US respectively.

Despite the availability of industry case studies, accurately measuring the learning-by-doing effect is challenging. None of the studies mentioned above have employed modern econometric techniques, particularly those involving quasi-random settings, to formally identify and estimate the strength of this effect. We believe this remains a fruitful area for future research.

5 Third-party effects

Government policies for renewable energy can have spillover effects on third parties through several channels. First and foremost, reductions in environmental externalities can accrue to parties that do not transact in the solar market. These positive spillovers come in both local and global forms due to different forms of air pollution. Changes in greenhouse gas emissions are the clearest example of international spillovers from any government intervention in renewable energy markets. Evidence on these environmental third-party effects was discussed above in Section 4.

There are several other potential forms of spillovers that are not directly related to the environmental impacts of renewable energy, some of which could be positive and others which could be negative. Manufacturing subsidies or barriers to trade can have static third-party effects through profit shifting and consumer surplus impacts, both of which have the potential to make foreign parties worse off. Consumer subsidies could also create static spillovers to other markets through their direct impact on firms' profits and their indirect impacts on equilibrium outcomes in other product markets.[9]

Government policy for renewable energy may also have dynamic third-party effects. For example, direct or indirect innovation policy could generate positive spillovers across international borders due to knowledge spillovers or international trade in renewable energy technology. On the other hand, policies that distort the allocation of production could have negative spillovers to other markets due to lost scale economies, agglomeration economies, or learning-by-doing.

This section reviews evidence of these potential spillovers and highlights areas where more research is needed.

5.1 Consumer subsidies

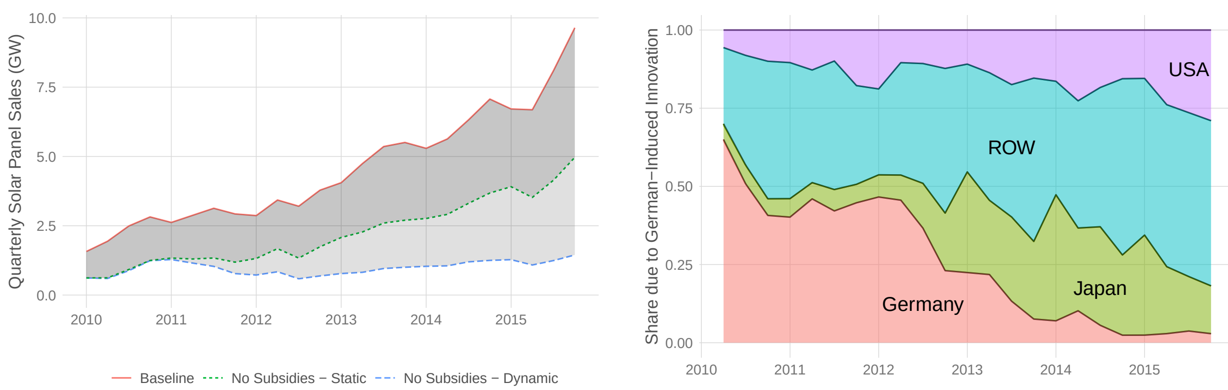
Spillovers from innovation Gerarden (2023) studies the impact of consumer subsidies on innovation by solar panel manufacturers. According to the paper's estimates, more than half of observed solar generation

[9]For example, if suppliers of internationally traded renewable energy technology such as wind turbines were capacity constrained, a demand subsidy in one market could reduce consumer surplus in another market due to higher equilibrium prices for turbines that spill over across markets.

capacity adoption over the period 2010-2015 would not have occurred in the absence of subsidies. Gerarden then considers how this increased demand affects manufacturers' innovation incentives. The paper develops a dynamic model of competition among firms whose profits in the product market depend on government subsidies as well as the quality of their own technology. Firms invest fixed costs to improve their technology endogenously over time.

Gerarden uses the model to simulate the status quo, a counterfactual scenario without subsidies with exogenous innovation by firms (identical to the technology improvements under the status quo), and a counterfactual scenario without subsidies with endogenous innovation by firms. Figure 16a summarizes the results. As described above, removing subsidies has a direct effect of reducing global solar adoption by roughly half (*No Subsidies - Static* relative to *Baseline*). Furthermore, after accounting for induced innovation by firms, the results suggest that solar adoption could have been flat over the time period 2010 to 2015 (*No Subsidies - Dynamic*). This is in stark contrast to the rapid growth of solar adoption observed over the past decade. 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.

Figure 16: Estimates of Induced Innovation and Spillovers from Gerarden (2023)



(a) Global Solar Adoption Because of Consumer Subsidies (b) Beneficiaries of German-Induced Innovation

Source: Both panels are reproduced from Gerarden (2023). Figure 16a plots model predictions for global solar adoption over time with and without subsidies. *Baseline* represents model predictions based on historical subsidies and production costs. *No Subsidies - Static* represents counterfactual outcomes after removing subsidies but treating innovation as exogenous (i.e., holding production costs fixed). *No Subsidies - Dynamic* represents counterfactual outcomes after removing subsidies and allowing for induced innovation by firms. See Gerarden (2023) for more details. Figure 16b plots predictions of the composition of global solar panel adoption due to innovation induced by German feed-in tariffs over the period 2010-2015. See Gerarden (2023) for more details.

These dynamic effects could 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 infancy (Figure 8a), and it was the largest market in the world in the early 2010s (Figure **??**). At the same time, a majority of solar panels in Germany, and the EU more broadly, were imported from abroad (Figure **??**). 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 feed-in tariffs in Germany to isolate their effects from the effects of other consumer subsidies. This yields reductions in global solar panel adoption similar to, but smaller in magnitude than, the results in Figure 16a. To understand spillovers across countries, Gerarden isolates the dynamic effects of German subsidies on innovation from the static effects on adoption, and quantifies their impact in terms of changes in equilibrium quantities from baseline. Figure 16b plots the composition of the global change in equilibrium quantities over time. German consumers of solar panels were initially the primary beneficiary of this innovation, but their share of whole declined significantly over time. In levels, the aggregate impact of German subsidies increased over time as the effects of induced innovation accumulated. In total over the period 2010-2015, Gerarden (2023) found that 88% of the adoption of solar panels 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 positive 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.

Bradt (2024) studies precisely this phenomenon in the California solar market. Bradt formulates a dynamic model of solar installer entry, exit, and competition in the product market that allows for appropriable and non-appropriable learning-by-doing. The results provide evidence of both forms of learning-by-doing. This qualitative finding is consistent with related work by Bollinger and Gillingham (2019). However, these two analyses come to somewhat different policy conclusions. 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 solar adoption and welfare in California, partly through its effects on learning. Interestingly, Bradt finds that an entry subsidy to encourage new solar installers to enter the market could be more efficient than the consumer subsidies offered by the California Solar Initiative.[10] That said, these conclusions may be sensitive to assumptions about the marginal cost of public funds, which are treated as costless transfers in Bradt (2024).

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.[11]

[10] Entry subsidies are not generically preferable, as they can encourage the entry of inefficient firms (Barwick et al., 2021).

[11] Myojo and Ohashi (2018) estimates small learning-by-doing effects and spillovers across firm in the Japanese solar panel

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.[12]

On the other hand, Covert and Sweeney (2024) study the entire 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.[13]

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 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 U.S. 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 U.S. 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 would increase profits for both domestic and foreign firms due to its overall market expansionary effect.

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.

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

[13] 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.

5.3 Barriers to trade

Spillovers from production Bollinger et al. (2024) analyze Chinese firms' response to U.S. 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 U.S. 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. U.S. 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 U.S., 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 (2023), though that paper is more narrow in its study period and market definition.[14]

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

[TBD pending incorporation of input we received at the "Expert Dialog on Subsidy Reform" conference.]

[14] Houde and Wang (2023) use data on the U.S. residential solar market from 2012 and 2018, whereas Bollinger et al. (2024) covers the entire U.S. solar market from 2010 to 2020.

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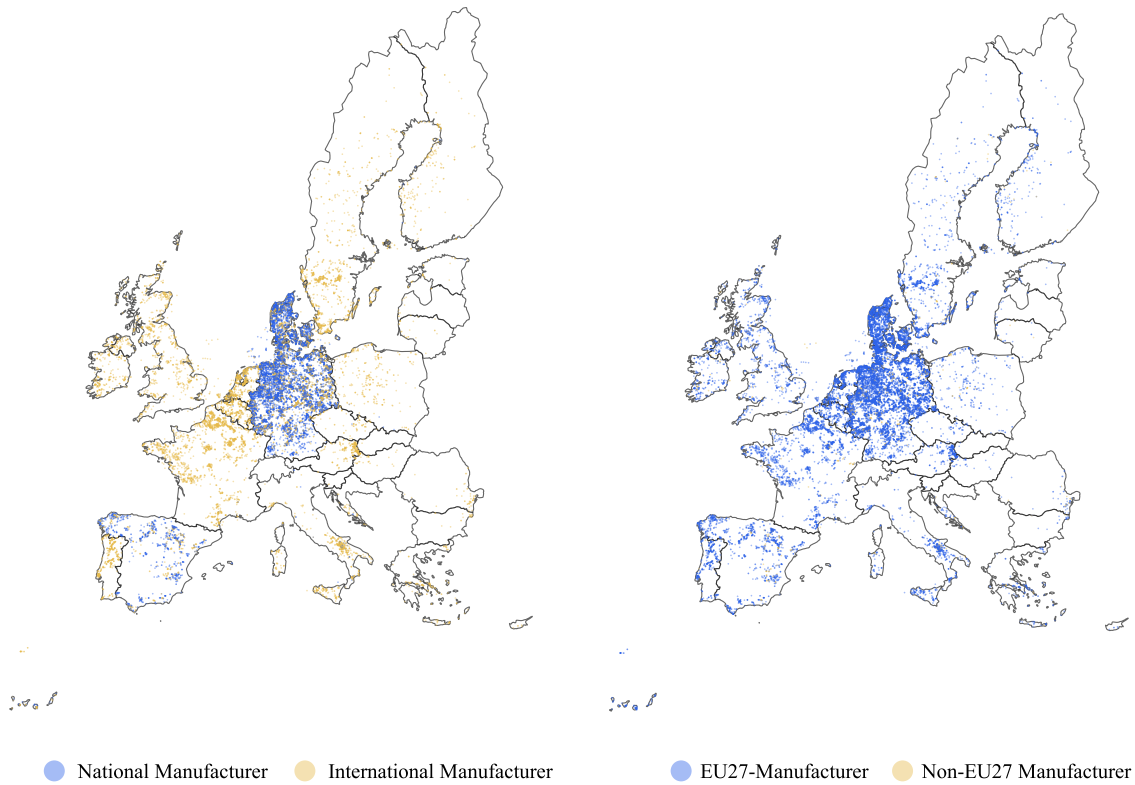
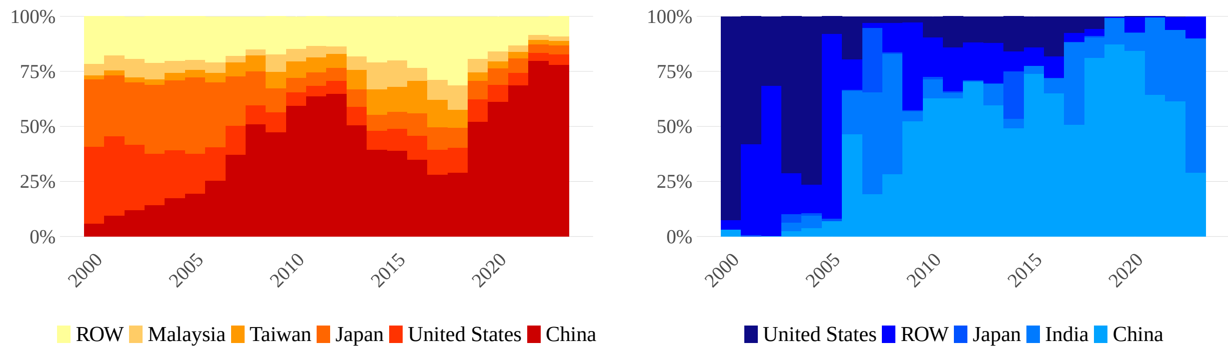
A Appendix: Additional Figures

Figure A.1: Location of installed wind turbines by manufacturing location, 2000-2022



Source: Own 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 manufaturer or not (left side) or whether they were produced by a EU27 manufacturer or not (right side).

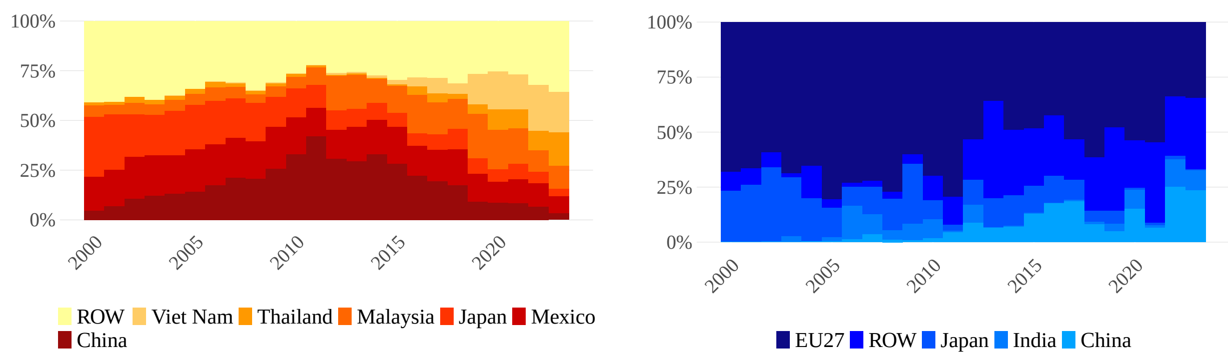
Figure A.2: EU Import of wind turbines and photovoltaic products by country share



(a) Photovoltaic products (b) Wind turbines

Source: Own visualization based on data from Eurostat. The graph illustrates the share of imports of photovoltaic manufacturing products (a) and wind turbines (b) into the EU from 2000 to 2023, showcasing the share of each partner country. There is a discernible trend of China's growing significance as a trading partner in both panels. Notably, a temporary decline in photovoltaic imports from China aligns with a rise in import shares from other Asian countries.

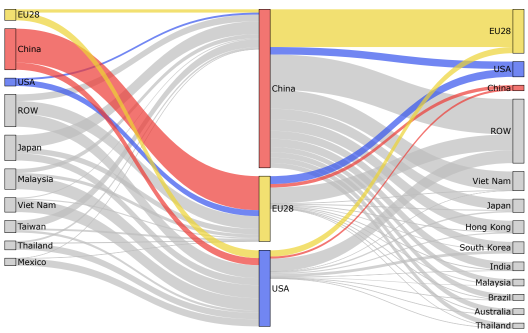
Figure A.3: US Import of photovoltaic products and wind turbines by country share



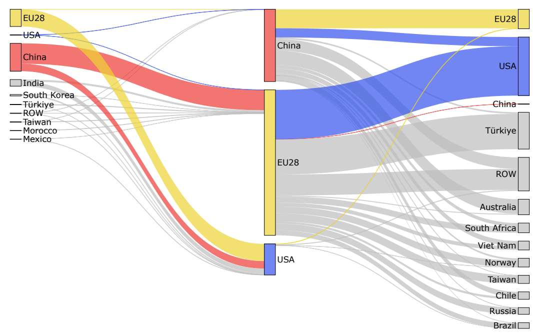
(a) Photovoltaic products (b) Wind turbines

Source: Own visualization based on data from UN Comtrade Database. The graph illustrates the share of imports of photovoltaic manufacturing products (a) and wind turbines (b) into the US from 2000 to 2023, showcasing the share of each partner country.

Figure A.4: Imports and Export of photovoltaic and wind power products of the EU28, US and China in 2020



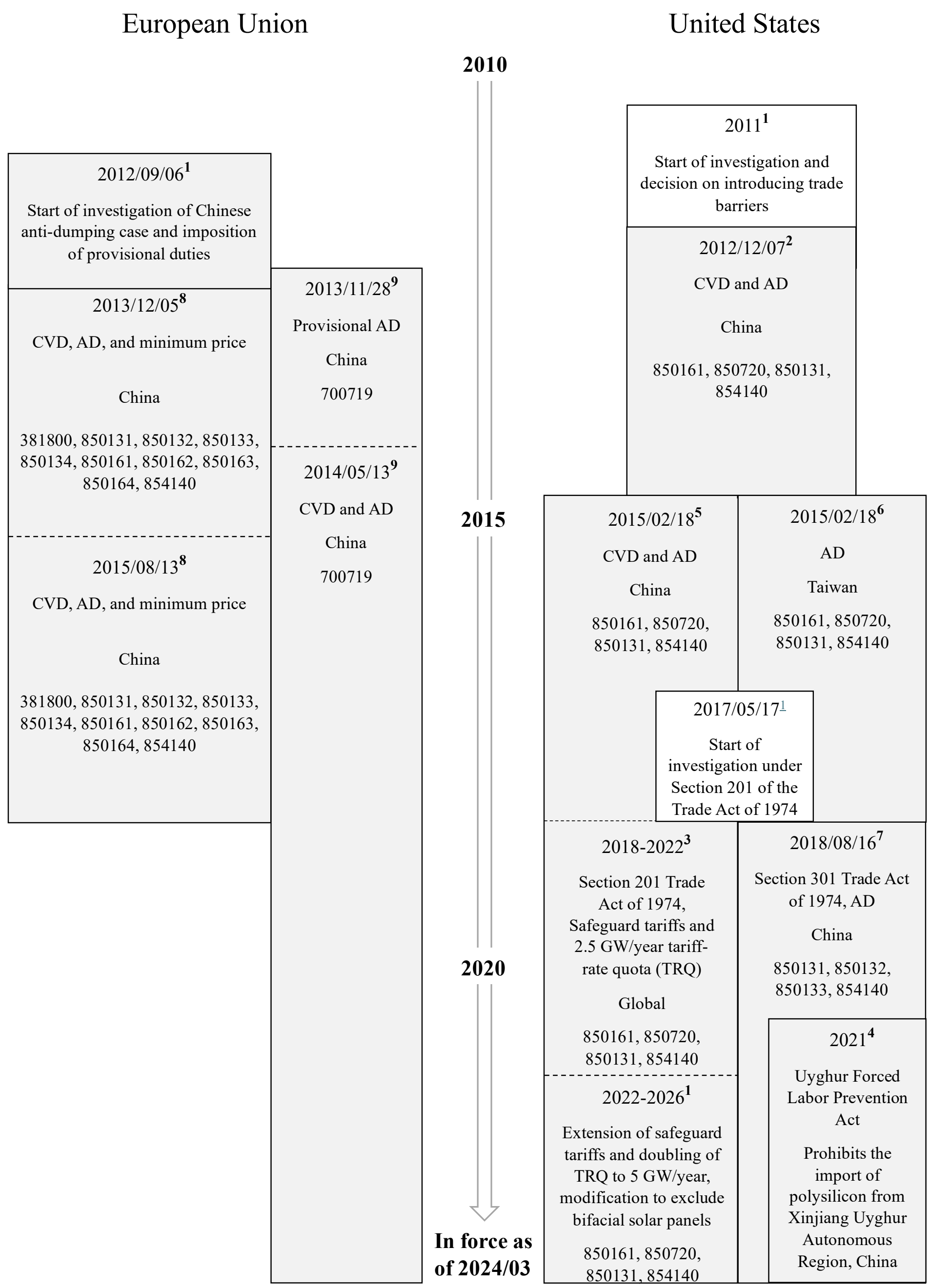
(a) Photovoltaic products, 2020



(b) Wind products, 2020

Source: Own visualization based on data from UN Comtrade Database. The graph illustrates the trade dynamics of the EU, United States, and China in photovoltaic products (panels (a) and (b)) and wind turbines (panels (c) and (d)) for the year 2020. Each panel is divided into two sections: the left side depicts the total imported value from various origin countries, while the right side represents the total value exported to partner countries, as reported by China, the US or the EU.

Figure A.5: Evolution of import tariffs imposed on photovoltaic manufacturing products in the European Union and the United States



Source: 1, 2, 3, 4, 5, 6, 7, 8, 9 . This graph illustrates the chronological evolution of import tariffs imposed on photovoltaic manufacturing products within the European Union and the United States since 2010. Trade policies introducing new barriers are represented by grey boxes, while white boxes denote the commencement of investigations. The organization of boxes adheres to the following schema: Commencement date or year of the trade barrier, Type and details of the implemented measure, Target region or country of the measure, HS Code(s) affected

Table A.1: Overview of relevant HS Codes for photovoltaic manufacturing products

HS Code 6 digits	Tariff Code	Description HS 6-digit	Type of tariff
381800	38180010	Chemical elements and compounds doped for use in electronics, in the form of discs, wafers, cylinders, rods or similar forms, or cut into discs, wafers or similar forms, whether or not polished or with a uniform epitaxial coating	EU2013
700719	70071980	Toughened "tempered" safety glass	EU2014
850131	US2018: 85013180; EU2013: 85013100	DC motors of an output $>$ 37,5 W but $<=$ 750 W and DC generators of an output $<=$ 750 W	EU2013, US2012, US2015, Section 201, Section 301
850132	EU2013: 85013200	DC motors and DC generators of an output $>$ 750 W but $<=$ 75 kW	EU2013, Section 301
850133	EU2013: 85013300	DC motors and DC generators of an output $>$ 75 kW but $<=$ 375 kW	EU2013, Section 301
850134	EU2013: 85013400	DC motors and DC generators of an output $>$ 375 kW	EU2013
850161	US2018: 85016100; EU2013: 85016120, 85016180	AC generators "alternators", of an output $<=$ 75 kVA	EU2013, US2012, US2015, Section 201
850162	85016200	AC generators "alternators", of an output $>$ 75 kVA but $<=$ 375 kVA	EU2013
850163	85016300	AC generators "alternators", of an output $>$ 375 kVA but $<=$ 750 kVA	EU2013
850164	85016400	AC generators "alternators", of an output $>$ 750 kVA	EU2013
850720	US2018: 85072080	Lead acid accumulators (excl. spent and starter batteries)	US2012, US2015, Section 201
854140	US2018: 85414060, EU2013: 85414090	Photosensitive semiconductor devices, incl. photovoltaic cells whether or not assembled in modules or made up into panels; light emitting diodes (excl. photovoltaic generators)	EU2013, US2012, US2015, Section 201, Section 301

Source: Descriptions were taken from WTO, HS Tracker. The table provides an overview of the relevant HS codes for photovoltaic products in the manufacturing industry. The 'Type of tariff' indicates the specific tariffs directed towards each manufacturing product. For instance, 'EU2013' signifies the tariffs introduced in 2013 within the European Union. An amendment of HS Codes in 2022 is incorporated in the graphs in this document; however, the new HS Codes are not explicitly listed here.

Table A.2: Overview of relevant HS Codes for wind manufacturing products

HS Code 6-digits	Tariff Code	Description HS 6-digit	Type of tariff
730820	EU: 73082000	Towers and lattice masts, of iron or steel	EU2021, US2020, US2021
730890	EU: 73089098	Structures and parts of structures, of iron or steel, n.e.s. (excl. bridges and bridge-sections, towers and lattice masts, doors and windows and their frames, thresholds for doors, props and similar equipment for scaffolding, shuttering, propping or pit-propping)	EU2021
850231	EU: 85023100	Generating sets, wind-powered (2002-2500); Generating sets, wind-powered (1996-2001)	EU2021, US2020, US2021

Source: Descriptions were taken from WTO, HS Tracker. The table provides an overview of the relevant HS codes for wind-energy products in the manufacturing industry. The 'Type of tariff' indicates the specific tariffs directed towards each manufacturing product. For instance, 'EU2013' signifies the tariffs introduced in 2013 within the European Union.

B Datasets

B.1 Solar

Investment/capacity

Dataset	Time Period	Unit	Countries	Relevant variables	Notes
Energy Research Database	2007-2023	project level	US	project awardees, project type, award type, funding program, activity status, time period, government costs	
IRENA Renewable Energy Statistics	2012-2022	Country	Global coverage	yearly installed and produced capacity of solar energy	
Global Solar Power Tracker	1984-2045	solar PV installation	175 countries (including Europe, US, China)	location, capacity, owner, operator, start and retirement year, status	includes planned installations in the far future
OBS-FV	2006-2023	solar PV installation	Portugal	location, involved entities, capacity, start year, type	definition of 'involved entities' is still unclear
USPV-DB	1986-2021	solar PV installation	US	location, capacity, start year, site type, axis type	

Costs

Dataset	Time Period	Unit	Countries	Relevant variables	Notes
IRENA Report 2022	2010-2022	Global	Global	global weighted average total installed costs, LCOE, average solar PV module prices	
IRENA Report 2022	2010-2022	Country	China, US, Germany, France, Spain, Italy, United Kingdom	utility-scale solar PV total installed cost, average cost of electricity	

Labor

Dataset	Time Period	Unit	Countries	Relevant variables	Notes
EurObserv'ER online database	2017-2021	Continent	EU28	total number of direct and indirect jobs	
IRENA Report	2012-2022	Global	Global	total number of jobs, technology type	

B.2 Wind

Investment/capacity

Dataset	Time Period	Unit	Countries	Relevant variables	Notes
IRENA Renewable Energy Statistics	2012-2022	Country	Global coverage	yearly installed and produced capacity of onshore and offshore wind power	
WindPower	1958-2023	wind farm	130 countries (including Europe, US, China)	location, manufacturer, manufacturer country, turbine model, hub height, capacity, developer, owner, operator, operator country, commissioning and decommissioning year	
USGS	1982-2023	wind turbine	US	location, manufacturer, manufacturer country, turbine model, hub height, capacity, commissioning year	capacity values are on wind farm level
OPSD	1978-2022	wind turbine	Denmark	location, manufacturer, manufacturer country, turbine model, hub height, rotor diameter, capacity, commissioning date	
OPSD	983-2020	wind turbine	Sweden	location, manufacturer, manufacturer country, capacity, commissioning date	

Costs

Dataset	Time Period	Unit	Countries	Relevant variables	Notes
IRENA Report 2022	2010-2022	Global	Global	global weighted average total installed costs, LCOE, average solar PV module prices	
IRENA Report 2022	2010-2022	Country	China, US, Germany, France, Spain, Italy, United Kingdom	utility-scale solar PV total installed cost, average cost of electricity	

Labor

Dataset	Time Period	Unit	Countries	Relevant variables	Notes
EurObserv'ER online database	2017-2021	Continent	EU28	total number of direct and indirect jobs	
IRENA Report	2012-2022	Global	Global	total number of jobs, technology type	

B.3 Others

Tariffs/Subsidies

Dataset	Time Period	Unit	Countries	Relevant variables	Notes
Supply					
Global Trade Alert	2008-2024	Country	Global	includes a broad range of trade and industrial policies with a brief text description, countries involved, codes for affected sectors and products, etc.	
World Bank TTBD	1980-2019	Country	34 countries (including Europe, US, China)	data on anti-dumping and countervailing measures: start date of investigation, date of imposition of measure, product, min and max value of measure	
US tariff data USITC	1997-2023	Country	US	product, ad valorem portion of the MFN duty rate, tariffs for special preference programs	
Demand					
Feed-in tariffs (OECD)	2000-2019	Country	69 countries (including Europe, US, China)	mean feed-in tariff, length of power purchasing agreement	DSIRE includes state-level data for US
DSIRE database (USA)	2000-2024	Subnational	US (state and local)		also covers some local policies

Trade

Dataset	Time Period	Unit	Countries	Relevant variables	Notes
Eurostat	1988-2023	Continent, Country	EU27 countries	value and quantity of photovoltaic and wind products imported into EU27 and exported to all countries in the world	
UN Comtrade Database	2000 - 2023	Country	EU27, US, China	value and quantity of photovoltaic and wind products imported and exported	