The Role of Government Policies in Renewable Energy*

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Contents

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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 capacity in these technologies has been enabled by a first phase of targeted subsidies to wind and solar, which we describe in detail below, with a second phase in which these technologies are already competitive for new investments. This large expansion in renewable power has also led to a nascent industry in wind manufacturing and solar panels becoming larger and more mature.

How large have subsidies been in the industry? To what extent can we associate renewable success with subsidies vs. other trends in the market? And what have been the consequences of trade tensions and tariff wars in this context? 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 subsidies can be controversial in many sectors, it is hard to argue that the development of the renewable power industry has been a failure. As we will review, the cost decreases have surprised many experts, jobs have been created in all jurisdictions involved, even if the job creation has been uneven, electricity costs have gone down for many countries even after accounting for subsidy costs, and wind and solar are now leading new investments in the power sector, with positive spillovers for the costs of climate policies and decarbonization goals.

While wind and solar are both success stories, the trajectories and experiences have been significantly different when it comes to 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. While technological progress in the solar industry has taken the form of improved materials and conversion factors, in the wind sector, these have materialized in the form of bigger wind turbines. These turbines, of massive scale, are produced by a handful of concentrated firms and are very 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 highest cost advantage, wind manufacturing exhibits substantial concentration and home bias.

The differences in the two technologies have also impacted their popularity and the public support towards subsidy policies. [Summarize differences in jobs, domestic or in-state requirements (e.g., RPS)]

In this paper, we review the evidence regarding these trends and impacts given the current empirical evidence. 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 subsidies and tariffs, while we discuss the overall assessment of 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.

Table 1: Comparison between Wind and Solar

	Wind	Solar
Market structure	Concentrated, economies of scale	Fragmented, with some leading brands
Technology	Significant LBD in size	Significant LBD in cell efficiency and installation
Labor market	Upfront, mostly non-local	Manufacturing and local (installation/maintenance)
Trade costs	Large, produced near-site even for foreign firms	Small, global supply chain
Subsidy approach	Large scale	Large scale and residential
Trade instruments	Limited interventions	Substantial interventions

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

2 Renewable sector overview

We provide a description of the overall trends in the renewable sector without getting yet into the causal factors behind the observed patterns. The most relevant data sources are summarized in Appendix B.

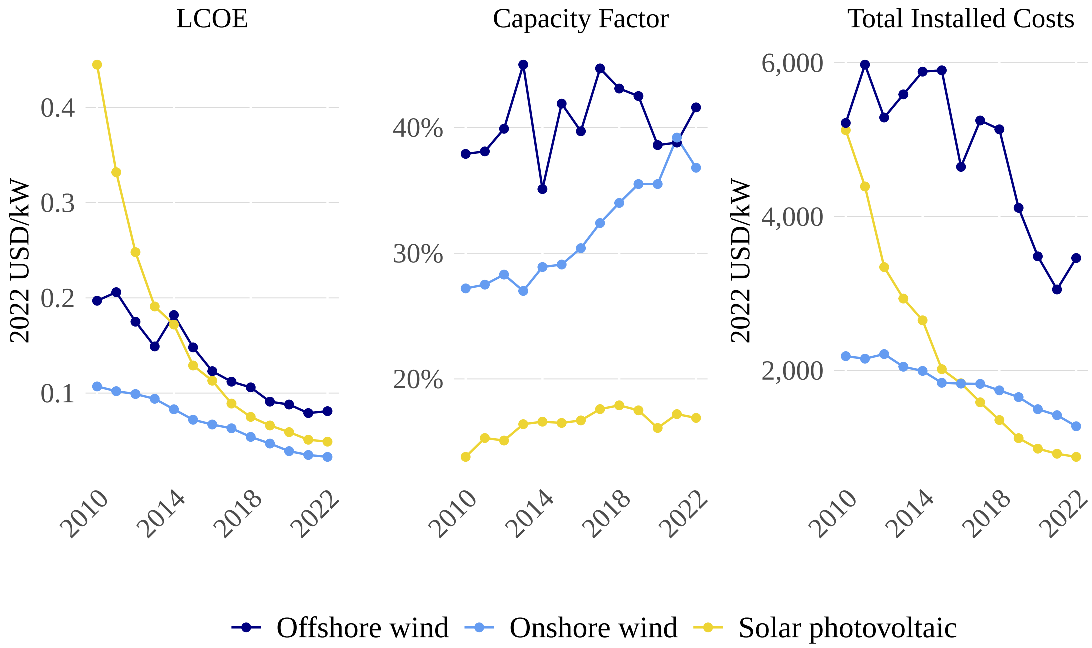
2.1 Trends in costs

The deployment of solar photovoltaic 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. Following intensified global competition for the leading role in renewable energy technology innovation and manufacturing, costs for the installation and operation of wind and solar energy technologies significantly decreased world wide. This section provides an overview of the development of costs for wind and solar technologies and explains the different cost trends across three technologies: solar photovoltaic, onshore and offshore wind.

The total installed costs of wind turbines encompasses the full scope of costs associated with the construction and installation of wind turbines. Overall, these costs decreased significantly for both onshore and offshore wind, as illustrated in the right panel of Figure 1.

For onshore wind, total installation costs decreased approximately by 42 % from 2010 to 2022. These costs were mainly influenced by the prices of wind turbines and Balance of Plant (BoP) cost reductions IRENA [2023b]. As Figure 2 shows, wind turbine prices hit a low between 2000 and 2002, then rose sharply due to higher commodity prices, supply chain issues, and advancements in turbine design IRENA [2023b]. Increased government support for wind energy led to high demand and coincided with times of tight supply, allowing manufacturers to charge higher prices. However, as the supply chain expanded and became more competitive, these constraints eased, and turbine prices peaked between 2007 and 2010 IRENA [2023b], then continuously declined. In 2022, prices ranged from USD 840 per kW to USD 1,175 per kW, except

Figure 1: Global weighted averages of LCOE, Capacity Factor and Total installed costs



Source: Data and visualisation were sourced from the IRENA Report on Renewable Power Generation Costs Chart Data, p.42 . This graph presents a summary of the global weighted levelized cost of electricity (LCOE), capacity factors and average total installed costs for solar PV, onshore wind power, and offshore wind power from 2010 to 2022.

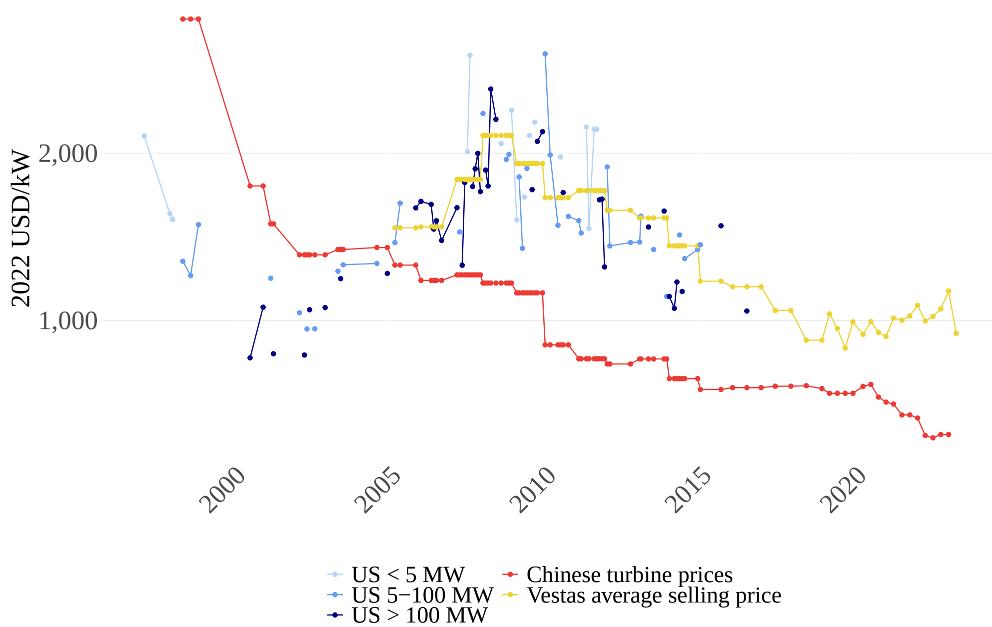
in China, where they dropped to around USD 310 per kW. Despite supply and demand imbalances, such as those caused by COVID-19, turbine prices have generally declined over the past decade, even as turbines have become larger and more efficient.

Albeit a decreasing trend in total installations costs for offshore wind technologies, total installed costs remained higher compared to onshore wind. Higher cost are caused by the inherent challenges of installing and operating wind turbines in deep waters. Yearly fluctuations in offshore wind costs can be attributed to supply chain bottlenecks and local characteristics of wind projects, which vary based on differential deployment patterns across markets and years. Mayor drivers for cost reductions for wind technologies were lower commodity prices and stable national politics, alongside financial support schemes and clustered projects in Europe [IRENA, 2023b]. The global average installed costs for solar photovoltaic was additionally fueled by trade tensions among the US, Europe and China, spurred by extensive Chinese subsidies in national solar photovoltaic manufacturing starting in the 2010s. The resulting trade war contributed to a steep 83 % reduction in total installed costs for solar photovoltaic between 2010 and 2022.

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. This relationship is illustrated in Figure 3.[1] Total average installed costs were and are particu-

[1]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.

Figure 2: Trends in wind turbine prices



Source:

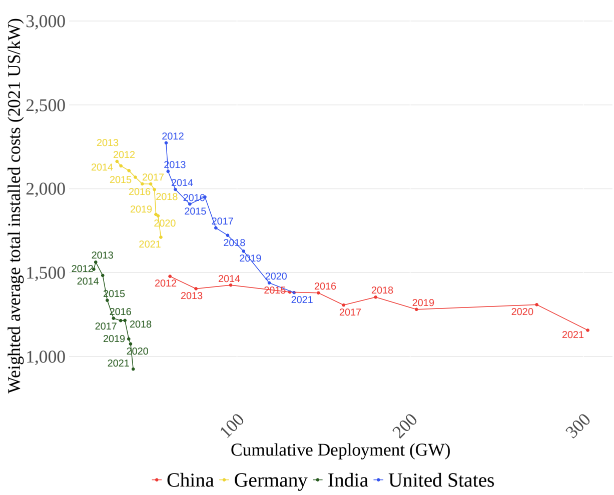
Source: Data and visualisation were sourced from the IRENA Report on Renewable Power Generation Costs Chart Data, p.72 . The graph illustrates the evolution of global wind turbine prices from 1997 to 2022. While most markets experienced a peak in turbine prices between 2007 and 2010, prices declined considerably thereafter. The Chinese wind turbine market stands out with continuous price declines.

larly low in India and China. China's experience curve is relatively flat, reflecting already low total installed costs from the earliest available data. Among European countries, Spain and Sweden stand out with the lowest total installed costs, as seen in Figure 3b, comparable to those in China, but India outperforms both. Despite relatively large deployments of onshore wind technologies in Germany, its total installed costs remain higher than those in other European countries and major global players like China, India, and the United States. For solar photovoltaic, Germany showed relatively high deployment rates, in comparison to India, China, and the United States considering its population size, and managed to have lower total installed costs than any other country in the years before 2015. However, after 2015, India and China caught up and significantly reduced their total installed costs. For both onshore and solar photovoltaic, the United States has considerably higher total installed costs than China and India.

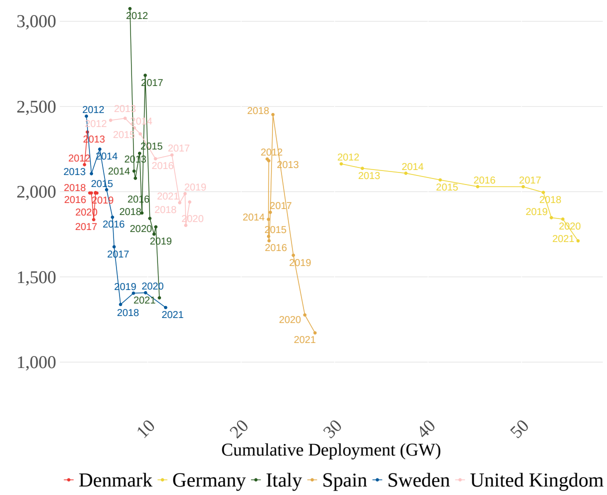
The remaining heterogeneity in total installed costs across regions for solar photovoltaic is influenced by variations in certain cost components, as illustrated in Figure 4. While this graph specifically compares the United States, China, and selected European countries, it's worth noting that other countries like Japan and Russia exhibit much higher total installed costs, whereas countries like India, Saudi Arabia, and Turkey lead with the lowest total installed costs as of 2022 [IRENA, 2023b].

A significant portion of the total costs compromises hardware costs such as costs for solar modules

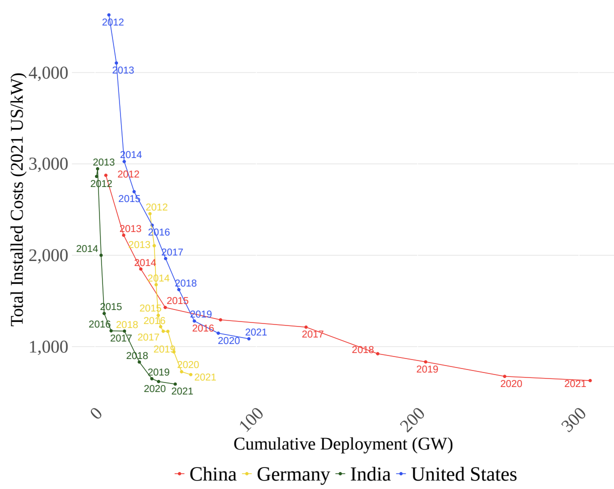
Figure 3: Industry-level experience curves for photovoltaic and wind power



(a) Onshore wind



(b) Onshore wind - Europe

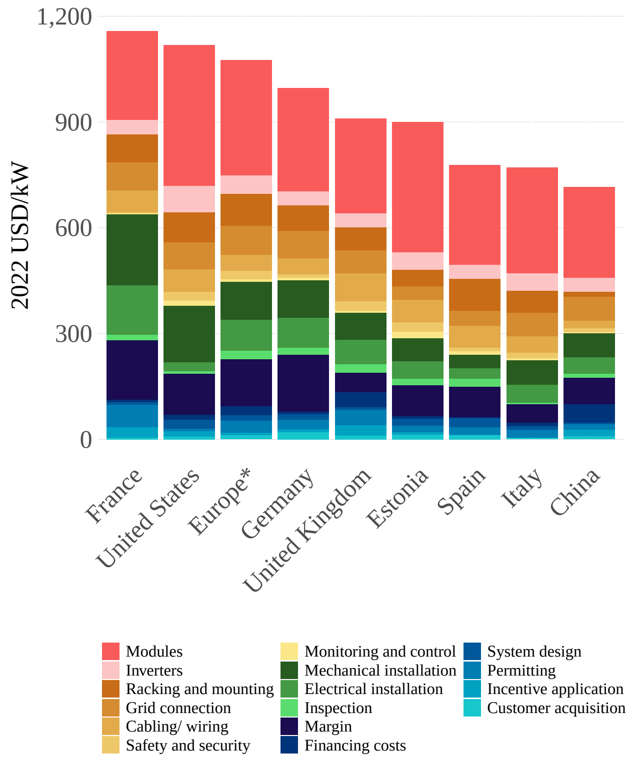


(c) Photovoltaic

Source: Own visualisation based on data from IRENA Chart Data, p.57 and IRENA Energy Statistics. The graph showcases the negative correlation between the deployment of renewable power and the weighted average of total installed cost across China, the United States, and selected European countries for onshore wind (a) and photovoltaic (c) technologies for 2012-2021. Panel (b) compares the experience curves of leading European countries in onshore wind deployment and development.

and inverters, as well as costs related to the installation such as equipment for racking, mounting, and grid connectivity. These costs are highest in the United States and lowest in China. Additionally, installation costs themselves vary across European countries, with France having higher installation costs and Spain demonstrating notably lower costs, outperforming both China and the United States. Regarding soft costs, depicted in shades of blue, financing costs constitute the largest portion for nearly all regions, while differences in other soft costs explain less variation in total installed costs. China's overall advantage in total

Figure 4: Breakdown of utility-scale solar PV total installed costs (2022)



Source: Data and visualisation were sourced from the IRENA Report on Renewable Power Generation Costs Chart Data, p.101 . The graph illustrates regional cost variations in solar PV technology, highlighting persistent differences across modules (panels), inverters, and Balance of System (BoS) components in 2022. Europe* shows the average of Bulgaria, Denmark, Croatia, Cyprus, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Romania, Slovenia, Spain

installed costs compared to Europe and the United States can primarily be attributed to lower hardware and installation costs.

The capacity factor, or the amount of electricity produced by installed power, increased across all technologies. For onshore wind, the capacity factor is influenced by wind conditions around a wind farm and its technology features, such as hub height and blade length. This increasing deployment of wind farms with higher heights and longer blades has been a key factor in the recent rise in capacity factor. However, in 2022, the capacity factor of onshore wind was lower than in 2021 due to the exceptional performance of 2021, driven by an increases deployment in regions with excellent wind condition, especially in the United States and Latin America. This level of performance was not sustained in 2022, partly due to a significant decline in deployment in China [IRENA, 2023b].

The global average capacity factor of offshore wind also increased, despite larger volatility caused by varying quality of locations across regions. The decline in capacity factor between 2017 and 2021 can be partly attributed to the increased share of offshore wind in China, where locations were less ideal (e.g. closer to the shore). The jump in the capacity factor in 2022 in turn can be explained by an increase in turbine size in China, driven by higher deployment and the push for more efficient wind farms following the end of the

Feed-in Tariff (FiT) program in 2022 [IRENA, 2023b].

The capacity factor for solar has also increased overall. The main drivers were improved performance and efficiency of solar systems, the use of solar trackers, and taking advantage of deployment in locations with higher radiation levels [IRENA, 2023b].

The levelized cost of electricity (LCOE), or the average net present cost per unit of electricity generated over the lifetime of a generator, are primarily influenced by the cost factors and the capacity factor described above, as well as operational and maintenance costs, and the cost of capital. For onshore wind, the turbine price is the largest part of the LCOE, so that there has been a continuous decline in LCOE as turbine prices have declined. As turbine prices stabilize, operational and maintenance cost are becoming increasingly important in further reducing LCOE [IRENA, 2023b]. For solar photovoltaic, the LCOE saw a significant 89% reduction in LCOE, falling from \$455/MW to \$49/MW, although this decline has slowed in recent years. This sharp decrease is mainly due to technological advancements and reductions in solar panel prices.

2.2 Trends in adoption

This section presents an overview of the trends in solar, onshore, and offshore wind energy adoption across key regions, namely the EU, China, and the US, while highlighting the underlying drivers and challenges faced by these regions.

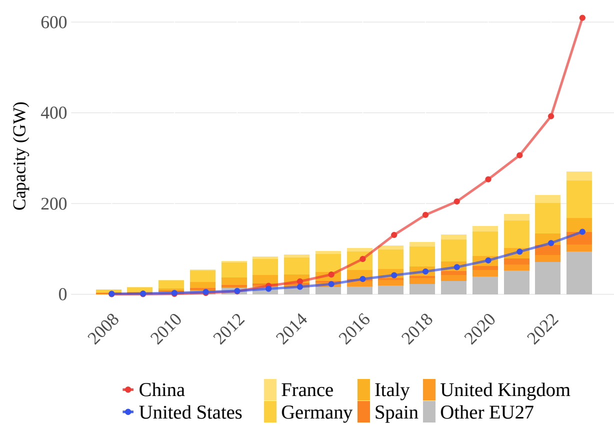
2.2.1 Solar PV

The deployment of solar energy in the EU started to gain momentum in the early 2000s. Technological advancement, such as the use of higher-efficiency solar cells that increased electricity production, and the adoption of new materials and technologies like monocrystalline and polycrystalline cells instead of traditional silicon-based cells, have made solar PV a more economically attractive investment. At the same time, economies of scale significantly lowered total installed costs, making it cost-competitive with fossil fuels and nuclear energy. National policies provided and continue to provide financial support for solar PV and EU policy initiatives, such as RePowerEU, have set ambitious targets, including 750 GW of solar capacity by 2030, further driving continuous solar power growth. These drivers led to a steady increase in solar PV deployment over the years, as seen in Figure 5.

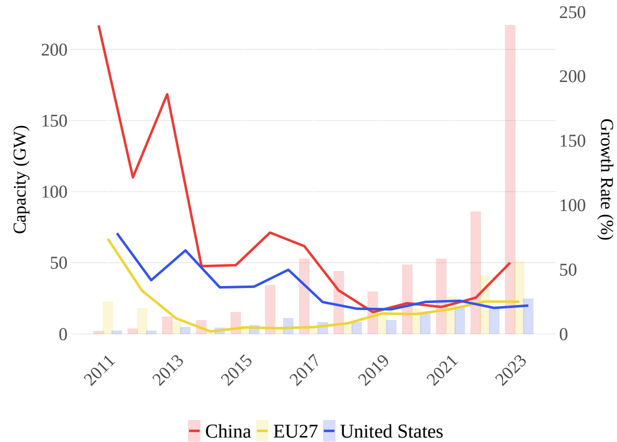
For most of the years, Germany remained the largest solar market in the EU, in terms of yearly added solar power and cumulative capacity. Support schemes, such as the FiT for medium and large-scale commercial solar systems or auctions for systems up yo 10 MW, accelerated Germany's solar deployment, despite a struggling solar manufacturing sector and supply chain bottlenecks caused by the COVID-19 pandemic. In recent years, solar energy has boomed in Germany, driven by already high electricity prices in 2021, which reached record highs after Russia's invasion in Ukraine. Measures taken to overcome dependence on Russia's fossil fuels thus contributed to solar becoming a highly attractive investment [IEA, 2023].

Even though Germany can be considered the solar power leader in the EU, the Netherlands leads overall with the highest solar capacity per capita, due to high growth in the residential sector driven by net-metering and stable auction schemes. However, in recent years, the Netherlands has faced political uncertainties due to

Figure 5: Deployment and growth rates of solar photovoltaic in China, the EU and the US



(a) Cumulative capacity



(b) Growth rates and annually added capacity

Source: Own visualisation based on data from IRENA Energy Statistics. The graph shows the cumulative capacity in GW and the growth rates of capacity from 2008 until 2023 for solar photovoltaic.

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].

Spain is the second largest solar market in the EU, showing especially large solar additions in recent years. The end of the sun tax in 2018, high electricity prices, and governmental support have significantly contributed to the deployment of solar in Spain. Given its great solar potential and attractive investment opportunities through, e.g. Power Purchasing Agreements (PPAs), the solar sector is benefiting from stable regulations and attracting national and international investments Schmela et al. [2023].

Barriers to the EU's solar deployment in recent years included rising central bank interest rates and inflation, which in turn increased financing and equipment costs in the EU, hampering solar expansion and leading to more project cancellations and undersubscribed auctions [IEA, 2023]. Additionally, a significant decrease in investment in solar energy at the start of 2011 led to a drop in solar deployment rates (see Figure 5b). In the case of Germany, the solar industry was strongly impacted by the gradual phase-out of the EEG feed-in tariff, which also affected confidence in the stability of policy and investment conditions Shivakumar et al. [2019]. Overall, the EU managed to significantly increase its solar capacity, with record numbers of added solar power in recent years.

As seen in Figure 5, both the EU and the US have experienced similar growth in solar deployment, with the EU leading in cumulative installations. These growth trends are reflected in the decreasing total installed costs of solar products, showing lower total installed costs for most European countries throughout. Thus, to boost national solar deployment, the US implemented financial schemes such as the American Recovery and Reinvestment Act (2021) or the recent Inflation Reduction Act (2022) to offer incentives like investment tax credits (ITC) and production tax credits (PTC) for solar energy. The aim is to tackle heightened international competition, especially from China, and volatile solar prices caused by supply chain disruptions, inflation during the Covid-19 pandemic, and import tariffs, while also strengthening US manufacturing and competitiveness Davis et al. [2024]. In 2023, the US thus installed a record of 32 GW, exceeding an installation of solar of more than 30 GW for the first time. In past years, the US overall saw an increase in solar deployment, due to continuous financial support through net metering, FiT, and RES, and decling solar cost. Remaining challenges, specifically in recent years, are high interest rates, interconnection delays, permitting delays, supply chain issues such as lower import volumes of solar modules, and policy uncertainty of federal and state policies Davis et al. [2024].

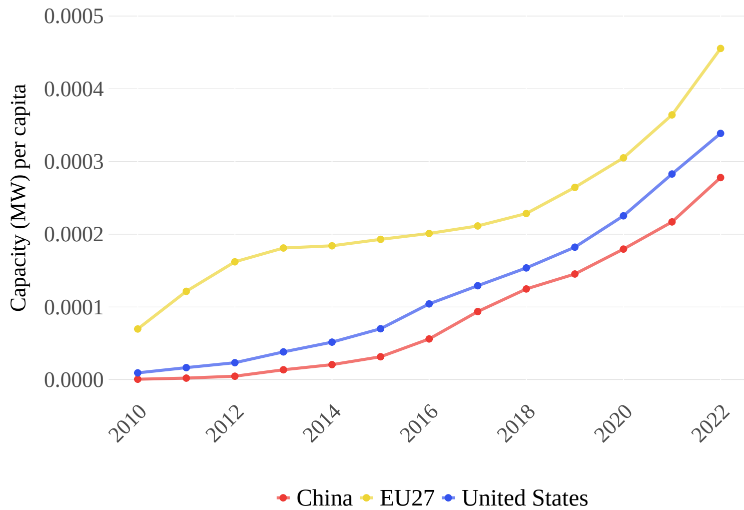
In comparison, China significantly accelerated its solar PV deployment since 2012, reaching a record total installed capacity of over 600 GW in 2023. As shown in Figure 5b, China had particularly high growth rates in the early 2010s, eventually aligning with the growth trends of the US and the EU around 2019. Although growth rates were comparable across China, the EU, and the US between 2019 and 2022, 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 in 2022 and 2023. China has benefited from a high domestic demand and strong, vertically integrated manufacturing. With most of the solar PV supply chain located within the country, China has maintained a relatively stable supply despite global fluctuations in raw material prices and rising interest rates. 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]. This program has already led to 66 GW of planned solar PV projects by the end of 2022 SolarZoom [2022].

While the figures highlight significant differences in solar PV deployment, it is crucial to point out the large difference in population between those regions. Considering China's population of around 1.4 billion (2023), almost 4 times as much as the US, Figure 6 shows the capacity for solar PV per capita. In contrast to the previous figures, the EU and the US lead in cumulative solar PV per capita. However, it is anticipated that China's per capita capacity for solar PV will see significant growth in 2023, driven by low population growth and high additions of solar PV capacity.

2.2.2 Onshore and offshore wind

As set out by the RePowerEU initiative aims, the new EU target for wind energy requires a total installed capacity of over 500 GW by 2030, which Costanzo et al. [2023] estimates to necessitate 33 GW of wind power added capacity per year between 2023 and 2030. Despite record additions of around 15 GW in both 2022 and 2023, totaling to 204 GW, the EU is still far from its goal. The largest onshore capacities in the EU are located in Germany, Spain, France, Sweden, Italy and Poland. Germany has been a pioneer in onshore wind power deployment, primarily driven by strong policy support and investments. Throughout the 2000s and early 2010s, Germany's FiTs spurred rapid growth, making it the largest onshore wind market in Europe, with nearly 61 GW of capacity by the end of 2023. The peak expansion year was 2017, with almost 5 GW added (see A.1a), 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]. While uncertainty in the industry and macroeconomic challenges

Figure 6: Solar PV capacity (MW) per capita



Source: Own visualisation based on data from IRENA Energy Statistics. The graph illustrates the capacity per capita (MW per capita) for onshore wind (a) and solar PV (b) from 2010-2022.

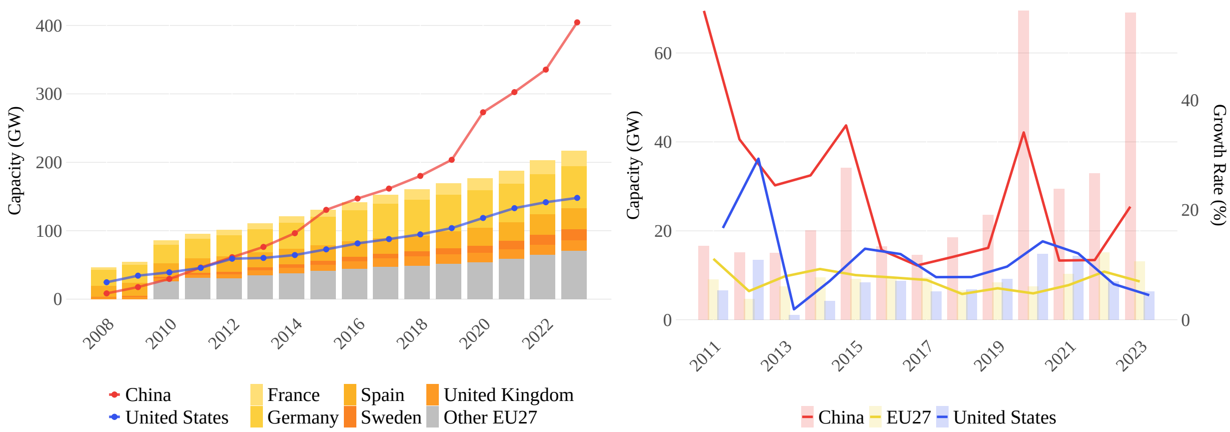
such as inflation, high interest rates, and limited raw materials arose during the COVID-19 pandemic and following Russia's invasion of Ukraine IEA [2023], regulatory changes in licensing and land use, along with new political ambitions, accelerated expansion and led to oversubscribed auctions in 2023. Remaining barriers include limited construction space, investor uncertainty, and slow licensing procedures Wehrmann [2024].

The second largest onshore wind market in the EU is Spain, with more than 30 GW of installed capacity as of 2023. Since 2019, Spain has continuously added more than 1 GW yearly until 2022, with a record of 2.2 GW of additional onshore capacity in 2022, an addition which was only outperformed in years before 2009. Notably, considering annual growth rates as shown in Figure A.1, Finland has shown significant growth, adding a record 2.4 GW in 2022, representing a 76% increase compared to the previous year, driven by the economic appeal of wind power and domestic demand [Hitachi-Energy, 2023].

Despite its growth, the EU has not fully met its annual deployment targets outlined in the RePower Initiative. However, advancements in technology 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. Yet, challenges emerged during the Covid-19 pandemic, including inflation, rising transportation costs, and supply chain disruptions, which impeded deployment and posed financial hurdles for developers and investors. Barriers to faster onshore wind deployment include local opposition, lengthy permitting processes, grid integration challenges, and site selection complexities.

Compared to the EU, the US showed higher growth rates almost continuously throughout the last decade, as seen in Figure 7b, and globally ranks on place 3 in terms of total installed capacity, following China and the EU. The sector's expansion is fueled by a combination of political goals, economic incentives through

Figure 7: Deployment and growth rates of onshore wind in China, the EU and the US



(a) Cumulative capacity

(b) Growth rates and annually added capacity

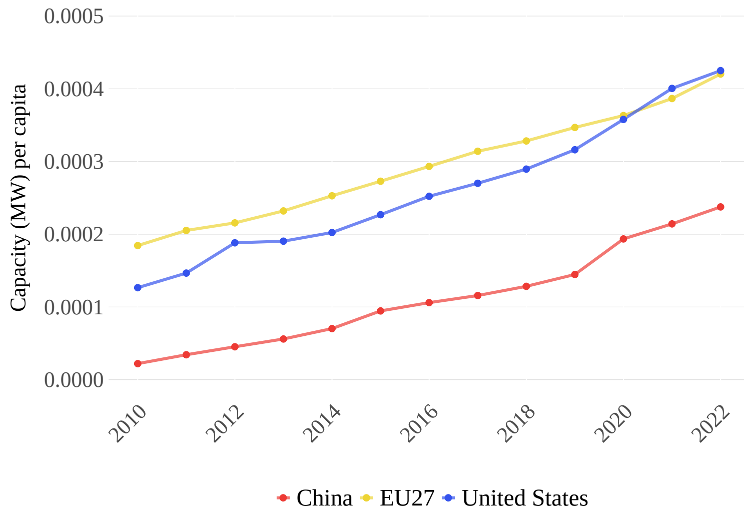
Source: Own visualisation based on data from IRENA Energy Statistics. The graph shows the cumulative capacity in GW and the growth rates of capacity from 2008 until 2023 for onshore wind.

financing schemes and cost reductions and technological advancements such as larger turbines. Federal policies like the Inflation Reduction Act (IRA), which extends the PTC and offers bonus credits, play a crucial role in shaping the market. While wind energy historically benefited from federal incentives like the production tax credit (PTC) and state-level policies, 2022 saw slower deployment due to challenges such as supply chain disruptions and higher interest rates and challenges like transmission constraints and local opposition Costanzo et al. [2023], BerkeleyLab [2024]. Despite these hurdles, forecasts indicate continued expansion, supported by federal incentives and increasing demand for clean energy Costanzo et al. [2023].

In comparison, China has witnessed extraordinary growth in onshore wind capacity since 2012. Within ten years, China has installed over 200 GW of onshore wind capacity, more than double the capacity of the EU27. In 2023 alone, China commissioned around 69 GW of onshore wind power, comparable to the combined capacity installed in the rest of the world in 2022 and 2023. This expansion has been largely propelled by immense investment initiatives through policies such as feed-in tariffs, subsidies, and renewable energy capacity targets outlined in successive Five-Year Plans. A pivotal aspect of China's renewable energy strategy is the establishment of clean energy bases, introduced in the 14th Five-Year Plan. These bases integrate expansive wind (and solar) parks with ultra-high-voltage transmission lines, facilitating the transportation of electricity to demand centers and supporting coal power plants IEA [2023]. By harnessing vast areas of desertified land in China's western regions, these bases mitigate land acquisition costs and enhance the overall economic feasibility of renewable energy ventures. However, China's renewable energy transition has encountered challenges. Despite endeavors to promote renewable energy adoption, China concurrently continued to invest in new coal-fired power plants, adding 106 GW of new capacity in 2022 IEA [2023].

As seen in Figure 8a, in 2020, the US managed to narrow the gap in per capita onshore wind installations compared to the EU. Since 2010, both the EU and the US have maintained substantially higher per capita onshore installation rates than China, nearly doubling those of China by 2022. This gap has consistently

Figure 8: Capacity (MW) per capita of onshore wind



(a) Onshore Wind

Source: Own visualisation based on data from IRENA Energy Statistics. The graph illustrates the capacity per capita (MW per capita) for onshore wind (a) and solar PV (b) from 2010-2022.

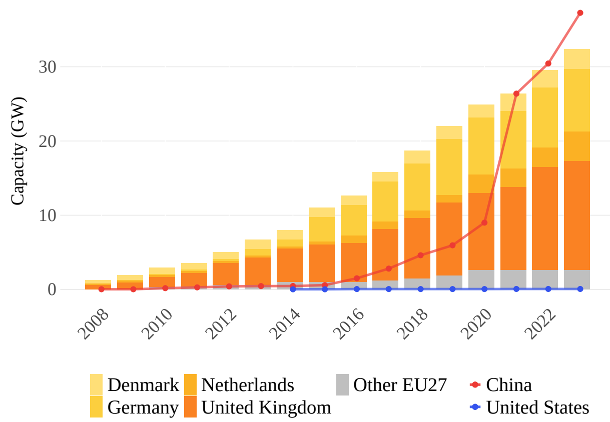
persisted between China on one side and the US and the EU on the other, although it was partially reduced by a substantial increase in onshore wind deployment in China in 2020.

In terms of offshore wind, Germany leads with the highest cumulative capacity in the EU, as seen in Figure 9a. However, neighboring countries like the Netherlands and Denmark, place 2 and 3 in the EU, have demonstrated greater efficiency in building offshore wind infrastructure [Thurau, 2024]. This difference can be partly attributed to Germany's insufficient funding for offshore wind and Denmark's extensive expertise in offshore wind projects, supported by continuous policy measures and innovative projects to advance technology. Additionally, the UK has historically been the global leader in offshore wind capacity, maintaining its leading position until 2020 when it was surpassed by China. Up until today, the UK is also home to the world's largest offshore wind farm, "Dogger Bank", boasting a capacity of 3.6 GW Equinor [2023].

The EU offshore wind industry recently saw a boost through increased cooperation among Member States with the Five Sea Basin non-binding agreement (2023). This agreement aims to develop and publish strategic integrated offshore network development plans, aligning with the EU's Offshore Renewable Energy Strategy to achieve at least 300 GW of offshore wind by 2050. Barriers to wind energy deployment in the EU remain. Permit application processes are still slow and complex, although there have been recent improvements. In some Member States, these processes are further delayed by local opposition and grid connection issues. Additionally, inflation and higher commodity prices have increased investment uncertainty, compounded by supply chain bottlenecks and raw material supply challenges, due to a large dependence of raw material and components imports from China.

Historically, the US had only deployed small amounts of offshore wind. As of 2023, the US houses three offshore projects, with the most recent and largest being the South Fork wind farm with a total capacity of

Figure 9: Deployment of offshore wind



(a) Offshore Wind

Source: Own visualisation based on data from IRENA Energy Statistics. The graph illustrates the total offshore capacity in GW by region from 2008 - 2023.

130 MW, completed in March 2024 [Durakovic, 2024]. Following an announcement by the Biden administration, plans are underway to add 30 GW of offshore wind capacity by 2030. So far, these plans have not shown any impact on the installed capacity, also due to recent setbacks in offshore wind projects. New York recently canceled 4 GW of offshore wind due to technical complexities after General Electric announced it would not build an 18 MW turbine [Durakovic, 2024].

China has seen large additions of offshore wind capacity in recent years, with a total addition of more than 17 GW in 2021, making it the country with the largest amount of offshore wind capacity. Concurrently, while China phased out feed-in tariffs (FiT) for solar and onshore wind in 2021, it continues to support offshore wind through FiT mechanisms.

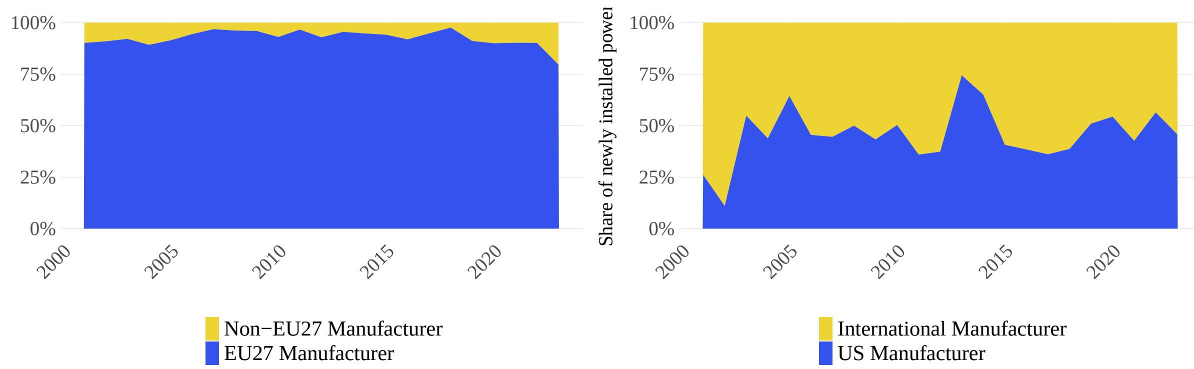
2.3 Market structure and trade patterns

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.

[TBA: Market shares by company, which now does not come across in any graph but will help highlight differences in economies of scale]

Figure 10 shows the country of origin for the manufacturers of wind turbines in Europe and the US. As Figure 10a 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.3, 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 13c and Figure 13c).

Figure 10: Comparison of country of origin for wind turbines in the EU and United States



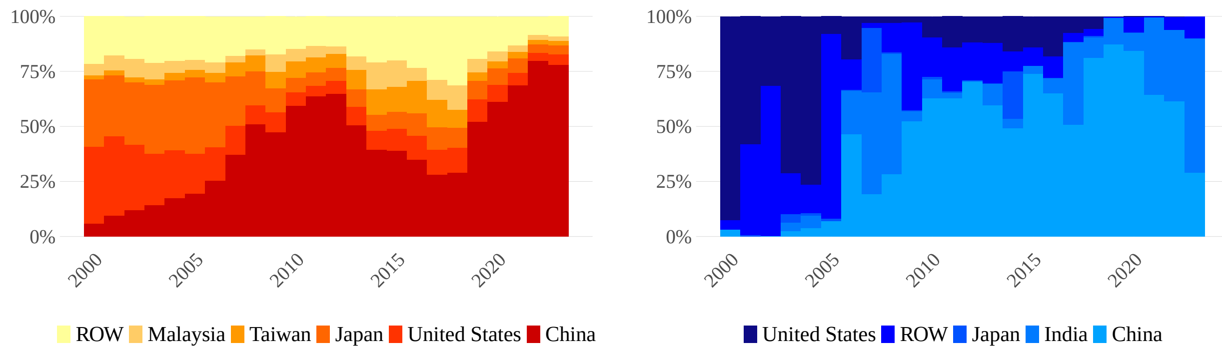
(a) European Union (b) United States

Source: Own visualisation 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.

The successful development of an European wind manufacturing industry is apparent when we compare the same patterns in the US. As seen in Figure 10b, 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 (Figure 12b).

[TBC]

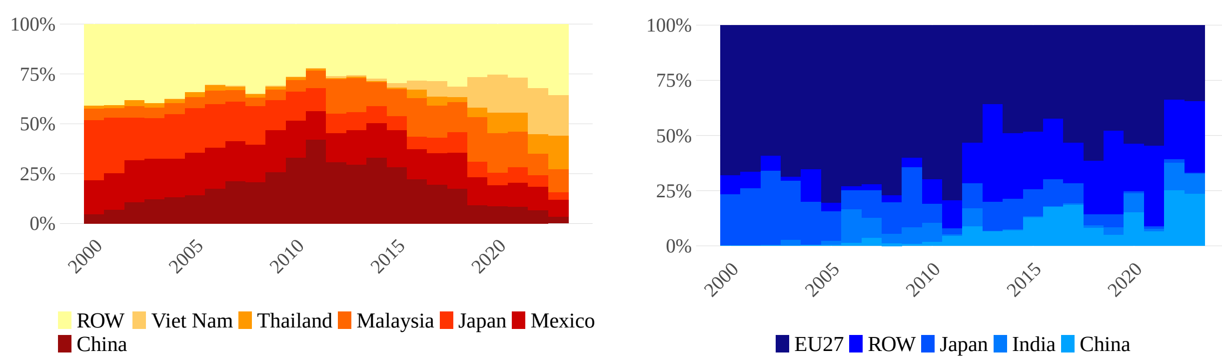
Figure 11: EU Import of wind turbines and photovoltaic products by country share



(a) Photovoltaic products (b) Wind turbines

Source: Own visualisation 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.

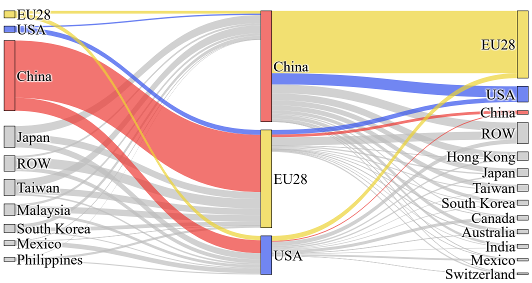
Figure 12: US Import of photovoltaic products and wind turbines by country share



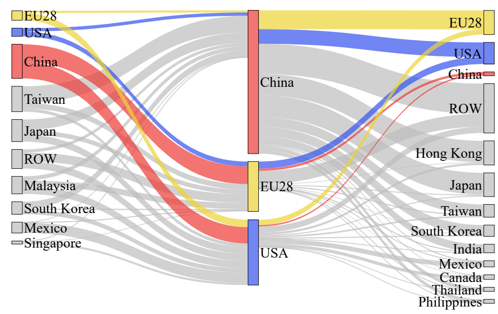
(a) Photovoltaic products (b) Wind turbines

Source: Own visualisation 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.

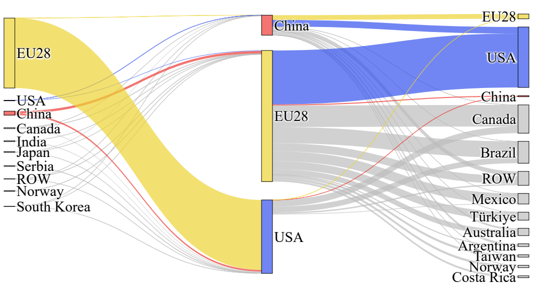
Figure 13: Imports and Export of photovoltaic and wind power products of the EU28, US and China



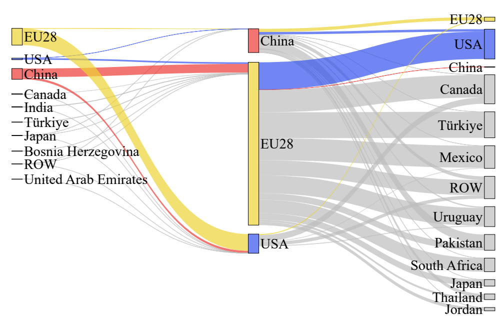
(a) Photovoltaic products, 2011



(b) Photovoltaic products, 2015



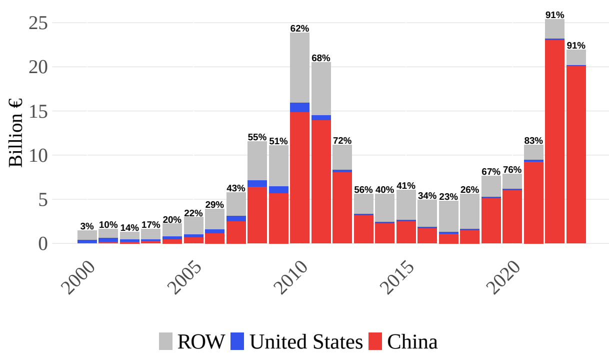
(c) Wind turbines, 2011



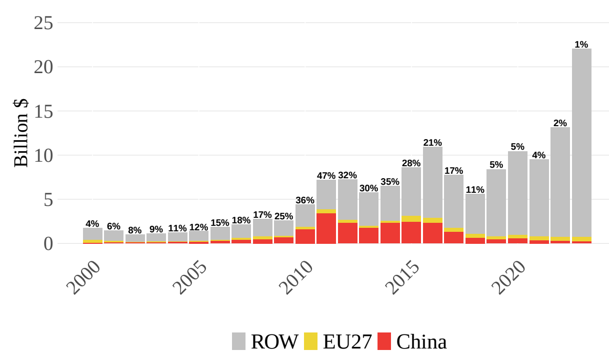
(d) Wind turbines, 2015

Source: Own visualisation 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 years 2010 and 2015. 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 14: Share of Chinese PV imports and exports of total imports and exports from 2000-2023



(a) European Union



(b) United States

Source: Own visualisation based on data from UN Comtrade Database. The graph depicts the total value of imported photovoltaic products with the HS Code 854140 (854141, 854142, 854143, 854149 after 2022) by the EU and the United States from the years 2000 to 2023. Each bar represents the yearly import value, with colors indicating the region of origin. For Chinese imports, the exact share of the total value is displayed in black text.

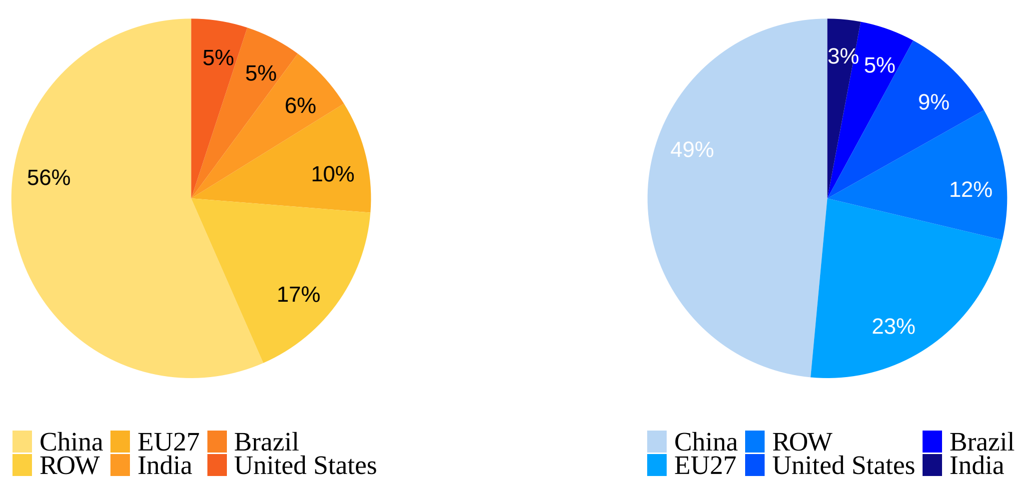
2.4 Labor

After reviewing manufacturing capacities in the EU, US, China, and other significant global players, this section provides insights into how countries' dominance in manufacturing is reflected in the number of national renewable energy jobs. Additionally, it explores the correlation between investments, renewable energy deployment, and employment within the renewable energy sector.

Renewable jobs within the wind and solar industries can be categorized into two main groups: direct and indirect jobs. Direct renewable jobs encompass roles in RES manufacturing, onsite installation, and operation and maintenance. Indirect jobs include jobs within 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 and Paroussos, 2018].

As of 2021-2022 there were 4.9 Million Jobs globally in the solar industry and 1.4 Million Jobs in the wind industry [IRENA, 2023a]. As shown in Figure 15, out of those 1.4 Million wind related jobs, China accounted for 49%, with the EU27 following at 23%. Combined, China, the EU27 and the US make up around 81 % of wind-related employment worldwide, underscoring their dominant role in both deployment and manufacturing of wind related technologies. In the solar industry, China's dominance is even more pronounced, with approximately 56 % of the around 4.9 Million global jobs situated in China. The EU27 comes in second with just 10% of global solar employment, highlighting China's sustained leadership in this sector.

Figure 15: Jobs in the Renewable Energy Sector in 2021-2022



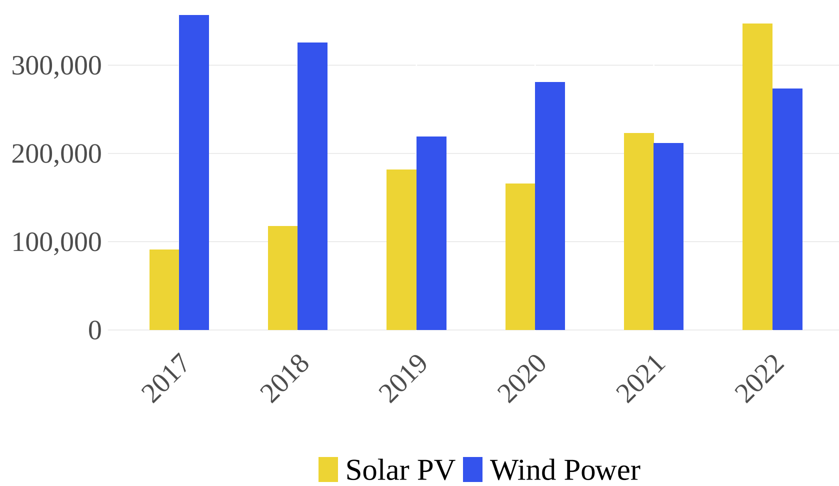
(a) Photovoltaic (around 4.9 Million Jobs in total)

(b) Wind power (around 1.4 Million Jobs in total)

Source:

Source: Own visualisation based on data from the IRENA Review of Renewable energy and jobs 2023 . The graph illustrates the distribution of global employment within the photovoltaic (a) and wind power (b) sectors, highlighting the workforce distribution across different countries or regions for 2021-2022.

Figure 16: Employment in Renewable Energy Sector EU27



Source: Own visualisation based on data from EurObserv'ER online database. The graph shows the total number of direct and indirect jobs related to the photovoltaic and wind sector from 2017 to 2022 in the EU27.

[TBC]

3 Industrial policies in use for renewable energy

In this section, we explore the wide array of industrial policies employed to foster the growth of renewable energy sectors globally. We categorize these policies into two main groups: demand subsidies, which are designed to encourage consumers to adopt renewable energy, and supply subsidies, which directly aid producers in this vital sector.

3.1 Demand subsidies

3.1.1 Feed-in Tariffs

Feed-in tariffs (FiTs) are a crucial policy tool used by 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 17a, 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 17b.

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.

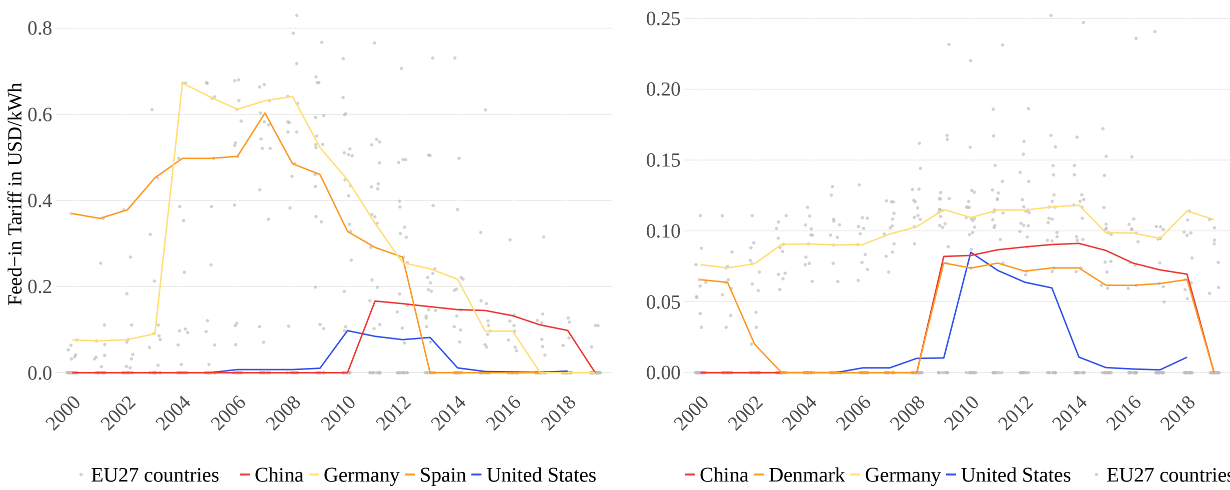
China implemented its own feed-in tariffs (FiTs) starting in 2010, with rates comparable to those offered in the EU27 countries. The FiT rates in China also varied regionally, reflecting differences in solar potential and economic conditions. A primary goal of the Chinese government was to achieve "grid 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.

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.

Figure 17: Feed-in tariffs for photovoltaic and wind power by country



(a) Photovoltaic (b) Wind Power

Source: Own visualisation 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.

- 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 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.

The ITC is available to both businesses and individuals, though the specific benefits may 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.

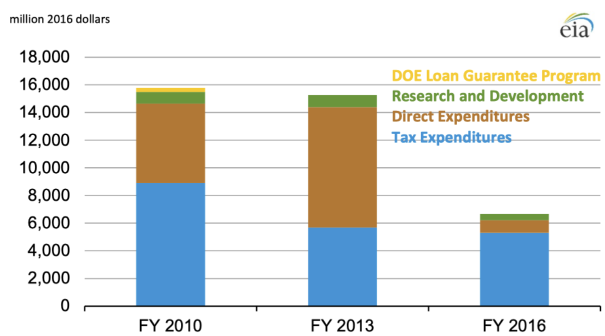
Production Tax Credit (PTC) The Production Tax Credit (PTC) offers a performance-based incentive, providing payments per unit of electricity generated by renewable energy projects. This credit is available for the first 10 years of a facility's operation.

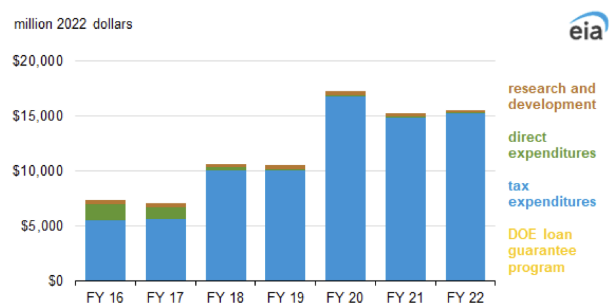
- The initial value of the PTC was \$0.015 per kWh in 1992 dollars, adjusted annually for inflation.
- By 2022, the value had increased to \$0.0275 per kWh (in 2022 dollars).

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.

Section 1603 Grant Program Between 2009 and 2012, the U.S. government offered an alternative to tax credits through the Section 1603 grant program. This program allowed eligible renewable energy projects to receive direct payments instead of tax credits. The Section 1603 grants accounted for the majority of direct expenditures for renewable energy between fiscal years 2010 and 2016. As shown in Figure 18 direct expenditures have played a more minor role in recent years, as evidenced by a shift back towards tax-based incentives.

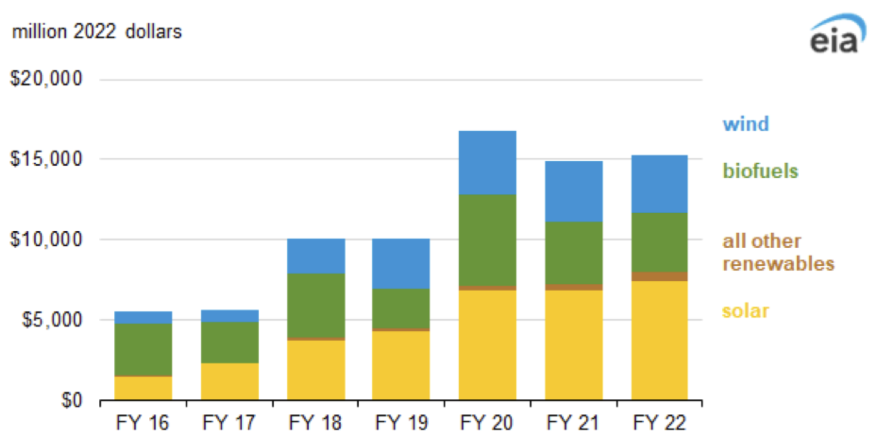
Figure 18: Renewable energy subsidies by instrument for the United States





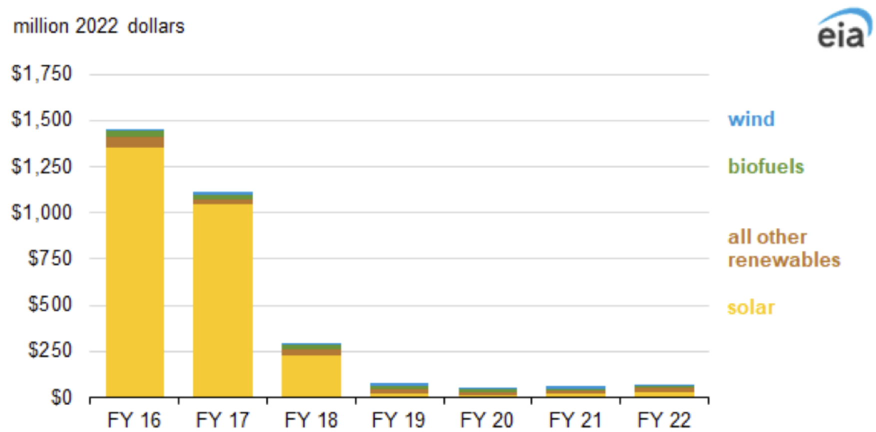
Source: Visualisations from Figure 2, U.S. EIA and Figure 8, U.S. EIA. The graph shows the total amount of subsidies from the U.S. Federal Government to renewable energy technologies by instrument.

Figure 19: Renewable energy subsidies via tax expenditures by technology for the United States



Source: Visualisation from Figure 9, U.S. EIA. The graph shows the total amount of subsidies from the U.S. Federal Government by renewable energy technology.

Figure 20: Renewable energy subsidies via direct expenditures by technology for the United States



Source: Visualisation from Figure 10, U.S. EIA. The graph shows the total amount of subsidies from the U.S. Federal Government by renewable energy technology.

Current and Upcoming Policy Developments under the Inflation Reduction Act (IRA) The Inflation Reduction Act of 2022 introduces several updates and new provisions to further support renewable energy through the tax code.

- The ITC and PTC have been extended and modified, with the ITC offering 30% through 2032 and the PTC expanding to include solar projects.
- The Advanced Manufacturing Production Tax Credit (45X MPTC) incentivizes the manufacturing of physical capital related to renewable energy, providing significant support for domestic production.

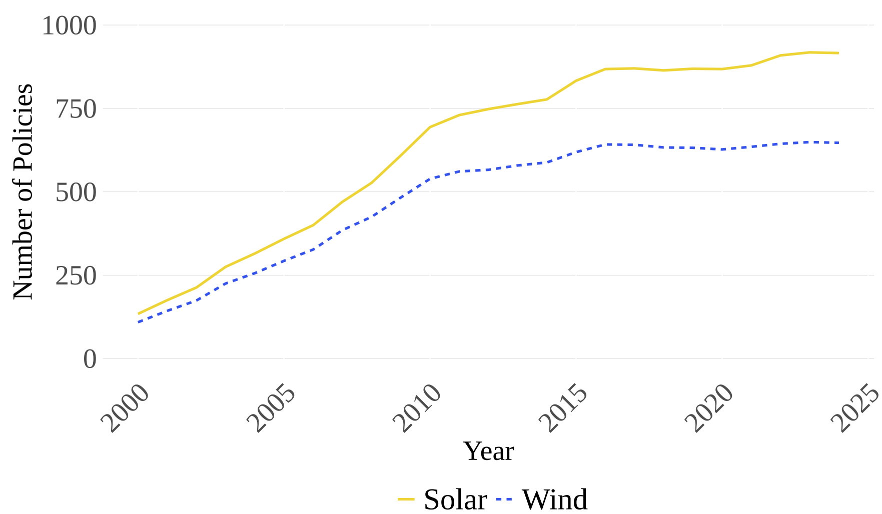
Financial Estimates for FY2023-FY2027 According to the Congressional Research Service (CRS) report, the cost estimates for various renewable energy tax provisions under the IRA for the period FY2023-FY2027 are as follows:

- Residential ITC (primarily solar): $13.1 billion
- PTC: $39.3 billion
- ITC (primarily solar): $89.7 billion
- Advanced Manufacturing PTC (45X, solar and wind): $72.7 billion
- Clean Electricity ITC (48E, energy storage): $14.8 billion

These estimates reflect the substantial financial commitment of the U.S. government towards supporting the growth and sustainability of renewable energy through various tax incentives and credits. The continued evolution of these policies under the IRA highlights the government's focus on advancing clean energy technologies and reducing carbon emissions.

State and Local Policies In addition to national policies, many states and local governments offer a variety of explicit and implicit subsidies to renewable energy, particularly solar (Figure 21). 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.

Figure 21: U.S. state and local renewable energy subsidies by technology



Source: Own visualisation based on the Database of State Incentives for Renewables and Efficiency (DSIRE) from https://www.dsireusa.org. The graph shows the total number of state and local policies by renewable energy technology (for solar and wind).

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.

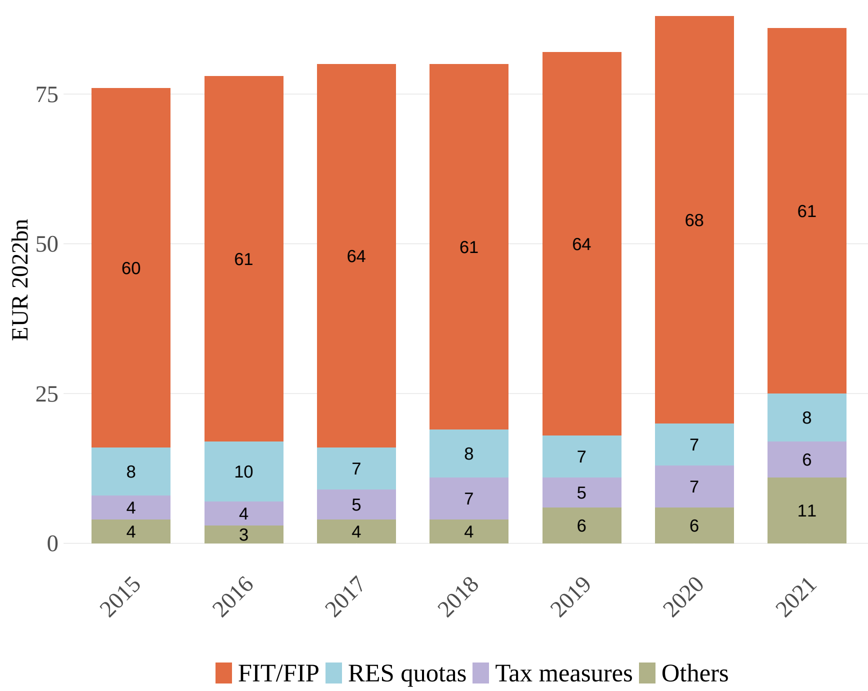
3.1.3 Investment Schemes: European Union

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 22, 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 23 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.

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

Figure 22: Renewable energy subsidies by instrument of EU27



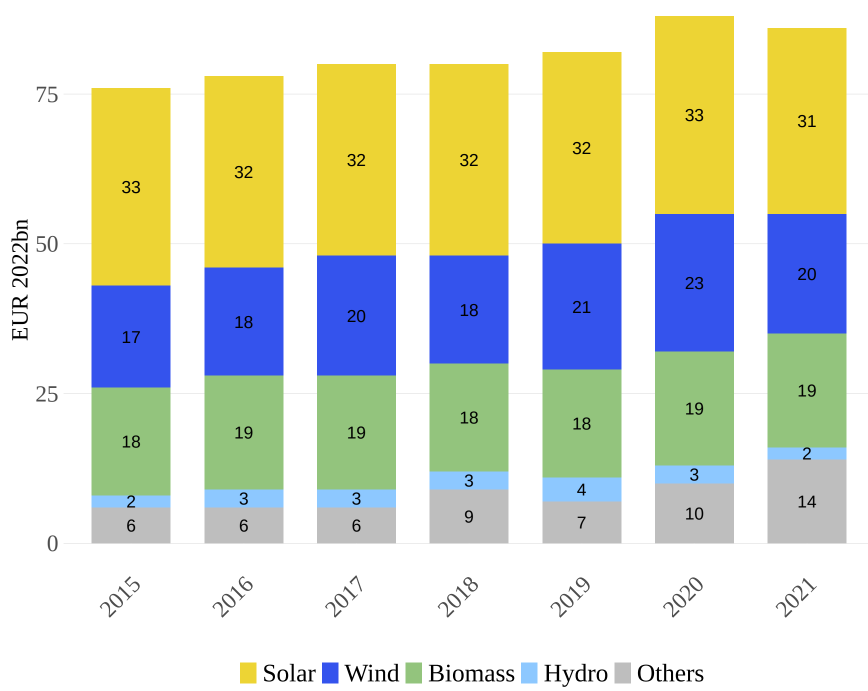
Source: Own visualisation based on data from Figure 6, Enerdata and Trinomics. The graph shows the total amount of subsidies in EUR 2022 bn by instrument across all EU Member States. The category "Others" also includes subsidies through direct investment.

EU. 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.

3.2 Supply subsidies

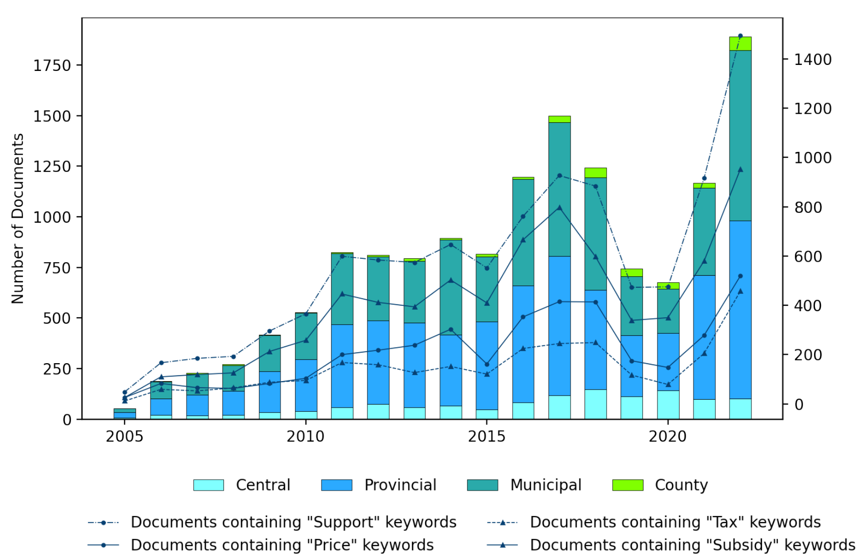
Direct supply subsidies to manufacturers are prevalent in many emerging economies, particularly in China, but systematic data on their quantitative impact remains scarce. Recent research by Juhász et al. [2022]. utilizes textual analysis, basing estimates of policy intensity on the frequency of relevant 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.

Figure 23: Renewable energy subsidies by technology for EU27



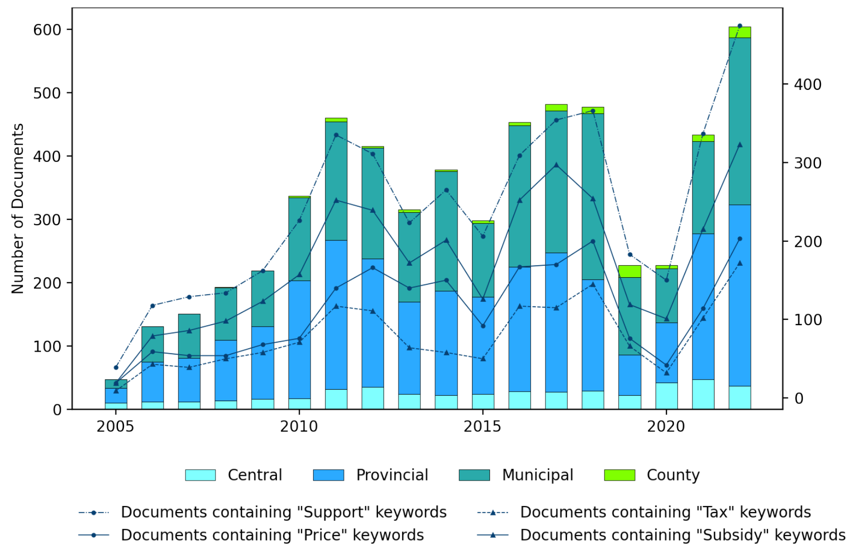
Source: Own visualisation based on data from Figure 11, Enerdata and Trinomics. The graph shows the total amount of subsidies in EUR 2022 bn by technology across all EU Member States.

Figure 24: Renewable Energy Subsidy Policy Documents in China: Solar



Source: Own visualisation based on data from PKULaw.

Figure 25: Renewable Energy Subsidy Policy Documents in China: Wind



Source: Own visualisation based on data from PKULaw.

In the United States, policies to promote renewable energy have primarily focused on demand 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 demand subsidies outlined above (Figure 18). In recent years, new policies to encourage manufacturing activity have been enacted. Most notably, the IRA included a provision to subsidized clean energy manufacturing through the Advanced Manufacturing Production Tax Credit ("45X MPTC"). According to the CRS, this policy is projected to be roughly one-third of the renewable energy tax provisions under the IRA over fiscal years 2023-2027. 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 supply subsidies to manufacturers tracked in the Database of State Inventices for Renewables and Efficiency is small relative to the number of demand 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 demand subsidies summarized based on the frequency counts in Table 2.

In Figures 24 and 25, 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 supply 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 26a, 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.

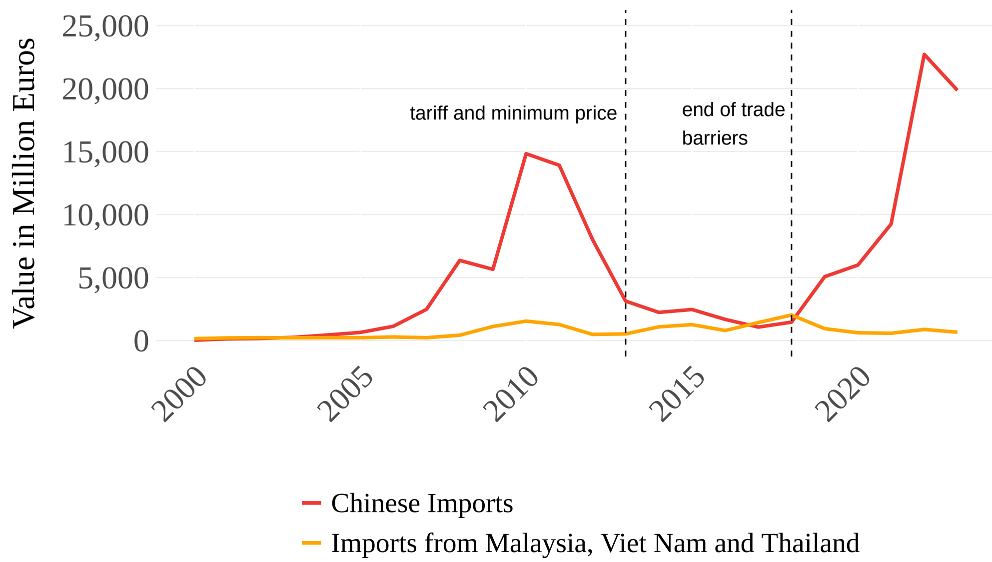
The situation in the United States stands in stark contrast. The U.S. not only maintained its 2014 anti-dumping and countervailing tariffs but further escalated these measures with two additional rounds of tariffs under Sections 201 and 301 during the Trump administration. Consequently, direct imports 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 26b.

3.3.2 Wind

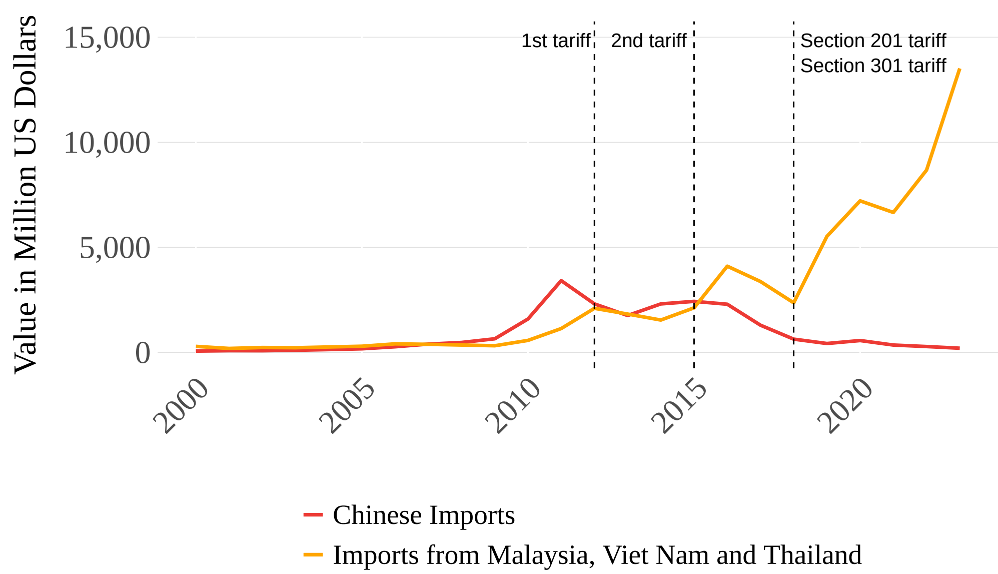
The United States has actively implemented trade barriers to protect its wind turbine industry. In 2013, the United States imposed countervailing duties on utility-scale wind towers from China and anti-dumping duties on utility-scale wind towers from both China and Vietnam. These CVD and AD measures 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 26: 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 and 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 Demand subsidies

Demand 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., Siler-Evans et al., 2012, Cullen, 2013, Gutierrez-Martin et al., 2013, Kaffine et al., 2013, Graff Zivin et al., 2014, Callaway et al., 2018, Novan, 2015, Kaffine et al., 2020, Dorsey-Palmateer, 2019, Sexton et al., 2021]. 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 and Gillingham, 2012, De Groote and Verboven, 2019, Hughes and Podolefsky, 2015, Gillingham and Tsvetanov, 2019, Langer and Lemoine, 2022]. For wind, by contrast, work has focused on utility scale adoption since it constitutes almost the entire market [e.g., Cullen, 2013, Hitaj, 2013, Johnston, 2019, Aldy et al., 2023]. 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., van Benthem et al., 2008, Gillingham and Tsvetanov, 2019]. 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 and 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 demand 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 [van Benthem et al., 2008, Bollinger and Gillingham, 2012, De Groote and Verboven, 2019, Langer and Lemoine, 2022]. 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 (Myojo and Ohashi [2018], Bollinger and Gillingham [2019], Bradt [2024]) 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 demand 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 Supply 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 supply 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 and 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 demand 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 supply 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. 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. Demand 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.[2]

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 Demand subsidies

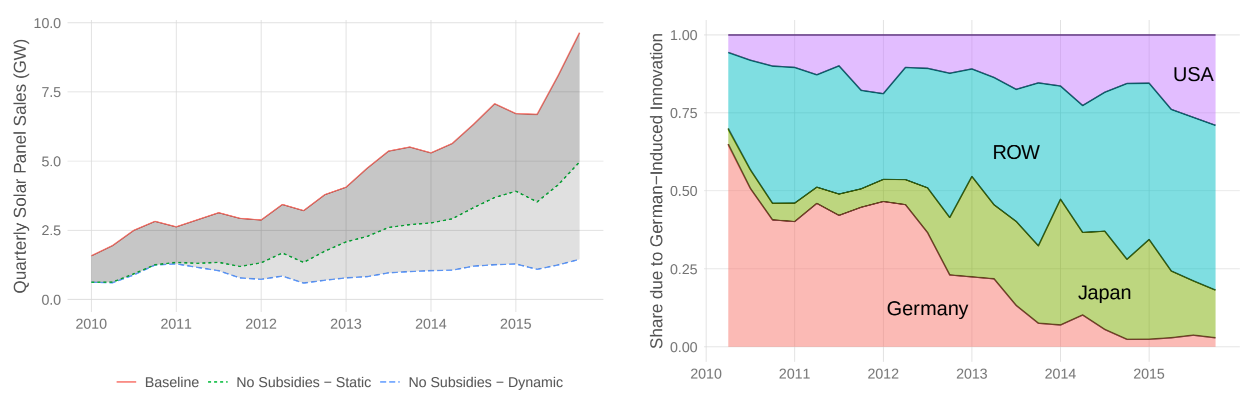
Spillovers from innovation Gerarden [2023] studies the impact of demand subsidies on innovation by solar panel manufacturers. According to the paper's estimates, more than half of observed solar generation

[2] For example, if suppliers of internationally traded renewable energy technology such as solar panels were capacity constrained, a demand subsidy in one market could reduce consumer surplus in another market due to higher equilibrium prices 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 27a 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 demand subsidies and other industrial policy can have first-order impacts on the overall evolution of the industry.

Figure 27: Estimates of Induced Innovation and Spillovers from Gerarden [2023]



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

Source: Both panels are reproduced from Gerarden [2023]. Figure 27a 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 27b 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 17a), and it was the largest market in the world in the early 2010s (Figure 5a). At the same time, a majority of solar panels in Germany, and the EU more broadly, were imported from abroad (Figure 14a). These facts, when taken together with the global induced innovation impacts described above, highlight the potential for Germany's demand 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 demand subsidies. This yields reductions in global solar panel adoption similar to, but smaller in magnitude than, the results in Figure 27a. 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 27b 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 demand 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 demand 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 demand 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 demand subsidies offered by the California Solar Initiative.[3] 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.[4]

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

[4] 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.[5]

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.[6]

5.2 Supply 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 supply 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.

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

[6] 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 increase. 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.[7]

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.

5.4 Future Research

There is limited evidence on both the relative importance of different mechanisms for third-party effects as well as the impacts of government policies through these third-party effects.

[7] 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.

6 Towards policy recommendations

[TBD pending input from the expert dialog.]

References

Jan Abrell, Mirjam Kosch, and Sebastian Rausch. Carbon abatement with renewables: Evaluating wind and solar subsidies in Germany and Spain. *Journal of Public Economics*, 169:172–202, jan 2019. ISSN 00472727. doi: 10.1016/j.jpubeco.2018.11.007.

Joseph E Aldy, Todd D Gerarden, and Richard L Sweeney. Investment versus output subsidies: Implications of alternative incentives for wind energy. *Journal of the Association of Environmental and Resource Economists*, 10(4):981–1018, 2023.

Hunt Allcott. Paternalism and energy efficiency: An overview. *Annual Review of Economics*, 8(Volume 8, 2016):145–176, 2016. ISSN 1941-1391. doi: https://doi.org/10.1146/annurev-economics-080315-015255. URL https://www.annualreviews.org/content/journals/10.1146/annurev-economics-080315-015255.

John W Anderson, Gordon W Leslie, and Frank A Wolak. Measuring the Impact of Own and Others' Experience on Project Costs in the U.S. Wind Generation Industry. Working Paper 26114, National Bureau of Economic Research, July 2019. URL http://www.nber.org/papers/w26114.

Ignacio Banares-Sanchez, Robin Burgess, David Laszlo, Pol Simpson, John Van Reenen, and Yifan Wang. Ray of Hope? China and the Rise of Solar Energy. Working paper, 2023.

Panle Jia Barwick, Myrto Kalouptsidi, and Nahim Bin Zahur. *Industrial Policy Implementation: Empirical Evidence from China's Shipbuilding Industry*. Cato Institute Washington, DC, USA, 2021.

BerkeleyLab. Large-scale wind and solar developers concerned about social factors affecting deployment, 2024. URL https://emp.lbl.gov/news/larg-e-scale-wind-and-solar.

Bryan Bollinger and Kenneth Gillingham. Peer effects in the diffusion of solar photovoltaic panels. *Marketing Science*, 31(6):900–912, 2012.

Bryan Bollinger and Kenneth Gillingham. Learning-by-doing in solar photovoltaic installations. *Available at SSRN 2342406*, 2019.

Bryan Bollinger, Kenneth Gillingham, Drew Vollmer, and Daniel Xu. Strategic avoidance and welfare impacts of solar panel tariffs. 2024.

Severin Borenstein. Private Net Benefits of Residential Solar PV: The Role of Electricity Tariffs, Tax Incentives, and Rebates. *Journal of the Association of Environmental and Resource Economists*, 4(S1): S85–S122, September 2017. ISSN 2333-5955, 2333-5963. doi: 10.1086/691978. URL http://www.journals.uchicago.edu/doi/10.1086/691978.

Severin Borenstein and Ryan Kellogg. Carbon Pricing, Clean Electricity Standards, and Clean Electricity Subsidies on the Path to Zero Emissions. *Environmental and Energy Policy and the Economy*, 4: 125–176, January 2023. ISSN 2689-7857. doi: 10.1086/722675. URL https://www.journals.uchicago.edu/doi/10.1086/722675.

Jacob Bradt. A policy by any other name: Unconventional industrial policy in the us residential solar industry. 2024.

James A Brander and Barbara J Spencer. Export subsidies and international market share rivalry. *Journal of international Economics*, 18(1-2):83–100, 1985.

Duncan Callaway, Meredith Fowlie, and Gavin McCormick. Location, location, location: The variable value of renewable energy and demand-side efficiency resources. *Journal of the Association of Environmental and Resource Economists*, 5(1):39–75, 2018. doi: 10.1086/694179. URL https://doi.org/10.1086/694179.

A. Kerem Coşar, Paul L. E. Grieco, and Felix Tintelnot. Borders, Geography, and Oligopoly: Evidence from the Wind Turbine Industry. *The Review of Economics and Statistics*, 97(3):623–637, August 2015. ISSN 0034-6535. doi: 10.1162/REST_a_00485. URL https://doi.org/10.1162/REST_a_00485.

Giuseppe Costanzo, Guy Brindley, Guy Willems, Lizet Ramirez, Phil Cole, Vasiliki Klonari, and Rory O'Sullivan. Wind energy in europe: 2023 statistics and the outlook for 2024-2030. Technical report, https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2023-statistics-and-the-outlook-for-2024-2030/, 2023.

Thomas R. Covert and Richard L. Sweeney. Winds of Change: Estimating Learning by Doing without Cost or Input Data. Technical report, Boston College, 2024.

Joseph Cullen. Measuring the environmental benefits of wind-generated electricity. *American Economic Journal: Economic Policy*, 5(4):107–33, November 2013.

Michelle Davis, Sylvia Leyva Martinez, Zoë Gaston, Sagar Chopra, Caitlin Connelly, Kaitlin Fung, Max Issokson, Elissa Pierce, Amanda Colombo, Colin Silver, Tyler Thompson, Forrest Levy, and Justin Baca. Us solar market insight executive summary - q2 2024, 2024. URL https://www.woodmac.com/industry/power-and-renewables/us-solar-market-insight/thank-you/?__FormGuid=8e2fb1e9-c50c-43ef-9601-e9e96361421a&__FormLanguage=en&__FormSubmissionId=92546e7a-6b21-443c-a2b2-6044e3fe336c.

Olivier De Groote and Frank Verboven. Subsidies and time discounting in new technology adoption: Evidence from solar photovoltaic systems. *American Economic Review*, 109(6):2137–2172, 2019.

Reid Dorsey-Palmateer. Effects of wind power intermittency on generation and emissions. *The Electricity Journal*, 32(3):25–30, 4 2019. doi: 10.1016/j.tej.2019.02.007.

Adnan Durakovic. New york cancels three offshore wind projects, 2024. URL https://www.offshorewind.biz/2024/04/22/new-york-cancels-three-offshore-wind-projects/.

Jonathan Eaton and Gene M. Grossman. Optimal trade and industrial policy under oligopoly. *The Quarterly Journal of Economics*, 101(2):383–406, 1986.

Equinor. World's largest offshore wind farm dogger bank produces power for the first time, 2023. URL https://www.equinor.com/news/202310-dogger-bank.

Panagiotis Fragkos and Leonidas Paroussos. Employment creation in eu related to renewables expansion. *Applied Energy*, 230:935–945, 2018. ISSN 0306-2619. doi: https://doi.org/10.1016/j.apenergy.2018.09.032. URL https://www.sciencedirect.com/science/article/pii/S0306261918313382.

Xue Gao and Varun Rai. Local demand-pull policy and energy innovation: Evidence from the solar photovoltaic market in china. *Energy Policy*, 128:364–376, 2019.

Shresth Garg and Sagar Saxena. Industrial Policy Under Imperfect Competition: Evidence from Utility-Scale Solar in India. 2023.

Todd D Gerarden. Demanding innovation: The impact of consumer subsidies on solar panel production costs. *Management Science*, 69(12):7799–7820, 2023.

Kenneth Gillingham and Tsvetan Tsvetanov. Hurdles and steps: Estimating demand for solar photovoltaics. *Quantitative Economics*, 10(1):275–310, January 2019. ISSN 1759-7323. doi: 10.3982/TE648. URL https://qeconomics.org/ojs/index.php/qe/article/view/648.

Luis E Gonzales, Koichiro Ito, and Mar Reguant. The Investment Effects of Market Integration: Evidence From Renewable Energy Expansion in Chile. *Econometrica*, 91(5):1659–1693, 2023.

Joshua S. Graff Zivin, Matthew J. Kotchen, and Erin T. Mansur. Spatial and Temporal Heterogeneity of Marginal Emissions: Implications for Electric Cars and Other Electricity-Shifting Policies. *Journal of Economic Behavior & Organization*, 107, Part A:248–268, November 2014. ISSN 0167-2681. doi: 10.1016/j.jebo.2014.03.010. URL http://www.sciencedirect.com/science/article/pii/S0167268114000808.

Felix Groba and Jing Cao. Chinese renewable energy technology exports: the role of policy, innovation and markets. *Environmental and Resource Economics*, 60:243–283, 2015.

F. Gutierrez-Martin, R.A. Da Silva-Álvarez, and P. Montoro-Pintado. Effects of wind intermittency on reduction of CO2 emissions: The case of the Spanish power system. *Energy*, 61:108–117, 11 2013. doi: 10.1016/j.energy.2013.01.057.

Jørgen Hansen, Camilla Jensen, and Erik Madsen. The establishment of the danish windmill industry—was it worthwhile? *Review of World Economics (Weltwirtschaftliches Archiv)*, 139(2):324–347, 2003.

Ann Harrison and Andrés Rodríguez-Clare. Trade, foreign investment, and industrial policy for developing countries. Working Paper 15261, National Bureau of Economic Research, August 2009. URL http://www.nber.org/papers/w15261.

Hitachi-Energy. Finnish wind energy shatters records, sets the stage for unprecedented sustainable journey, 2023. URL https://www.hitachienergy.com/es/es/news/features/2023/09/finnish-wind-energy-shatters-records-sets-the-stage-for-unprecedented-sustainabl

Claudia Hitaj. Wind Power Development in the United States. *Journal of Environmental Economics and Management*, 65(3):394–410, May 2013. ISSN 0095-0696. doi: 10.1016/j.jeem.2012.10.003. URL http://www.sciencedirect.com/science/article/pii/S0095069612001003.

Sebastien Houde and Wenjun Wang. The incidence of the us-china solar trade war. *Available at SSRN 4441906*, 2023.

Anders Hove. Synergies between china's whole county pv program and rural heating electrification, 2023. URL https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/05/CE6-Synergies-between-Chinas-Whole-County-PV-program-and-rural-heating-electrifi pdf.

Jonathan E Hughes and Molly Podolefsky. Getting green with solar subsidies: evidence from the california solar initiative. *Journal of the Association of Environmental and Resource Economists*, 2(2):235–275, 2015.

IEA. Renewables 2023 - analysis and forecast to 2028. Technical report, International Energy Agency, 2023. URL https://iea.blob.core.windows.net/assets/96d66a8b-d502-476b-ba94-54ffda84cf72/Renewables_2023.pdf.

IRENA. Renewable energy and jobs: Annual review 2023. 2023a. URL https://www.irena.org/Publications/2023/Sep/Renewable-energy-and-jobs-Annual-review-2023.

IRENA. Renewable power generation costs in 2022. 2023b. URL https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf?rev=cccb713bf8294cc5bec3f870e1fa15c2.

Sarah Johnston. Nonrefundable tax credits versus grants: The impact of subsidy form on the effectiveness of subsidies for renewable energy. *Journal of the Association of Environmental and Resource Economists*, 6 (3):433–460, 2019.

Réka Juhász, Nathaniel Lane, Emily Oehlsen, and Verónica C. Pérez. The Who, What, When, and How of Industrial Policy: A Text-Based Approach. SocArXiv uyxh9, Center for Open Science, August 2022. URL https://ideas.repec.org/p/osf/socarx/uyxh9.html.

Daniel T. Kaffine, Brannin J. McBee, and Jozef Lieskovsky. Emissions savings from wind power generation in texas. *Energy Journal*, 34(1):155 – 175, 2013. ISSN 01956574.

Daniel T Kaffine, Brannin J McBee, and Sean J Ericson. Intermittency and co2 reductions from wind energy. *The Energy Journal*, 41(5), 2020.

Ashley Langer and Derek Lemoine. Designing dynamic subsidies to spur adoption of new technologies. *Journal of the Association of Environmental and Resource Economists*, 9(6):1197–1234, 2022.

Boqiang Lin and Ranran Luan. Do government subsidies promote efficiency in technological innovation of China's photovoltaic enterprises? *Journal of Cleaner Production*, 254:120108, 2020.

Matti Liski and Iivo Vehviläinen. Gone with the Wind? An Empirical Analysis of the Equilibrium Impact of Renewable Energy. *Journal of the Association of Environmental and Resource Economists*, 7(5):873–900, 2020. doi: 10.1086/709648. URL https://ideas.repec.org/a/ucp/jaerec/doi10.1086-709648.html.

Satoshi Myojo and Hiroshi Ohashi. Effects of consumer subsidies for renewable energy on industry growth and social welfare: The case of solar photovoltaic systems in japan. *Journal of the Japanese and International Economies*, 48:55–67, 2018.

Gregory F. Nemet. Subsidies for new technologies and knowledge spillovers from learning by doing. *Journal of Policy Analysis and Management*, 31(3):601–622, 2012. doi: https://doi.org/10.1002/pam.21643. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/pam.21643.

Kevin Novan. Valuing the wind: Renewable energy policies and air pollution avoided. *American Economic Journal: Economic Policy*, 7(3):291–326, August 2015.

Anna Pegels and Wilfried Lütkenhorst. Is Germany's energy transition a case of successful green industrial policy? Contrasting wind and solar PV. *Energy Policy*, 74:522–534, 2014.

Claire Petersen, Mar Reguant, and Lola Segura. Measuring the impact of wind power and intermittency. *Energy Economics*, 129:107200, 2024. ISSN 0140-9883. doi: https://doi.org/10.1016/j.eneco.2023.107200. URL https://www.sciencedirect.com/science/article/pii/S0140988323006989.

Yueming Qiu and Laura D. Anadon. The price of wind power in China during its expansion: Technology adoption, learning-by-doing, economies of scale, and manufacturing localization. *Energy Economics*, 34(3):772–785, 2012. ISSN 0140-9883. doi: https://doi.org/10.1016/j.eneco.2011.06.008. URL https://www.sciencedirect.com/science/article/pii/S0140988311001307.

Michael Schmela, Raffaele Rossi, Christophe Lits, Jonathan Gorremans, Antonio Arruebo, Dries Acke, Catarina Augusto, Jonathan Bonadio, Naomi Chevillard, Alexander Rohlf, José Donoso, Michelangelo Lafronza, Alessio Cipullo, Edoardo Sorti, Federico Brucciani, Paulina Wojciechowska, Stanislaw M. Pietruszko, Wijnand van Hooff, Nold Jaeger, Marinthe Bos, Salomé Durand, Lisa Grün, Wannes Demarcke, Dr. Ir. Fawaz Al Bitar, Stelios Psomas, and Ádám Szolnoki. Eu market outlook for solar power 2023-2027, 2023. URL https://www.solarpowereurope.org/insights/outlooks/eu-market-outlook-for-solar-power-2023-2027/detail.

Steven Sexton, Justin Kirkpatrick, Robert Harris, and Nicholas Muller. Heterogeneous Solar Capacity Bene ts, Appropriability, and the Costs of Suboptimal Siting. *Journal of the Association of Environmental and Resource Economists*, 5 2021. doi: 10.1086/714970.

Abhishek Shivakumar, Audrey Dobbins, Ulrich Fahl, and Antriksh Singh. Drivers of renewable energy deployment in the eu: An analysis of past trends and projections. *Energy Strategy Reviews*, 26:100402, 2019. ISSN 2211-467X. doi: https://doi.org/10.1016/j.esr.2019.100402. URL https://www.sciencedirect.com/science/article/pii/S2211467X19300951.

Kyle Siler-Evans, Inês Lima Azevedo, and M. Granger Morgan. Marginal emissions factors for the u.s. electricity system. *Environmental Science & Technology*, 46(9):4742–4748, 2012.

SolarZoom. National development and reform commission: The total scale of wind and everbright bases is 450gw, and the total number of pilot projects in the county is 66gw, 2022. URL https://mp.weixin.qq.com/s/xnV3bVqWKveIwLJVE49HsA.

Jens Thurau. Can germany meet its ambitious wind energy targets?, 2024. URL https://www.dw.com/en/can-germany-meet-its-ambitious-wind-energy-targets/a-68165099.

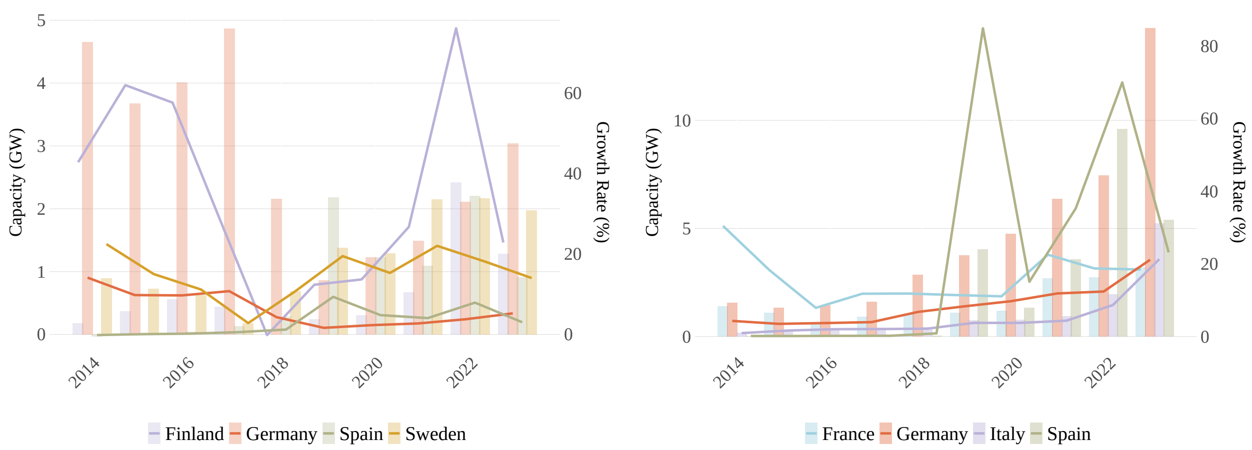
Arthur van Benthem, Kenneth Gillingham, and James Sweeney. Learning-by-Doing and the Optimal Solar Policy in California. *The Energy Journal*, 29(3):131–151, January 2008. ISSN 0195-6574. URL http://www.jstor.org.ezp-prod1.hul.harvard.edu/stable/41323173.

Benjamin Wehrmann. German onshore wind power – output, business and perspectives, 2024. URL https://www.cleanenergywire.org/factsheets/german-onshore-wind-power-output-business-and-perspectives.

Qiang Zhi, Honghang Sun, Yanxi Li, Yurui Xu, and Jun Su. China's solar photovoltaic policy: An analysis based on policy instruments. *Applied Energy*, 129:308–319, 2014.

A Appendix: Additional Figures

Figure A.1: Growth rates and yearly added capacity for selected EU27 countries

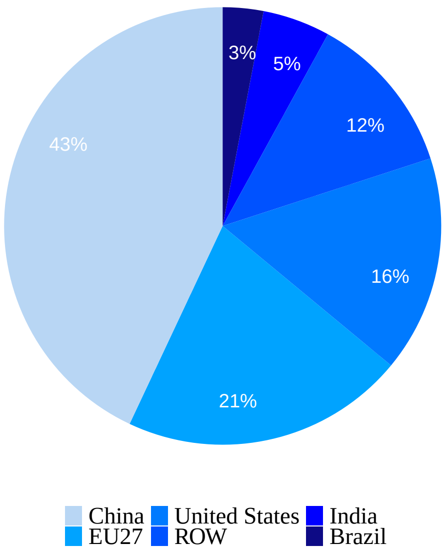


(a) Onshore Wind

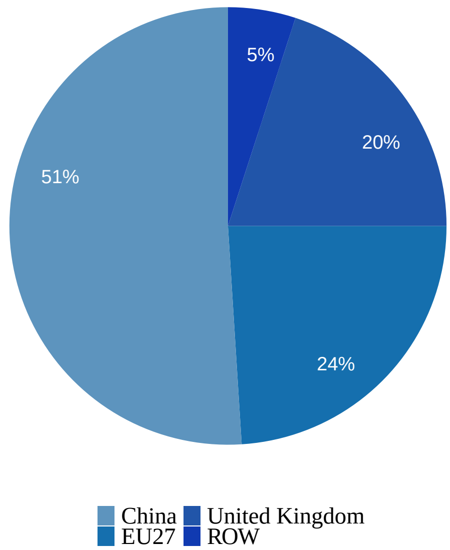
(b) Solar PV

Source: Own visualisation based on data from IRENA Energy Statistics. The graph illustrates the growth rate and the total capacity in GW added for each year from 2011-2023 for onshore wind (a) and solar PV (b).

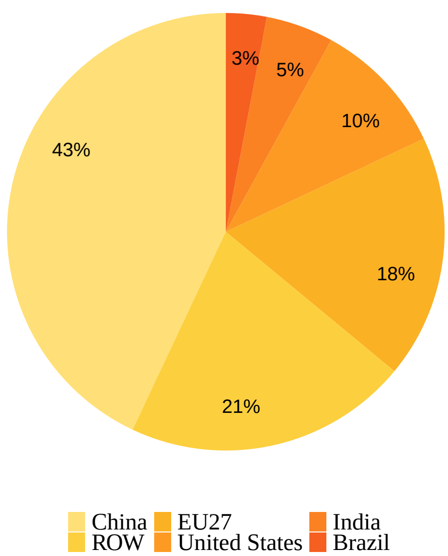
Figure A.2: Share of cumulative capacity (GW) of solar photovoltaic, offshore and onshore wind, 2023



(a) Onshore wind



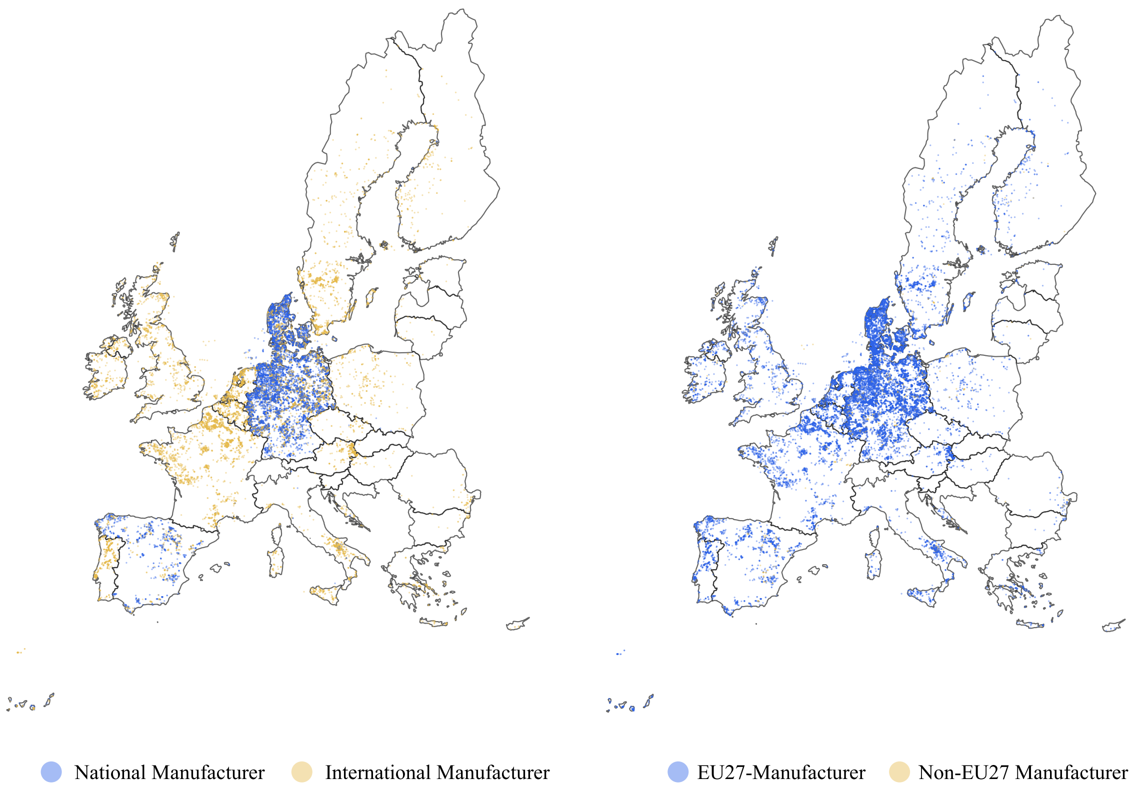
(b) Offshore wind



(c) Solar Photovoltaic

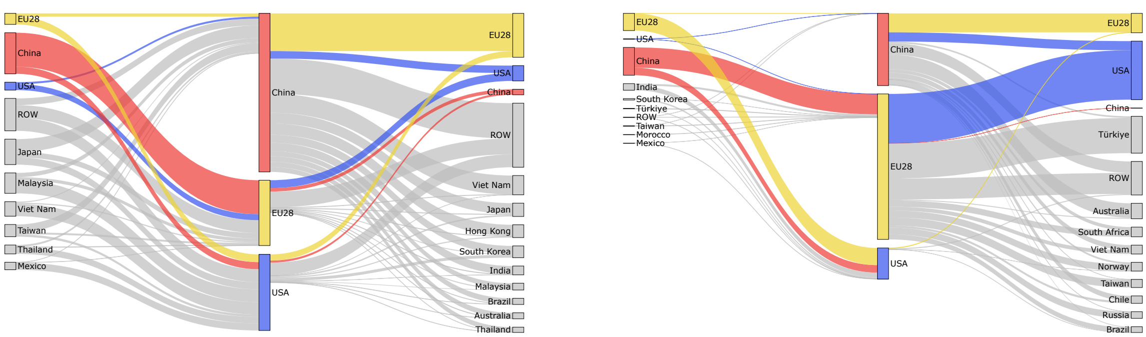
Source: Own visualisation based on data from IRENA Energy Statistics. The graphs show the share of cumulative capacity in GW in 2023 for solar photovoltaic, and onshore and offshore wind in international comparison.

Figure A.3: Location of installed wind turbines by manufacturing location, 2000-2022



Source: Own visualisation 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.4: Imports and Export of photovoltaic and wind power products of the EU28, US and China in 2020

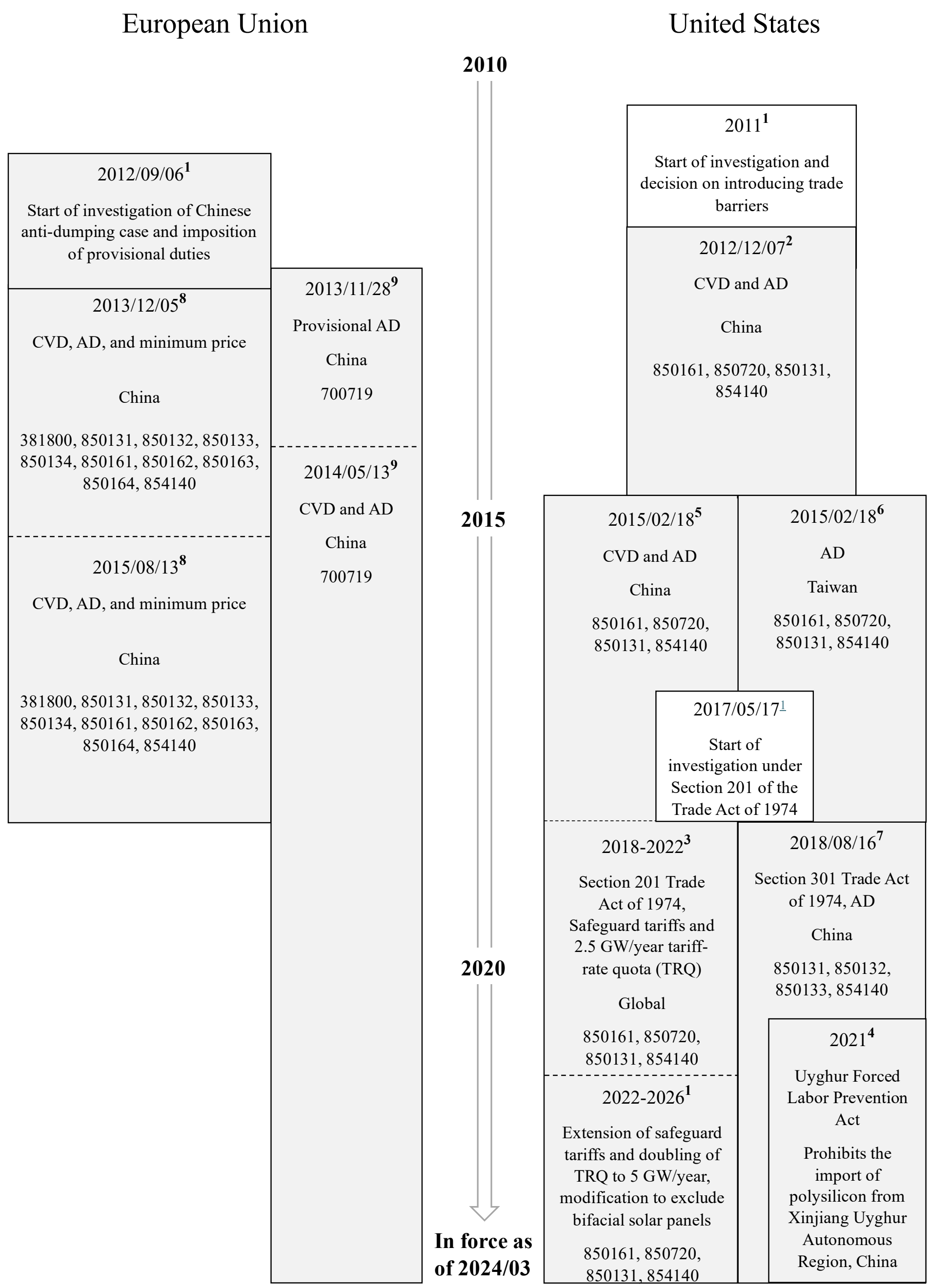


(a) Photovoltaic products, 2020

(b) Wind products, 2020

Source: Own visualisation 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	