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Identifying and explaining "pulses" in renewable power growth

Master's Thesis in Master Programme Sustainable Energy Systems

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Abstract

The urgency of addressing the advancing climate crisis makes it necessary to reduce emissions, which requires high growth rates of renewable energy sources, particularly wind and solar power. However, despite this urgent need for accelerating renewables growth, many countries are facing stagnation in the deployment of solar and wind power.

This study identifies historical cases of stagnation and subsequent re-acceleration in national cases of solar and wind power by visually analyzing their growth curves. Six of the identified cases are selected for an in-depth investigation using a three-perspective framework. This approach involves examining various factors such as policy changes, market dynamics, demand fluctuations, technological advancements, and external influences that contribute to both stagnation and re-acceleration phases. Through a structured comparison of these cases, the study aims to develop more generalized theoretical insights into the factors influencing stagnation and the strategies for achieving re-acceleration. These factors influencing the growth patterns are changes in supply and demand trends as well as growing demand of low-carbon sources. Additionally, the global market dynamics and social resistance can influence deployment. However, the factor that has a direct impact on the deployment are policies. This thesis presents findings on the effectiveness of various policies at different stages of technological development. For instance, feed-in tariffs are highly effective for the initial promotion of new technologies. However, as these technologies mature, feed-in tariffs become less effective and should eventually be replaced by a tendering system. By providing insights into these mechanisms behind the growth patterns of renewable energy sources, this research offers valuable knowledge for policymakers that are aiming at accelerating the transition toward a sustainable energy future as envisaged by climate mitigation scenarios.

Another pertinent question addressed in this study is whether the growth rate before or after the stagnation phase is faster. This comparison helps estimating the effectiveness of measures aimed at re-accelerating renewable development, as ambitious climate mitigation scenarios require growth rates higher than those historically observed.

Keywords: energy transitions, renewable electricity, photovoltaic, wind, technology diffusion, policy learning

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List of Acronyms

AT Austria.

BG Bulgaria.

COP Conference of the Parties under the United Nations Framework Convention on Climate Change.
CZ Czech Republic.

DE Germany.
DK Denmark.
DKK Danish krone.

EEG Renewable Energy Sources Act (Erneuerbare Energien Gesetz).
ES Spain.
EU European Union.
EUR Euro.

FIP feed-in-premium.
FIT feed-in-tariff.

GEA Green Electricity Act.
GER Green Electricity Regulation.
GIS global innovation system.
GR Greece.

IPCC Intergovernmental Panel on Climate Change.

kWh Kilowatt hour.

MW Megawatt.
MWh Megawatt hour.

NZ New Zealand.

OECD Organisation for Economic Co-operation and Development.
OeMAG Austrian Green Power Settlement Agency.

PH Philippines.
PK Pakistan.
PPCA Powering Past Coal Alliance.
PV photovoltaic.

R&D Research and Development.
RD Royal Decree.
RDL Royal Decree Law.
RES Renewable Energy Sources.

TWh Terawatt hour.

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Introduction

Reducing for example carbon emissions is crucial for mitigating climate change, as it is highlighted in the IPCC report 2022 [1]. Electrification, particularly through wind and solar power, plays a significant role in emission reduction strategies [2]. Ambitious climate mitigation scenarios require a high growth rate of solar and wind energy, higher than historical observed rates, according to studies on renewables by researchers like Cherp et.al. [3] and Vinichenko et.al. [4]. Some researchers argue that the potential for wind and solar energy might be even greater than envisioned by these scenarios [5], [6]. Global and regional climate strategies, such as the commitment to triple global installed renewable energy generation capacity decided by COP28, require not only continuation but also significant acceleration of the current renewable energy growth. Additionally, initiatives like the REPowerEU plan, aimed at ending the European Union's dependence on Russian energy, also demand a similar level of acceleration [7]–[9]. However, despite the importance of renewable energy growth, many countries are facing stagnation in the deployment of wind and solar power [3], [4]. This raises a question whether the re-acceleration is possible and how it can be achieved.

Typically, the growth trajectory of a technology follows an S-curve, starting with irregular growth, followed by acceleration, until it reaches a stable growth rate, and eventually slows down to stagnation. The theoretical S-curve is characterized by a single inflection point, that represents the transition from accelerating to decelerating growth [3], [10]. Scholars use this theory to explain the growth patterns of renewable energy and measure growth rates [3], [4]. In terms of the S-curve model, stagnating countries are already close to the growth ceiling, and a single-curve model offers no chance for re-acceleration. However, real-world diffusion may involve multiple inflection points, which makes the use of stacked or consecutive S-curves a more accurate depiction of growth dynamics [11]. In those cases the growth may stagnate and subsequently re-accelerate. Understanding the causality behind these cases is crucial for restarting the growth of renewables or preventing stagnation in order to meet climate targets.

The aim of this study is to explore cases of stagnation and subsequent re-acceleration in the national cases of solar PV and onshore wind power growth, with the goal of providing insights into the mechanisms behind the growth patterns of renewable energy sources, in order to offer knowledge for policymakers, industry stakeholders, and researchers that are trying to accelerate the transition towards a sustainable energy future envisioned by climate mitigation scenarios.

To reach this goal, several countries that have already faced stagnation with a following re-acceleration in onshore wind or solar PV are chosen and investigated. Specifically, the following research questions are answered:

- RQ1: What are the cases of stagnation and subsequent re-acceleration of renewable growth?
- RQ2: What are the causes of stagnation and re-acceleration?
- RQ3: Will the growth rates after the re-acceleration be faster or slower than before stagnation?

Therefore, the first objective is to identify historical instances where the growth of renewable energy sources, particularly onshore wind and solar power, experienced periods of stagnation followed by re-acceleration. Identifying these cases and critical points in time will provide insights into the dynamics of growth trajectories in the deployment of renewable energy. The method to identify turning points relies on the visual analysis of the cumulative installed capacity curve and especially the annual additions in deployment, as the latter curve offers a more precise insights into timing.

Understanding the causes behind stagnation and subsequent re-acceleration is crucial. This objective involves an in-depth investigation of diverse factors, such as policy changes, market dynamics, technological advancements, and external influences, that contribute to both stagnation and re-acceleration phases. The research is done by applying the tree perspectives framework [12]. A structured comparison of the chosen cases is carried out according to a comparison protocol to develop more generalized theoretical statements and provide specifications of causal mechanisms [13].

Another aspect of this study is to evaluate whether the growth rates observed after the re-acceleration phase are faster or slower than those before the period of stagnation. By analyzing the growth trajectory after the re-acceleration, the effectiveness of measures aimed at restarting renewable energy deployment can be estimated. Additionally, the actual maximum growth rates are compared to fitting-based single-curve growth rates to evaluate the methodology of measuring growth rates based on a single S-shaped curve.

The following paragraphs outline the structure of this Master's Thesis Project, detailing the different chapters and their content.

Chapter 2 of this thesis involves a review of literature about growth curves and growth metrics. Furthermore, it includes explanations of the socio-technical, techno-economic, and political perspectives and categorizes energy-related policies. Additionally, it provides detailed explanations of the most significant types of policies relevant to this study.

Following this, in Chapter 3 the methodology used in this thesis is outlined. This includes a section dedicated to case studies and general case comparison methods.

Moreover, this chapter elaborates the criteria for identifying stagnation and subsequent re-acceleration of solar PV or onshore wind energy. It also outlines the selection process for the potential cases. Additionally, the process of selecting the most illustrative cases for an in-depth analysis from the initially chosen list of possible cases is described. Six distinct cases are ultimately chosen, including three with solar PV and three with onshore wind.

In Chapter 4 these cases are investigated following a structured framework, which includes exploring their history, international market dynamics, country-specific conditions, domestic industry landscapes, and relevant policies.

To discuss the results, in Chapter 5 a comparative analysis based on a structured case description is made to evaluate the selected cases and their respective developments. This process shows both similarities and differences and provides insights into successful strategies for implementing a re-acceleration in countries that face stagnation in renewable energy adoption, for example by referring to potential differences in growth rates before and after stagnation.

The last Chapter 6 summarizes the findings of this thesis, answers the research questions and lists the limitations.

2

Literature Review

2.1 Growth models

S-shaped curves, in particular the Gompertz curve have been used in demographic studies since the 19th century [14]. In 1962 Rogers [15] first published his Diffusion of Innovation Theory, that proposes that the adaption of innovations tends to follow an S-shaped curve. This growth curve is depicted with time (t) along the x-axis and quantity (N) along the y-axis. Rogers primarily focuses on the adoption and diffusion of innovations within social systems, while Grübler [10] expands the perspective in 1996. He applies the S-curves to the energy sector and analyzes transitions in technological change. According to this Technology Diffusion theory, the adoption of innovative technologies such as solar PV and wind power typically follows and S-shaped curve, characterized by four different phases [16], [17]:

The initial **formative phase** is characterized by a slow and erratic growth caused by high costs and uncertainty [18]. The phase ends with the so-called "take-off" [17], [19], [20]. This marks the moment when the socio-technical regimes established around the new technologies, become capable of steady expansion [21]. During the formative phase only a small group of innovators and early adopters are attracted to the technology [15].

The take-off initiates the **acceleration phase**. During this phase growth accelerates due to positive feedbacks in economic profitability, technology learning and policy support, often referred to as increasing returns. Increasing production and therefore deployment leads to decreasing costs, which in turn leads to larger deployment [22].

In the **stable growth phase**, the acceleration stops due to increasing social resistance and system integration [3]. The early and late majority of consumers adopt the technology [15]. The point of maximum growth rate is in the stable growth phase and is called inflection point. Indeed, before the inflection point, the growth rate is accelerating, while afterward, it begins to decelerate [23].

The final phase is called **saturation** or **stagnation phase** and begins when remaining laggards adopt the technology [15]. The growth starts to slow down markedly and eventually reaches the ceiling. The market share of the technology no longer increases due to various factors. These include increasing marginal costs [24], [25], grid and system integration challenges [17], [26], [27] and geophysical constraints

[28], as well as political and social resistance [17].

As previously noted, the take-off ends the formative phase. In this work the take-off point is defined as the year in which solar or wind power reaches 1% of the total electricity supply, denoted as the take-off year, $T_{1\%}$, according to Cherp et. al. [3].

Figure 2.1 illustrates an S-curve depicting the quantity (N) over time (t), that provides an overview of mechanisms and factors active at the different growth phases. Additionally, it highlights the inflection point in the curve.

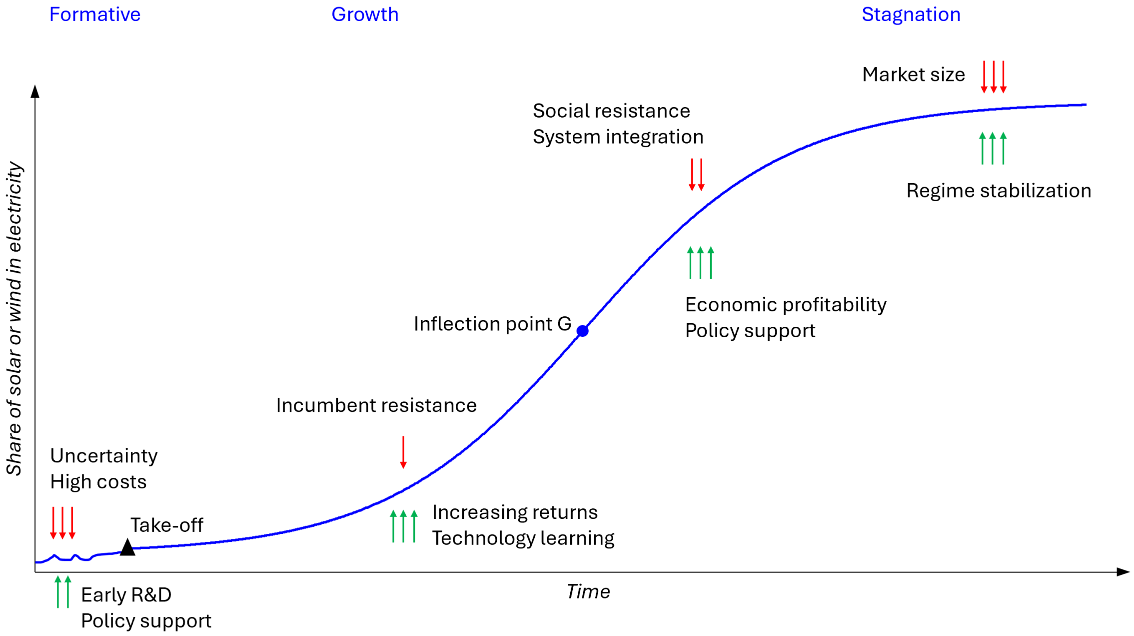


Figure 2.1: Example of an S-curve with mechanisms that lead to the different growth phases, adapted from Cherp et. al. [3].

The S-curve is typically represented mathematically by either the logistic or the Gompertz curve [23]. Scholars use these theoretical curves fitted to empirical data to measure the maximum growth rate of technologies [23].

The formula for the logistic curve is represented by Equation 2.1 [23].

$$f(t) = \frac{L}{1 + e^{-k(t-t_0)}} \tag{2.1}$$

Equation 2.2 presents the formula for the Gompertz curve [23].

$$f(t) = L \cdot e^{-k(t-t_0)} \tag{2.2}$$

For both curves the variables fulfill the same purposes:

- L represents the maximum reachable quantity, with its change it stretches the curve vertically
- k determines the growth duration (e.g. the time between 10% and 90% of the maximum level), and therefore has impact on the slope of the curve.

- t_0 represents the inflection point when the maximum growth rate is achieved, with its change shifting the curve to the left or right. For the logistic curve the inflection point occurs precisely at half of the maximum quantity, which is at $\frac{L}{2}$, whereas for the Gompertz curve the inflection point is lower at $0.37L$ [23].

The real-world diffusion, however, may deviate from a single S-shape, instead it can show consecutive S-shapes, which means there are several sections described by different functions. Sood et. al. [11] conducted a case study to support the hypothesis of consecutive S-curves. Their findings showed that only approximately 30% of the analyzed technologies follow a single S-shaped growth, the remainder could be more accurately approximated with multiple, stacked S-curves rather than a single one. This can be explained by the fact that one technology contains different sub-technologies, that emerge successively, for example the development of wind turbines with higher rated capacity.

Kulmer et. al. [29] extended this approach to renewable energy sources and tried to explain the transitions between the growth phases of the deployment of solar PV, domestic heat pumps and the use of electric vehicles in Austria with the help of the Multiple Streams Approach. This is an approach similar to the Three Perspectives described in Section 2.2, as the three streams politics, policies and technology are analyzed in order to reconstruct socio-political developments related to market diffusion.First, the turning points have to be identified, and then the reasons for them are explained. To identify the turning points, which means the years when the growth function changes, in contrast to this work, which relies on visual identification, Kulmer et. al. use a mathematical technique. First, they fit data to a combination of theoretical curves, including those described in Section 2.1, and then they select the best-fitting one and identify the turning points mathematically based on this model [29]. In their studies they conclude, that market take-off typically occurs when the three streams politics, policy, and technology converge. Binding targets and regulations need to be accompanied by actions in all three streams [29].

Even though the single S-curve is not applicable to all cases of technology growth, it is still widely utilized in energy and climate research for forecasting innovative technologies [30], [31].

2.2 Three Perspectives

Economists and historians have been interested in how the use of energy resources changes in the long run since the 1960s at least [12]. Their exploration of past transitions has often been driven by the aim of getting insights into potential future transitions. In 1984, Kingdon proposed a Multiple Stream Approach, that suggests that three interconnected streams influence the policy process: the politics stream, that reflects shifts in public opinion; the policy stream, that represents the sequence of formal decisions and legislation; and the problem stream, that shows issues that concern policymakers and the public [29], [32].

In 2018, Cherp et. al. [12] introduced an approach that contains three perspectives: the techno-economic, socio-technical, and political perspective, that provide a more comprehensive understanding of the dynamics that influence energy transitions [12]. This approach will be applied in this thesis and is therefore explained in the following paragraphs.

According to this approach, national energy transitions involve the co-evolution of three distinct systems. Firstly, these systems have unique boundaries, elements, and connections. Secondly, each system can evolve separately and autonomously from the others. Thirdly, these co-evolving systems have influence on each other. Consequently, national energy transitions include the simultaneous evolution of techno-economic, socio-technical, and political action systems.

The techno-economic perspective focuses on energy systems characterized by energy flows, conversion processes and uses, and their coordination through energy markets. In particular it examines supply and demand changes and shifts in energy sources. The corresponding mechanisms within the perspective include the depletion of resources, that leads to increasing extraction costs and thus may drive shifts to other resources or reduce consumption. Additionally, maintaining a supply-demand balance over longer periods of time is crucial. This concept of supply-demand balance is often used together with the neoclassical economic idea of market equilibrium, which means that under competitive market conditions energy supply and demand are in a stable equilibrium. Another mechanism is that energy demand is influenced by factors such as population growth and economic expansion [12].

The socio-technical perspective addresses technological change and innovation driven shifts, in particular the emergence and diffusion of new technologies. It has the understanding of technology as a social phenomenon, which includes knowledge and practices embedded in infrastructure and technical artefacts. A fundamental aspect of this perspective is technology learning, with Wright's Law playing a pivotal role. According to Wright's Law, increased deployment leads to cost reductions. This phenomenon can be visualized through an experience curve, where the decline in costs is depicted as a function of cumulative production [33]. Central to this perspective is also the concept of technology diffusion, which means that these artefacts are shared among human actors and circulate within social networks. Another mechanism within the socio-technical perspective is the technology lock-in, when beneficial innovations face barriers because they are incompatible with dominant regimes, built around incumbent technologies. Such innovation often occurs within niches, which are socio-technical systems with fluid boundaries, diverse actors, and flexible rules and practices. Niches are less stable, but more capable of radical innovation than systems functioning within established regimes. Moreover, innovation involves technology learning, which includes advancements in energy efficiency. Enhanced energy efficiency can in turn reduce the energy demand [12].

The political perspective focuses on the role of changing policies on energy systems. Because most energy policies are adopted and implemented by governments acting on behalf of nation states, the state is the primary unit of analysis in the political perspective. One mechanism in this regard is the state autonomy, which means that that states are independent actors [34] as they pursue national interests [35] or state imperatives such as internal stability, external sovereignty, and economic advancement [36]. Energy policies are designed to address national interests, including ensuring a secure supply-demand balance [37], minimizing reliance on energy imports or maximizing exports [38], guaranteeing reliable access to electricity, securing industrial competitiveness, and creating employment opportunities [39]. Another mechanism is the concept of increasing returns, which means that a policy makes alternative options less appealing over time, similar to technology lock-in. Additionally, existing institutional frameworks and policies can inhibit both policy and institutional change. Policy diffusion is another important phenomenon, whereby different states adopt similar policies. This diffusion can occur through coercion, international harmonization, regulatory competition, transnational communication, lesson drawing, transnational problem-solving, emulation, international policy promotion and independent problem solving [40], [41]. For instance, research by Schaffer and Bernauer [42] how European Union membership influences the adoption of renewable energy policies.

2.3 Energy-related policies

The objectives of energy-related policies have several key goals. These include mitigating climate change, meeting the domestic energy demand and increasing energy security through facilitating a transition towards low-carbon energy sources, which do not rely on fossil fuel imports [43]. Another objective involves the expansion of energy access, especially in rural and economically disadvantaged areas, which is called socioeconomic development. Moreover, policymakers often want to realize economic benefits, ranging from job creation to making profits and facilitating overall economic growth [44]–[46]. For some countries, supporting domestic manufacturing of renewable energy technologies (often with a view to technology exports) is an important part of their motivation for supporting renewable energy deployment [43]. In the long run, this may lead to technology cost reduction due to learning.

To achieve these policy objectives, policymakers implement a range of measures and allocate resources accordingly. Policies for renewable energies can be classified into two main streams: supply-side and demand-side. Supply-side initiatives contain support for Research and Development (R&D) and production enhancement. Demand-side measures, however, focus on encouraging the adoption and diffusion of renewable energies with the help of incentives like subsidies for electricity production or installations [47].

This classification can be further divided into two categories for the supply-side and three categories for the demand-side. The following Table 2.1 shows the full classification of energy-related policies and gives some examples for each category.

Table 2.1: Classification of energy-related policies [48]–[50]

Supply-side policies
fiscal incentives
academic funding
national/international public research center
public-private partnership
prize
public finance
venture capital
soft/convertible loan

Demand-side policies	
fiscal incentives	**regulations**
tax-reduction/exemption	quantity-driven:
	tendering/bidding
grant	price-driven:
energy production payment	feed-in-tariff
	feed-in-premium
public finance	quality-driven:
investment	green labeling
guarantee	access:
loan	priority access to network
public procurement	priority dispatch

Feed-in-tariffs (FIT) guarantee renewable energy producers a fixed remuneration for one unit renewable electricity for typically 15 to 20 years. This rate reflects the real cost of generating power from each renewable energy technology, inclusive of a fair rate of return. FITs typically mandate grid operators to purchase all generated renewable electricity, regardless of the overall electricity demand. Generally, FITs are funded through a small top-up to the electricity price for end consumers. This means that additional costs are spread across all users through national burden-sharing mechanisms. When crafting FITs, policymakers aim for a balance between ensuring investment security for renewable energy producers and minimizing expenses for end consumers [51].

Under a feed-in-premium (FIP), the remuneration for a renewable electricity producer is composed of two elements: the prevailing hourly market price of electricity on conventional power markets, and a decreased tariff payment. This reduced tariff payment must be set at a level that ensures the profitability of renewable energy ventures remains feasible. This combination of two remuneration components is a challenge for policymakers in setting the FIP for each technology, as market prices are fluctuating. Forecasting the development of market prices is crucial to prevent windfall profits in case of high market prices and to ensure sufficient returns on investment in case of low market prices [51].

Tender or bidding systems are mechanisms used by policymakers to allocate support for renewable energy projects based on quantity. This involves a call for tender, basically an auctioning process, for a specific renewable energy project of a particular size. The financial support can be based on either the total investment cost of the project or on the cost of power generation per unit of electricity produced. Rather than providing upfront support based on investment costs, tender mechanisms typically rely on the power generation costs per unit of electricity. In this approach, bidders offer renewable electricity at a fixed price per kilowatt-hour over a specified period. The bidder who requires the least financial support wins the tender and gains exclusive rights to benefit from the granted support [51].

The main factor shaping the global renewables energy transitions is technology learning, which is influenced by two key factors: technology costs and deployment rates. The relationship between deployment and costs can be represented in experience curves, which show costs as a function of cumulative deployment (experience) [52]. According to Breetz et. al. [52] politics is the hidden dimension of experience curves that influences both, costs and deployment. Therefore they argue, that different policies shape costs and deployment at different stages of the experience curve. This means that during the phases of initial growth, stable growth and when the phase of stagnation should be ended, different policies are useful to sustainably re-accelerate deployment.

During the formative phase the political aim is to introduce the technology to the market. This is called technology push and a good measure to reach this is to offer funding for R&D. During the accelerating growth the technology needs to get more competitive with other technologies in order to be able to grow further without support, which is called market pull. This can be achieved by introducing targets and RES standards, offering feed-in-tariffs (FIT) or feed-in-premiums (FIP) or giving grants and credits. After a technology has reached the stable growth phase, the aim is to maintain the high growth for a long period of time and manage the opposition. Too reach this, targets should be ratched up, permitting processes have to be simplified and tradable green certificates can be introduced. It is also useful to switch to tendering systems instead of feed-in-tariffs. If the growth is already slowing down and has to be re-accelerated, targets should be further ratched up, the permitting process also should be simplified more and land could be designated to a specific renewable energy [53].

However, moving along the experience curve does not guarantee the right policies, which makes policy learning necessary. This is the process of adapting policies over the lifetime of a technology and gaining knowledge about the use-cases of different policies in different stages of the experience curve of a technology. Policy learning implies that policymakers and other stakeholders learn from their past experiences and adjust their behaviors, strategies, and policy objectives accordingly. This process leads to a refinement and improvement of policies over time, as knowledge is gained for future decision-making and actions through insights from practical experience [54]. Another mechanism of adopting policies appropriate to the current stage is policy diffusion, which means that countries are likely to adopt politically feasible policies from their neighboring countries with similar political and economic conditions [55].

Policy and technology are showing parallels, as technology also possess learning and diffusion mechanisms, like described in Section 2.1.

3

Methods

This chapter describes the methods used in this work. The fundamental method to investigate the phenomena of stagnation and re-acceleration in solar PV and onshore wind in different countries are case studies, more specifically structured case comparison. Furthermore the criteria utilized to identify periods of stagnation and subsequent re-acceleration is outlined. In addition, the systematic approach used to select cases and the structure of the case investigation is described.

3.1 Case studies and case comparison

Case studies are a commonly used method to search for causal explanations based on a logically related theoretical argument that produces testable implications [56]. By examining specific aspects of historical episodes in detail, case studies aim to develop or evaluate historical explanations that might have broader applicability to other events. Because it is a very intuitive method, for a considerable period of time there was no systematic development of methods for it [13]. According to George and Bennett [13], cases are defined as instances of a class of events, which refers to a phenomenon of scientific interest that the analyst chooses with the goal of developing theory about the similarities or differences among cases in this class of events.

Levy [56] categorizes case studies based on their research purposes:

- Idiographic case studies, that want to describe or understand a single case
- Hypothesis-testing case studies
- Plausibility probes, that are comparable to pilot studies in experimental or survey research.
- Hypothesis-generating case studies

The last category of case studies, the hypothesis-generating case studies are the most important for this work and therefore explained further. These kind of case studies aim to generalize beyond the data by investigating one or more cases to develop more general theoretical statements, which can then be tested using other methods. Case study analysts are able to suggest further explanatory and contextual variables, causal mechanisms, interaction effects, and scope conditions [57], but as the name says they only construct hypothesis, not theory. Theory, in this context, refers to a logically interconnected set of propositions, and case studies provide insufficient constraints to generate robust theories. However, case studies can be helpful to explain cases that do not fit to existing theoretical explanations and therefore refine or replace existing hypotheses. A significant contribution of hypothesis generating case studies is the specification of causal mechanisms, which is a leading research objective of many case study analysts, as well as exploring reciprocal causation and endogeneity effects [13]. Case study researchers get inside the “black box” of decision making [58].

There is a variety of case study design and selection strategies and it is crucial that analysts state their selection criteria for cases.

George and Bennett [13] describe the method of structured, focused comparison. In this context, "structured" means that the researcher collects general questions that reflect the research objective and asks these questions of each studied case to guide and standardize the data collection and systematize the comparison and cumulation of the outcomes.

On the other hand, "focused" means that only certain aspects of the historical cases are analyzed. This focused approach allows researchers to concentrate on the most relevant aspects for their research objectives. The requirements for this approach are to clearly identify classes and sub-classes of events of which a group of cases or a single case contain of. The research objective and related strategy have to be defined and asked of each case and variables of theoretical interest, that enable policymakers to influence outcomes, should be employed.

The method of case studies offers some strong advantages. High levels of conceptual validity are reached and the indicators that best represent the theoretical concepts of interest can be identified and measured. Additionally, new variables and hypotheses can be identified through the analysis of outlier cases, causal mechanisms can be analyzed in individual cases, and the conditions that activate this causal mechanism can be identified. Furthermore, complex causal relations can be modeled and assessed [13].

However, there are also limitations and trade-offs. One concern of statistical researchers is that there could be a “selection bias” [59], where case study analysts may deliberately choose cases with similar outcomes, which can be appropriate in some instances but not in all. Moreover, case studies can only make estimated conclusions on how many gradations of a variable affect the outcome in a particular case. They are also accused for having a “degrees of freedom problem”, which is a term for the potential inability to differentiate between competing explanations on the base of evidence. Furthermore, case studies lack representativeness, what amounts to a trade-off among the aims of reaching theoretical parsimony, establishing explanatory richness, and keeping the number of cases manageable [13].

In this work cases are chosen following specific criteria that aim to create a range of cases that allow a structured comparison. In order to be able to compare the selected cases, they have to be investigated. For this purpose a case analysis protocol is created and used to guarantee the same approach for every case investigation.

3.2 Case selection

The case selection focuses on two mature renewable electricity sources – solar PV and onshore wind – and the process unfolds in two stages. In the first step, all cases demonstrating stagnation followed by re-acceleration in solar PV or onshore wind energy deployment are identified according to Section 3.4. A case is constituted by a combination of a country and an energy source that meet specific criteria: the total electricity system size must exceed 30 TWh, and the share of the respective energy source must surpass 1% by 2021. This initial screening yielded a total of 83 cases, of which 17 exhibited stagnation followed by re-acceleration. These identified cases are listed in Table 3.1.

The second step is a narrower selection of six cases for in-depth analysis, keeping an eye on holding the balance between solar PV and onshore wind cases. The refined selection criteria aim to choose the most illustrative cases, considering various factors such as what are the most prominent cases with clear patterns of stagnation and re-acceleration. The occurrence of multiple stagnation and re-acceleration phases in specific cases is an additional criteria. Moreover, efforts are made to ensure comparability among selected countries by considering factors like geographical location and environmental conditions relevant to the energy source. Furthermore, for one country there is one case of solar PV and one onshore wind case to enable comparison between the different sources, within the same national context.

The steps of the process are depicted in Figure 3.1.

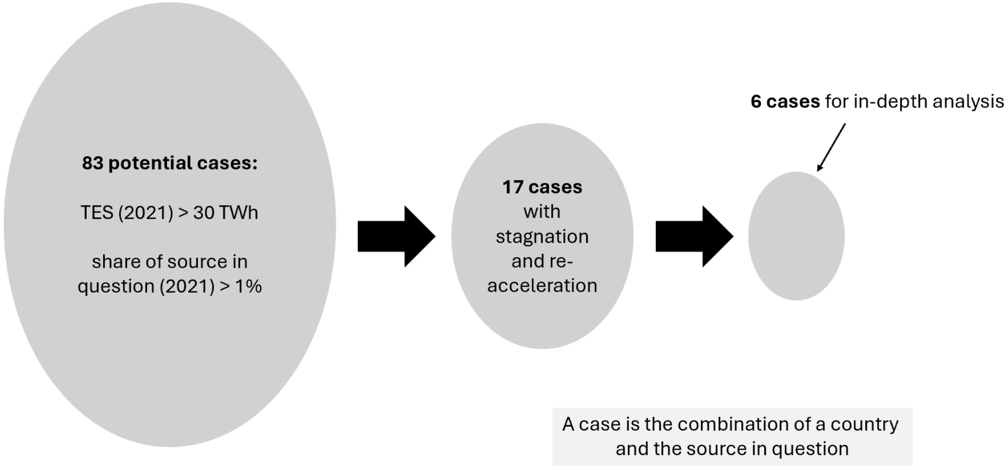


Figure 3.1: Illustration of the different steps of the case selection process.

The following paragraphs briefly explain why specific cases were selected.

Germany (DE) was chosen for solar PV due to its significant system size during both its stagnation in 2012 and re-acceleration in 2017, with electricity generation reaching 628.34 TWh and 644.04 TWh, respectively. Countries with larger energy systems face greater challenges in achieving high shares of renewable energy, necessitating a higher absolute capacity of solar PV installations. Germany's solar PV share rose from 6.12% in 2017 to 10.71% in 2022 during its period of re-acceleration.

Spain (ES) and Greece (GR) were selected for their clear solar PV growth trajectories. Both countries, located in southern Europe, offer valuable comparability in terms of solar PV conditions while possessing unique policy frameworks and industrial landscapes. Stagnation began around their respective take-off years, with Spain experiencing its stagnation in 2008 and Greece in 2013. However, their solar PV shares at the onset of stagnation differed significantly, with Spain at 0.83% (one year before take-off) and Greece at 6.39% (one year after take-off). Both countries had their re-acceleration in 2018. Notably, Spain's system size is five times larger than that of Greece, highlighting a substantial difference between the two nations.

Austria (AT) has a long wind energy history, with its initial growth dating back to 2004. Notably, Austria experienced two distinct periods of stagnation followed by re-acceleration. The first stagnation occurred between 2006 and 2011, while the latest episode was observed from 2019 to 2020, only showing signs of a beginning re-acceleration. Remarkably, during the second stagnation phase, the share of onshore wind power had already reached 10.51%, which indicates a mature and established presence in Austria's energy landscape.

Denmark (DK) stands out as an early pioneer in wind energy, with its take-off year in 1989. Renowned as a global leader in wind power, Denmark played a pivotal role in leading the adoption and advancement of wind technology. The stagnation period began in 2002, when wind power accounted for 12.42% of the energy mix. The re-acceleration phase, which commenced in 2008, pushed Denmark to expand its share of onshore wind to a remarkable 55% by 2022. This growth trajectory underscores the effectiveness of strategies implemented to overcome the stagnation phase in Denmark.

To assess whether similar mechanisms drive the slowdown and re-acceleration of wind and solar PV or if these technologies operate independently, Spain (ES) was selected as a case study for both technologies. The proximity of the stagnation years and simultaneous re-acceleration in 2018 suggests a potential correlation, indicating shared underlying factors for both technologies at least for the re-acceleration. Notably, Spain exhibited the highest share of onshore wind power among the selected cases, standing at 18% during the stagnation year of 2012.

However, the selection has a limitation in its focus on OECD countries, particularly EU members. These nations have a longer history with renewable technologies due to their early adoption of renewable technologies [3]. Consequently, they are more likely to have experienced periods of stagnation followed by re-acceleration [3].

While there are potential cases in developing countries like the Philippines (PH) and Pakistan (PK), as well as newly joined EU member states such as the Czech Republic (CZ) and Bulgaria (BG), they present challenges. The Philippines show more of a slowdown, and the re-acceleration is not as evident. Pakistan's wind re-acceleration is slow and just beginning, while the Czech Republic and Bulgaria are only showing early signs of re-acceleration and therefore do not provide sufficient data. The same applies to New Zealand (NZ), that would be an OECD country but not a member in the European Union.

The following Table 3.1 summarizes the important data about the countries with stagnation and subsequent re-acceleration and highlights the selected cases:

Table 3.1: Summary of all the countries with stagnation and following re-acceleration of solar PV (S) and onshore wind power (W). The orange marked cases are the finally selected ones.

Country	Techno-logy	Share 2022 [%]	Size 2022 [TWh]	Share stagn. [%]	Size stagn. [TWh]	Share re-acc. [%]	Size re-acc. [TWh]	Year of stagn.	Year of re-acc.	Take-off year
Belgium	S	7.74	95.15	3.23	81.73	3.9	84.93	2013	2017	2011
Bulgaria	S	3.36	50.65	3.23	43.04	3.65	40.22	2013	2020	2012
Czech Republic	S	2.95	84.98	2.48	86.61	2.77	83.73	2012	2021	2011
Germany	S	10.71	560.55	4.27	618.34	6.12	644.04	2013	2018	2009
Denmark	S	5.81	34.42	1.5	34.42	3.25	29.51	2013	2019	2013
Spain	S	11.51	285.16	0.83	310.67	4.69	271.87	2009	2019	2009
Greece	S	12.42	52.35	6.39	57.12	7.12	53.25	2014	2018	2012
Italy	S	9.74	284.73	7.52	287.07	8.74	286.39	2013	2021	2011
Philippines	S	1.6	112.81	1.27	94.39	1.36	102.49	2017	2020	2016
Austria	W	10.56	65.92	2.81 10.51	62.28 70.86	3.12 9.81	62.26 69.19	2007 2017	2011 2021	2004
Denmark	W	55	34.42	12.42	39.28	18.92	36.62	2003	2008	1989
Spain	W	21.71	285.16	18	293.77	18.72	271.87	2010	2019	1999
Finland	W	16.13	72.66	7.14	67.12	8.35	69.98	2017	2018	2014
Netherlands	W	17.72	121.25	7.18	113.83	9.53	120.79	2016	2019	2003
New Zealand	W	7.26	44.1	4.48	43.27	5.28	43.18	2011	2021	2005
Pakistan	W	2.71	152.17	2.26	139.9	2.1	136.87	2018	2020	2017
Poland	W	10.98	179.73	7.58	166.09	9.27	163.04	2016	2019	2010

3.3 Structure of case investigation

Chapter 4 analyzes solar PV and onshore wind deployment in different countries, specifically how it is influenced by unique historical, market, and environmental factors. By considering these diverse influences, a systematic comparison of the different trajectories is possible.

Before each case is analyzed individually, the international solar PV market dynamics, developments relevant to the specific renewable energy source and EU policies are examined. Insights into emerging market forces and global trends provide important context for understanding each country's position within the international market.

To ensure a structured and focused approach for the comparison of the different cases in Chapter 5, all the case investigations follow the same structure:

In the first step the trends in energy supply and demand and dependent on electricity imports and exports of the country are examined. Factors such as the sources of energy that are substituted by renewables, the amount of imported and domestic resources, the country's self-sufficiency ratio in energy production, and any energy security concerns that may exist are explored by investigating data from IEA [60].

Afterwards, the focus lies on the country's grid condition and international trading possibilities. Understanding the grid's capacity, reliability, and interconnections with neighboring countries provides insight into the challenges for integrating renewable energy sources into the existing energy system.

Moreover, it is investigated whether the country had developed a domestic manufacturing industry in the solar PV or onshore wind energy sector. This aspect is crucial as it could help explaining political decisions.

Furthermore, the country's geographical and environmental conditions that influence renewable energy deployment in each country are investigated. Factors such as wind potential, solar irradiation, the country's landscape and the geographical location play an important role.

The next step is to identify the moments in the country's renewable energy journey where deployment of onshore wind or solar PV stagnated and then experienced a re-acceleration according to the procedure in Section 3.4. Understanding the factors that led to these turning points provides insights into the drivers and barriers to renewable energy deployment with respect to the maturity of the renewable source.

The last section describes the country's solar PV or onshore wind trajectory from initial growth to any periods of stagnation and subsequent re-acceleration. Special attention is given to the three perspectives by explaining the evolution of policies. A a systematic analysis of available policy documents, academic literature and reports was carried out to explain these political decisions relying on the factors of the socio-technical and techno-economic perspective. Additionally, the normalized capacity growth rates, like described in Section 3.5, before and after stagnation, as well as based on the whole curve-fitting are reported.

By adopting a structured approach, the Results chapter of this thesis (Chapter 4) offers a comprehensive analysis of renewable energy deployment in different countries. The structured comparison by applying the three perspectives helps to identify correlations between events and can offer insights into causal links and mechanisms.

3.4 Criteria of stagnation and re-acceleration

The method utilized to identify periods of stagnation and re-acceleration relies on visual analysis of deployment curves. This involves plotting both the cumulative installed capacity and the annual additions in deployment on the same graph, as illustrated in Figure 3.2. The capacity data source is IRENA [61], while generation data was taken from IEA [60] and IRENA [61] for onshore wind. In this representation, the cumulative installed capacity is depicted as a blue area, while the annual additions are shown as red bars. Additionally, a red dotted line representing the 3-year-average of the additional capacity is included.

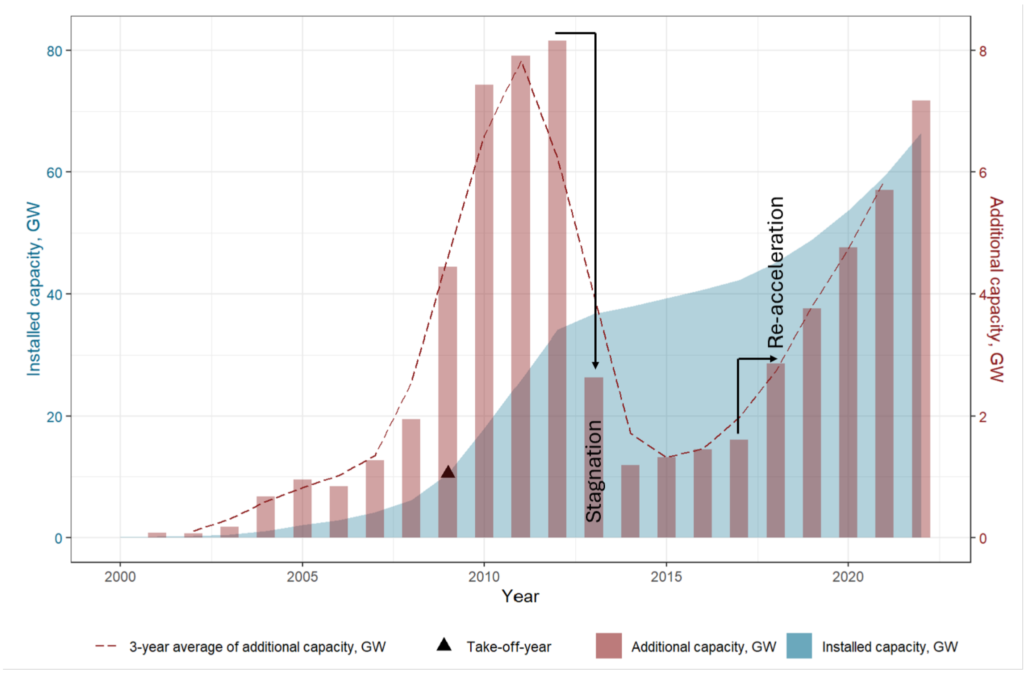


Figure 3.2: Example of the German solar PV growth curve with cumulative installed capacity and annual additions in deployment.

The cumulative installed capacity provides an indication of when stagnation and re-acceleration occur, as the slope of the curve decreases and approaches almost zero during the period of stagnation or is at least much slower, and rises again during re-acceleration. However, the annual additions offer more precise timing, highlighting the exact years when stagnation or re-acceleration commence. Specifically, for periods of stagnation following years of high deployment, the year when stagnation begins is identified as the one showing the first significant decrease in deployment, in Figure 3.2 it is 2013. Conversely, for re-acceleration, it is the year exhibiting the first substantial increase in deployment, in Figure 3.2 it is 2018.

3.5 Growth metrics

To measure and compare growth, various growth metrics have been developed, tailored to specific use cases.

The average growth rate R can be calculated using the following equation 3.1. It can be calculated over one or more years, in this work it will be calculated over three years.

$$R = \frac{S_1 - S_0}{N \cdot \overline{T_{01}}} = \frac{S_1 - S_0}{N \cdot (T_0 + T_1)} \cdot 2 \tag{3.1}$$

T refers to the total electricity supply, while S represents the electricity generation from the source in question. The indices 0 and 1 denote different points in time. $\overline{T_{01}}$ is the average of the total electricity supply between the years 0 and 1. N denotes the time span in years.

This growth rate captures the actual growth and reflects the systemic significance of the change, as it normalized to the size of the electricity system. This normalization makes it comparable across countries. However, it has the limitation that it may not perform adequately for longer periods of time [23].

For characterizing the periods of initial and restarted growth, the maximum 3-year average growth rate for each period is used, which means N is equal to 3 in this case.

At the inflection point of an S-curve, the growth rate is referred to as the maximum growth rate G. To measure it, Cherp et. al. [3] developed a new metric, in which growth curves are fitted to the deployment of wind and solar over time.

The maximum growth rate G for the logistic model can then be calculated using Equation 3.2.

$$G_{log} = \frac{L \cdot k}{4} \tag{3.2}$$

For the Gompertz model, G can be calculated using Equation 3.3.

$$G_{gmp} = \frac{L \cdot k}{e} \tag{3.3}$$

L and k are both variables utilized in the respective growth model, which are determined by fitting algorithms. L represents the maximum reachable quantity, which stretches the curve vertically with its change, and k compresses the curve horizontally, and therefore has impact on the slope of the curve [3]. G can be normalized to the total electricity supply at the inflection point to ensure comparability across different countries [3].

Based on the fits, the inflection point t_0 can be identified, along with a diagnostic measure of "maturity", that is used to assess the robustness of G and classify growth as accelerating, stable, or decelerating. Maturity is defined as the ratio of the value of the fitted curve in the last observation year to the asymptotic value L [3].

3.6 Import dependency of electricity supply

Import independence or self sufficiency plays a crucial role in ensuring security of supply. In the realm of electricity, import dependence typically manifests as reliance on imported fossil fuels and, to a lesser degree, on imported electricity. Therefore, nations aiming to decrease their import dependence may opt to increase domestic fossil fuel production or transition towards non-fossil sources of electricity generation, however, the second option should be preferred [62].

The import dependence of electricity supply is determined by several factors, according to Vinichenko [62]. Firstly, it considers the import dependence of individual generation sources, such as fossil fuels (coal, oil, and natural gas), as well as the proportion of these sources in the national generation mix. Additionally, it accounts for net imports of electricity. Specifically, import dependence calculations focus only on fossil fuels, where renewable energy sources are classified as domestic, and nuclear energy is treated as "quasi-domestic." Import dependence of a fossil fuel is determined by the proportion of domestic supply met with imports, calculated as the ratio of net imports (imports minus exports) to domestic supply (domestic production plus net imports), like defined in Equation 3.4.

$$D_f = min\left(0, \frac{I_f - E_f}{P_f + I_f - E_f}\right) \tag{3.4}$$

In this equation, D_f represents the import dependence of the fuel f, P_f denotes its domestic production, I_f indicates total imports of the fuel, and E_f stands for its exports. According to this definition, for a net exporter of the fuel (a country with negative net imports), import dependence is zero, indicating full independence of supply.

The import dependence of electricity supply is calculated according to Equation 3.5.

$$D_{el} = \sum_f D_f F_f + \frac{I_{el} - E_{el}}{P_{el} + I_{el} - E_{el}} \tag{3.5}$$

where D_{el} represents the import dependence of electricity supply, D_f denotes the import dependence of the supply of fossil fuel f calculated according to the previously described Equation 3.4, and F_f indicates the share of this fuel in the generation mix. The second term represents the contribution of electricity exports and imports to import dependence. I_{el} stands for the total electricity imports, E_{el} indicates the electricity exports and P_{el} represents the country's domestic electricity production. This share is determined based on the amount of electricity generated from the fuel, rather than its primary thermal content. The calculation logic follows a similar approach to that used for fossil fuels as described earlier. However, this term can be negative for a country that is a net exporter of electricity [62].

4

Results

This chapter explains the trajectories of renewable energy deployment across selected nations. Each country is shaped by its own historical, market, and environmental influences. Within this framework, the examination of renewable energy deployment follows a structured approach, characterized in Section 3.3.

4.1 Global and regional context

The following section gives an overview about the national and regional context influencing energy transitions. First, the international solar PV market development will be described. Second, regional and EU policies will be addressed.

4.1.1 International solar PV market

In order to understand the dynamics within a particular country, comprehensive knowledge about the global solar PV market is indispensable. Understanding the broader international context of solar PV is crucial for a thorough analysis of local developments and trends. Therefore, this section provides an overview of the evolution of the global PV market.

Until 2007, Germany and Japan had been the dominant players in both PV installations and production, covering the entire value chain, when the global PV industry competition was weak. But then the globalization of the PV market began and China entered into the market, supported by government initiatives and led by its export-oriented strategy [63], [64]. The beginning of Chinese mass-production intensified global competition, leading to unexpected sharp declines in price as depicted in Figure 4.1 [65]. The actual importation price (P3) ended up lower than the anticipated price (P2) due to the beginning mass production of solar cells and modules. Consequently, this price drop led to a surge in installations, surpassing the expected quantity (Q2) to reach Q3. However, the figure also highlights a drawback of this substantial price drop: a decline in European, specifically in German production quantity from QG2 to QG3 [48]. Effectively, Germany and other countries were increasingly subsidizing Chinese solar PV manufacturing.

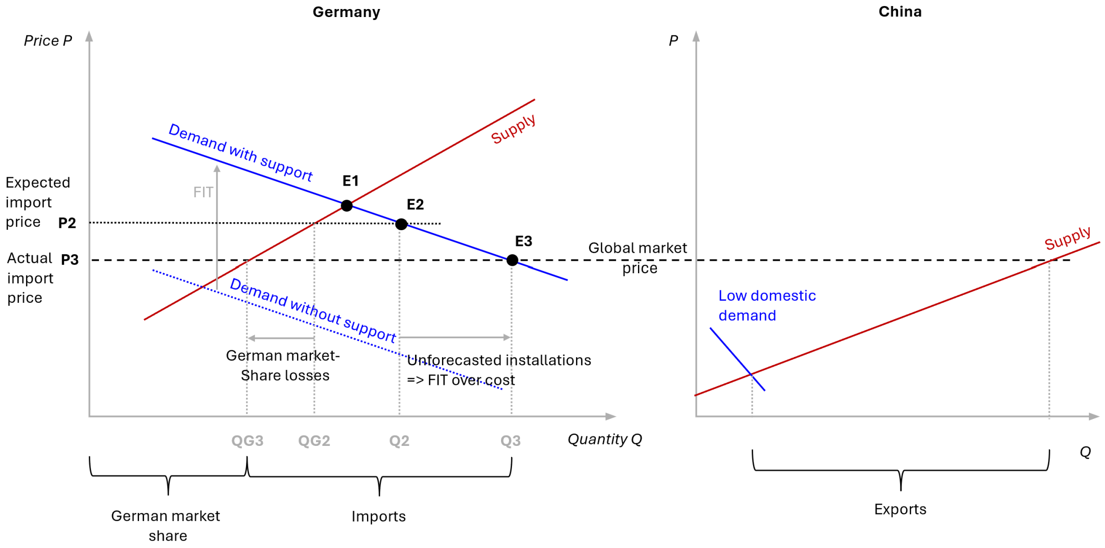


Figure 4.1: Effects on prices and installation and cell production quantity after China's emergence in the German market; adapted from [48].

In response to the global economic recession in 2008 and the decreasing prices, many European countries were compelled to scale back their policy support for solar PV installations, as it caused high costs [48]. However, this measure did not yield the anticipated results of limiting the overinstallation. Instead, it spurred fiercer competition in the global PV market, prompting Chinese manufacturers to further decrease production costs and expand their production lines despite the economic downturn [48]. The resultant oversupply of PV materials and equipment in the global market destabilized the PV market, so it lost its equilibrium. Consequently, numerous European companies across the entire PV value chain either declared bankruptcy or ceased production due to their inability to withstand global price pressures in the period of 2009 to 2012 [48]. However, China's export-oriented strategy, reliant on overseas markets, also suffered from declining demand, leading to closures of Chinese firms as well [66].

4.1.2 International and EU policies

To address climate change and secure international commitment, various international and regional, including EU, policies have been introduced. These policies encompass a range of initiatives to reduce greenhouse gas emissions, promote renewable energy deployment, improve energy efficiency, and simplify international cooperation and collaboration on climate action.

The first important international treaty was the Kyoto Protocol in 1997, that set binding emission reduction targets on developed countries. The total emissions have to be reduced by at least 5% during the period 2008 to 2012 compared to 1999 levels. The European Community signed the protocol in 1998 and in 2002, the EU ratified the Kyoto Protocol by the Directive 2002/358/EC. However, several industrialized countries refused to ratify the Protocol, for example the US and Australia. It eventually came to force in 2005 [67], [68].

In 2001, the European Commission set a directive (2001/17/EC) for promoting renewable energy usage in electricity generation. It set national targets for RES production for individual EU member states and demanded its adoption by the members [69].

In 2005, the European Union Emissions Trading Scheme (EU ETS) was introduced to help the EU meet its targets under the Kyoto Protocol. It is the world's first and largest carbon market and covers different sectors (energy, industry, aviation). Greenhouse gases emitted by business are capped and the companies can trade emission allowances. It covers 45% of the EU emissions [70].

In 2008, the EU Climate Action and Renewable Energy Package was introduced. It contains various legislative measures, one of them is known as the 20-20-20 rule, as greenhouse gases should be reduced by 20% by 2020 (compared to 1990) and the share of RES in the EU energy mix should be increased to 20%. Additionally, a 20% improvement of energy efficiency should be achieved by 2020. The EP 2009/28, known as the Renewable Energy Directive, was also part of it. This directive mandated all member countries to outline their targets for the share of renewable energy in their electricity mix. It is the successor of the Directive 2001/17/EC [71].

The Chinese solar PV industry experienced significant growth starting in 2009, resulting in panel price drops as discussed in Section 4.1.1 [48]. Consequently, the European Commission implemented trade barriers on Chinese solar panels in 2013 in an effort to protect the struggling European solar PV manufacturing sector, that could not withstand the competition and was in risk to decline. However, the barriers failed to rescue the industry and were consequently removed in 2018, also to help re-accelerating solar PV deployment in Europe [72].

The Paris Agreement, established in 2015, aims to mitigate global warming, with a primary objective of limiting the rise in average global temperatures to below 2°C, and ideally to 1.5°C, compared to pre-industrial levels. Unlike the Kyoto Protocol, which primarily targeted developed nations, the Paris Agreement involves commitments from both developed and developing countries [73].

The Powering Past Coal Alliance (PPCA) was launched at COP23 in 2017, after more governments introduced measures to end coal power generation, inspired by early movers like the United Kingdom and Canada. 27 national, provincial, state and city governments joined immediately by endorsing the PPCA Declaration and less than one month afterwards, the Alliance doubled its size and is continuously growing [74]

The European Green Deal, introduced in 2019, is the EU's long-term vision to become climate-neutral by 2050. It is an initiative, that encompasses a set of policies across sectors such as energy, transport, agriculture, and industry to reduce greenhouse gas emissions and promote sustainable development [75].

The REPowerEU plan of 2022 aimed at ending the European Union's dependence on Russian energy and emphasized the need of phasing out fossil fuels. The plan outlines measures to achieve a renewable energy share of 45% in final energy consumption by 2030 through saving energy, diversifying the energy supply and bolstering investments in renewable energy deployment [7].

The participants in the COP28 global renewables and energy efficiency pledge committed to collectively triple the global installed renewable energy generation capacity and double the global average annual rate of energy efficiency improvements by 2030, in order to meet the goal of the Paris Agreement [8].

4.2 Germany solar PV

Germany has been a pioneering nation in the context of solar PV, leading the way in promoting and adopting solar energy technology through progressive policies and widespread implementation.

General power supply and demand trends
Figure 4.2 illustrates the electricity supply in Germany categorized by fuel type and whether the fuel originates from domestic or imported sources. Overall, Germany's electricity demand, depicted by the black line, exhibited a gradual decrease after 2010, with periods of electricity exports observed. Examining the various sources of electricity production, Germany's extensive reliance on coal throughout its history becomes obvious. Despite possessing abundant domestic coal resources, including lignite and hard coal, Germany reduced first nuclear and since 2016 also coal usage, driven by its transition towards renewable energies, especially significant increases in wind and solar PV production. In fact, nuclear power was entirely phased out in 2023. While Germany historically operated numerous hard coal mines, economic feasibility lowered over time, leading to the closure of the last hard coal mine in 2018, despite decades of state subsidies dating back to the 1960s. Moreover, Germany primarily relied on hard coal imports, predominantly sourced from Russia, the United States, and Australia, contributing to the relatively high share of imported coal. Approximately one third of coal-generated electricity was derived from hard coal, while the remaining two-thirds were from lignite, a resource in which Germany had been the leading producer until China surpassed it in the early 2000s [76], [77].

Prior to 1990, when domestic coal dominated electricity generation, Germany maintained a high self-sufficiency rate according to the definition in Section 3.6, which then diminished with increased reliance on imported coal and gas. However, the reduction in nuclear power and the expansion of the renewables sector led to a resurgence in the self-sufficiency ratio, as it can be seen in Appendix A.1. Germany's energy security was largely unchallenged until Russia's attack on Ukraine, which underscored its dependence on Russian natural gas, albeit after the re-acceleration of solar PV deployment.

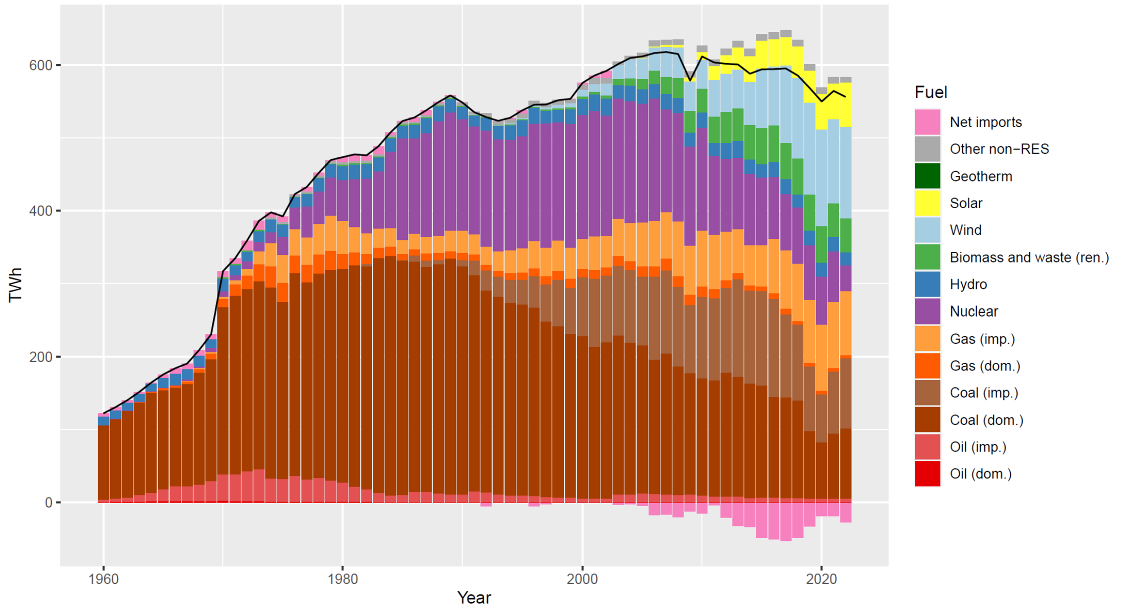


Figure 4.2: Electricity supply in Germany by fuel type and domestic or imported. Data: IEA Energy Balances [78], graph by V. Vinichenko.

Grid condition and interconnection

Germany's electrical grid is interconnected with neighboring countries, enabling the exchange of electricity. While there are no restrictions on electricity import and export within the European Union, surplus electricity generated in Germany's northern regions, particularly from offshore wind turbines, poses challenges as it exceeds local demand and neighboring countries' needs. Notably, Germany's grid infrastructure struggles to transmit excess energy from the north to the industrial hubs in the south. Efforts to bolster grid infrastructure and effectively integrate renewable energy sources are ongoing to ensure a reliable and efficient energy system [79].

Manufacturing

As already noted in Section 4.1.1, Germany once boasted the world's largest solar PV industry but was overtaken by China in 2007. The industry experienced continued growth until 2011, albeit at a slower pace from 2009 to 2011, before facing a sudden crash [48]. Numerous German companies across the entire PV value chain, such as Q-Cells, Schott Solar, and Bosch, either declared bankruptcy or ceased production due to their inability to withstand global price pressures [48].

Solar potential

In Germany the conditions for solar PV are less than optimal. One pivotal factor influencing a country's solar PV potential is solar irradiance, which denotes the amount of sunlight reaching the Earth's surface per unit area [80]. While Germany's solar irradiance levels are moderate compared to sunnier equatorial regions, advancements in solar PV technology, including enhancements in panel efficiency and design, have rendered solar PV production feasible even in areas with lower irradiance. Notably, solar irradiation is higher in southern regions of Germany, resulting in increased solar energy generation in those areas, as illustrated in Appendix A.2 [81].

Germany has a temperate climate characterized by mild summers and relatively cold winters. Cloud cover and precipitation are common throughout the year, which affects solar PV production. However, even on cloudy days, diffuse sunlight still contributes to solar energy generation. Germany's geographic location in Central Europe means it is situated at relatively high latitudes compared to sunnier regions near the equator [82]. Despite its northern latitude, Germany's flat terrain and expansive land area provide ample opportunities for solar PV installations, including rooftop solar panels on residential and commercial buildings, ground-mounted solar farms, and solar installations on industrial sites [83].

Stagnation and re-acceleration points

In Figure 4.3, the growth of installed solar PV capacity in Germany is depicted. Both, the cumulative installed capacity and the annual additions, are illustrated to facilitate the identification of stagnation and re-acceleration points, as described in Section 3.4. Stagnation is observed to commence in 2013, followed by a short period of constantly low deployment and a re-acceleration of growth beginning in 2018. Since then, the annual additionally installed capacity has exhibited steady growth. In Germany there was no complete stop of installations, only a slow-down. The average 3-year growth rate, calculated as described in Section 3.5, has a maximum value of $13.28\frac{MW}{TWh}$ before stagnation and $10.46\frac{MW}{TWh}$ afterwards. The maximum growth rate for the fitted curve is $8.03\frac{MW}{TWh}$, which can be reliably measured as the maturity is with 0.95 above 0.5, which means the inflection point has been passed.

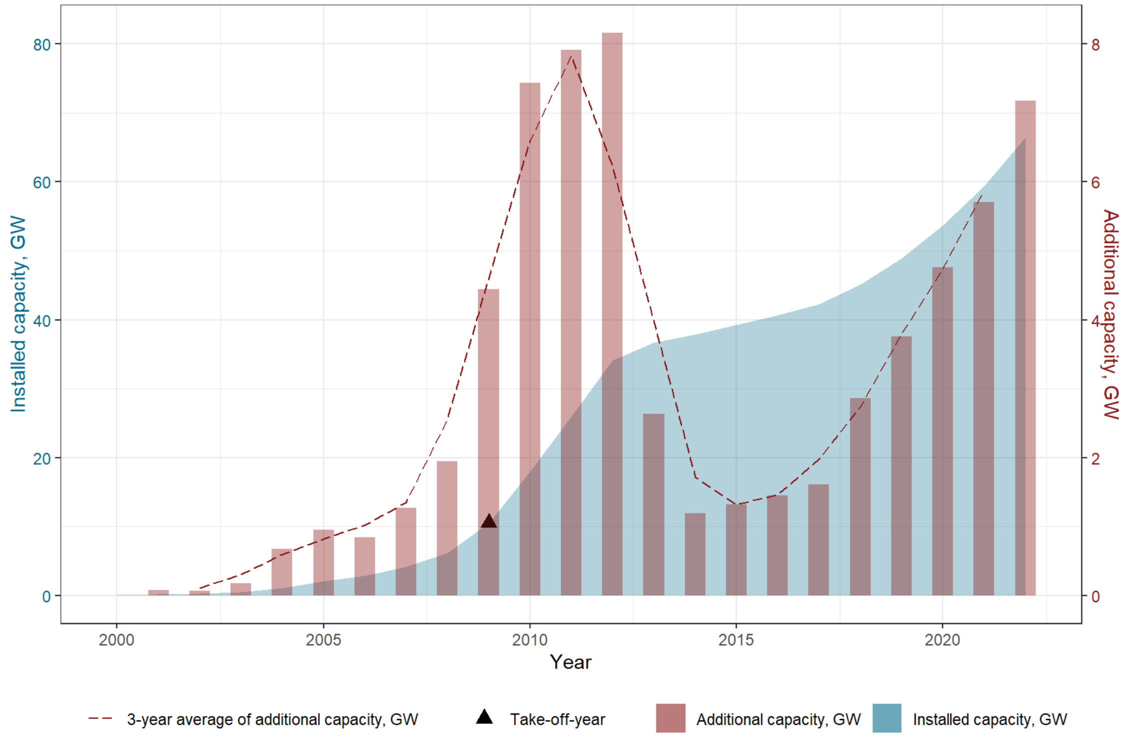


Figure 4.3: Change point diagnosis for Germany.

Initial growth

Germany experienced a significant surge in solar PV development during the period between 2000 and 2010, positioning itself as one of the pioneering nations in this domain [48].

The government's early efforts to promote renewable energies, dating back to the 1970s during the oil crisis, aimed to enhance national energy security, but also domestic manufacturing and export capability [43], [84]. However, the pivotal moment came with the enactment of the Renewable Energy Sources Act (EEG) in 2000, which provided the legislative framework necessary for advancing the country's transition toward greater reliance on renewable sources [85]. Central to this legislation was the introduction of the FIT scheme, designed to incentivize renewable energy production [85]. This scheme, guaranteeing a fixed feed-in tariff for 20 years, played a crucial role in driving Germany's solar PV boom in 2004 [86].

Concurrently, Germany implemented the 100,000 Solar Roofs Initiative (1999-2003), building upon the foundation laid by its predecessor, the 1,000 Solar Roofs Initiative (1991-1995) [85], [87]. To offset the conclusion of these initiatives, enhancements to the FIT scheme were introduced in 2004 [63], propelling Germany to global leadership in PV system installations since 2005, accounting for 32 % of global installations [66], [88].

The robust growth in solar PV deployment, coupled with early investments in research and development and collaboration between research institutions, universities, and industry stakeholders, facilitated the commercialization of the solar PV sector and spurred technological advancements [87], [89], [90]. Consequently, the sector witnessed a significant decline in prices since the 1980s [91]. Economically, this growth translated into higher profits and increased employment, as illustrated in Table 4.1 [92].

Table 4.1: Solar PV employment estimation in Germany (2003-2006: [93]; 2008-2012: [88]; 2013: [84])

Germany	2003	2006	2008	2009	2010	2011	2010	2013
Solar PV jobs	10,000	35,000	48,000	65,000	133,000	128,000	100,000	87,000

Domestic demand surpassed domestic cell production in 2004 and has consistently remained higher thereafter [48]. Consequently, Germany resorted to importing a part of the installed PV modules [94], [95].

In 2009, there was a rapid decrease in the price of solar PV systems, leading to a surge in deployment. This price drop was largely attributed to the increasing market share of Chinese cell producers in the global PV market, beginning around 2007 [48], as described in 4.1.1. The government responded to the price drops by reducing the FIT in order to curb the uncontrolled proliferation of installations, recognizing that they posed a financial burden and incurred unforeseen costs [48], [96].
The Chinese mass production also caused a reduction in the German market share within the solar PV sector, but the deployment sill increased, driven by the availability of cheaper products. While this shift resulted in job losses due to a shrinking industry, like Table 4.1 shows, the expanding deployment also created new employment opportunities [48].

Stagnation
In Germany, there was no complete stop in deployment, but a slow-down, that set in by 2013, prompted by another revision of the EEG. This revision was a reaction to the excessive and ineffective spending on subsidies, driven by the rapid deployment resulting from decreasing solar PV panel costs. Under the prior EEG version the deployment did not decrease, so this update entailed reduced FITs and established an overall expansion target of 52 GW, beyond which the EEG compensation would be zero. To facilitate this expansion, an annual extension corridor of 2,500 MW was introduced. Additionally, a monthly degression rate of 1% for PV systems put into operation from the beginning of each month was implemented. Furthermore, starting from November 2012, the concept of the "breathing lid" was introduced, adjusting the degression rate based on whether the annual expansion corridor was met or exceeded. Moreover, a market integration model was introduced for building systems with capacities ranging from 10 to 10,000 kW. From 2014 onward, the remunerable amount of electricity for systems commissioned from April 1, 2012, was capped at 90% per calendar year. Any excess electricity not eligible for remuneration could either be consumed or sold to the network operator at market value [97].

The European Commission responded to the challenge of competition from Asian competitors by imposing trade barriers, setting minimum prices on Chinese imports in 2013 [72].

Subsequent amendments to the EEG in 2014 introduced further reductions in FITs. Moreover, for new installations exceeding 500 kW, the requirement was established for electricity to be sold on the market by the system operator. The base degression rate, effective from August 1, 2014, was halved to 0.5 percent per month compared to the previous 1 percent. In cases where the target corridor was undershot by up to 900 megawatts, the degression decreased monthly to 0.25 percent. If the undershoot exceeded 900 megawatts but remained below 1,400 megawatts, there was no degression in the subsequent quarter. Additionally, from 2014 onwards, self-consumers with systems larger than 10 kW were required to pay a so-called EEG-surcharge [97].

Re-acceleration

Starting from 2017, financial support for all energy sources was determined through auctions, with technology-specific auctions ensuring that different types of renewable energies did not compete against each other [97]. The re-acceleration phase began in 2018 when the extension corridor of 2500 MW was exceeded for the first time since 2013, marking a substantial increase of 68% compared to 2017 [98]. Particularly noteworthy was the surge in solar PV deployment towards the end of December 2018, with installations totaling 376.6 MW out of 2960 MW [99]. This spike in deployments was largely attributed to declining PV prices. Starting from mid-2018, China's decision to scale back subsidies for new solar installations led to an oversupply of equipment, causing a global reduction in solar panel prices. Furthermore, the European Union's decision to lift import barriers on Chinese-made panels in 2018 contributed to this trend by further lowering prices, as it failed to sustain European manufacturers in the market and only slowed down deployment [100], [101].

The surge in solar PV installations in December 2018 also coincided with a significant number of completed tender projects. This can be attributed to the deadline for connecting photovoltaic open-space installations awarded in the pilot tender of December 2016, which expired on December 15, 2018 [99]. The introduction of a competitive process for determining payments to renewable installations above 750 kW capacity, instead of fixed FIT rates, through an EEG reform in 2016 further facilitated this growth [102]. Additionally, the Energy Collection Act passed in November 2018 outlined tenders for up to 4 GW of solar PV capacity between 2019 and 2021, which would not be subject to the 52-GW ceiling set by the government [100]. However, by January 2019, nearly reaching 46 GW of installed capacity, the 52 GW ceiling was already on the verge of being surpassed, indicating a strong willingness to invest in solar PV [100].

Another contributing factor to the increased solar PV deployment was the rising cost of CO_2 certificates and electricity, prompting industries and private homeowners alike to seek ways to produce their own electricity as a cost-saving measure. It also became more profitable to deploy low-carbon sources. Additionally, the growing trend towards heat pumps and financial incentives for private charging stations for electric cars further incentivized the production of self-generated electricity [103].

In conclusion, stagnation ensued as global manufacturing costs dropped, largely due to increased production in China, leading to a surge of installations and increased spending on subsidies without significant benefit to German panel manufacturing. The German policy-makers struggled to adapt to this new situation, in particular, by adjusting support policies. Additionally, the European Commission implemented import barriers to mitigate the impact. Subsequent re-acceleration occurred following the removal of these barriers, coupled with further decreases in solar panel prices and the introduction of more flexible support policies. Simultaneous nuclear phase-out and the beginning of coal decline at the end of the 2010s led to increased demand for low-carbon sources. Finally, European carbon policies also contributed to making solar PV a more attractive energy sources. A summary of the pivotal policies is illustrated in the following Figure 4.4.

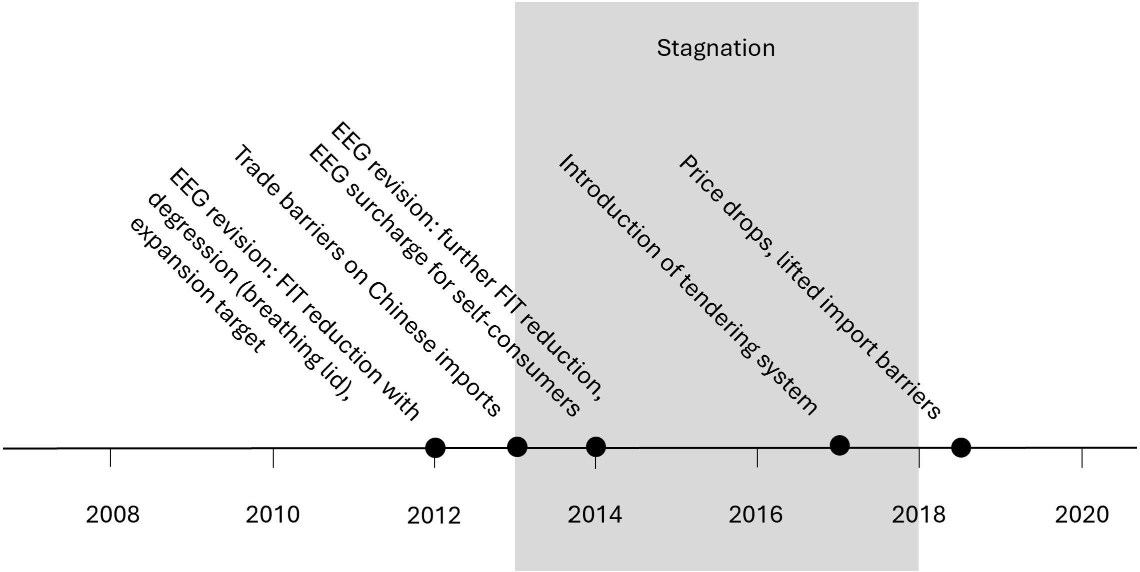


Figure 4.4: Timeline of pivotal German policies

4.3 Greece solar PV

Greece possesses immense potential for solar photovoltaic energy production, benefiting from its abundant sunlight and favorable climate, driving significant growth in the solar PV sector.

General power supply and demand trends

Until 2008, Greece experienced a consistent increase in electricity demand, primarily met by domestic coal and, starting from 1998, supplemented by imported gas, as shown in Figure 4.5. Following the global financial crisis in 2008, overall demand decreased, albeit with some fluctuations. Correspondingly, the use of domestic coal declined rapidly. In 2019, the government announced a lignite phase-out by 2028 [104], leading to a larger decrease of coal in that year. Since 2001, demand consistently exceeded supply, leading to a significant reliance on electricity imports. Presently, imported gas constitutes the largest share of Greece's electricity system, followed by wind power, which has shown continuous growth since 2000. Peaks in demand in 2007 and 2008 were met by increased imports of gas, resulting in a peak in import dependency. The emergence of solar PV growth in 2009 suggests a potential correlation with these events. Additionally, from 2013 to 2020, electricity imports surged alongside solar PV stagnation, indicating potential government efforts to drive re-acceleration.

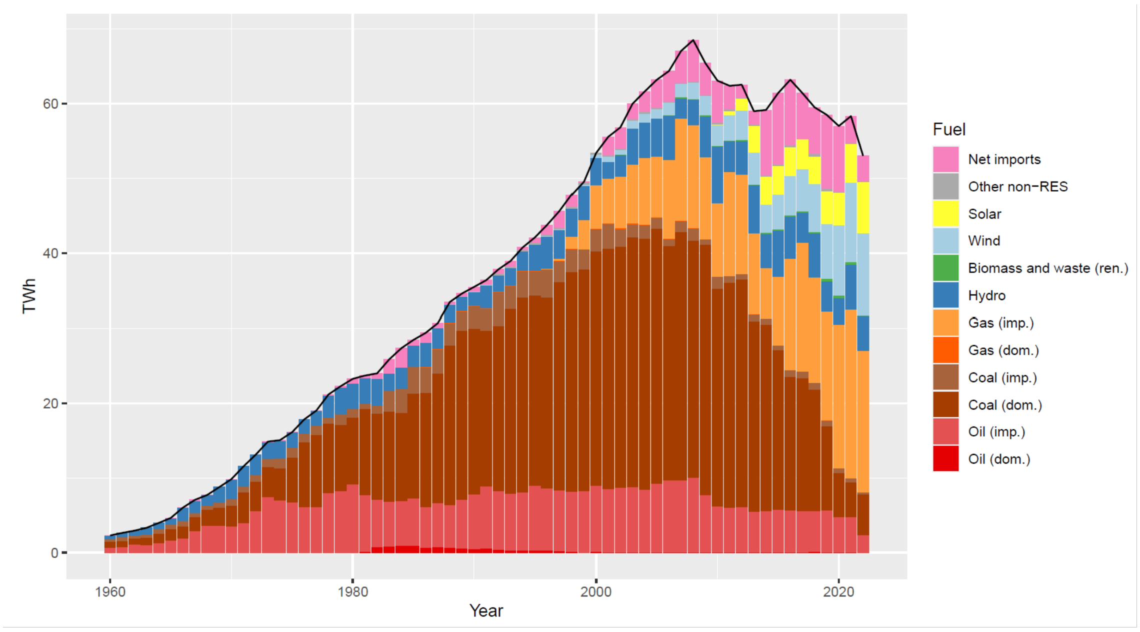


Figure 4.5: Electricity supply in Greece by fuel type and domestic or imported. Data: IEA Energy Balances [78], graph by V. Vinichenko.

Grid condition and interconnection

The condition of the Greek electricity grid is relatively modern and well-maintained, with ongoing efforts to expand its infrastructure in order to meet the requirements for the growing renewable sector. Currently, a lot of the islands are still not connected to the mainland grid, but this should be reached until 2030. On islands the main electricity generation is oil-fired, which explains the consistent amount of oil in the electricity supply shown in figure 4.5 [105].

In terms of interconnection with other countries, Greece has been working on enhancing its connections with neighboring countries to strengthen energy security and facilitate cross-border electricity trade. Currently, Greece is connected to its neighboring countries through several interconnection points, including interconnections with Bulgaria, Albania, Italy, and North Macedonia, that should even be increased in the next years. Additionally, an interconnection with Egypt is established [105].

Manufacturing
Greece does not have a substantial domestic solar PV manufacturing sector, instead the country relies on imported solar PV panels and equipment to achieve its renewable energy goals. This dependency on imports comes from factors such as the absence of major manufacturing facilities, the inability to ensure competitive production costs, and the prevalence of well-established solar PV markets in other regions [106].

Solar potential
Greece has favorable conditions for solar PV generation due to its abundant solar irradiation and geographical characteristics. The country receives ample sunlight throughout the year, with high levels of solar irradiation, especially in regions with clear skies and minimal cloud cover [107]. In Appendix A.3 the solar irradiation over the whole country is shown.

Geographically, Greece's diverse terrain, including vast plains and mountainous areas, provides various opportunities for solar PV installations. Coastal regions, islands, and areas with lower elevation typically experience higher levels of solar irradiation, making them ideal locations for solar PV projects. Additionally, Greece's latitude, which lies within the solar-rich Mediterranean region, further enhances its solar energy potential [107].

Stagnation and re-acceleration points
The Greek solar PV growth curve is shown in Figure 4.6. The cumulative installed capacity and the annual additions, are illustrated to facilitate the identification of stagnation and re-acceleration points. The initial growth in solar PV deployment started in 2009 and the annually added capacity grew in big steps until 2013, but suddenly became almost zero in 2014. It stayed like this until the growth started to re-accelerate in 2018, almost showing the same growth pattern like in the initial growth phase but with slightly higher annual capacity additions. The re-accelerated growth seems to be stable. The average 3-year growth rate has a maximum value of $12.98\frac{MW}{TWh}$ before stagnation and $16.28\frac{MW}{TWh}$ afterwards. The maximum growth rate for the fitted curve is $9.15\frac{MW}{TWh}$. The inflection point is still in the future, which is indicated by the maturity 0.46 being below 0.5. But as the two values are close together, the maximum growth rate can still be considered plausible.

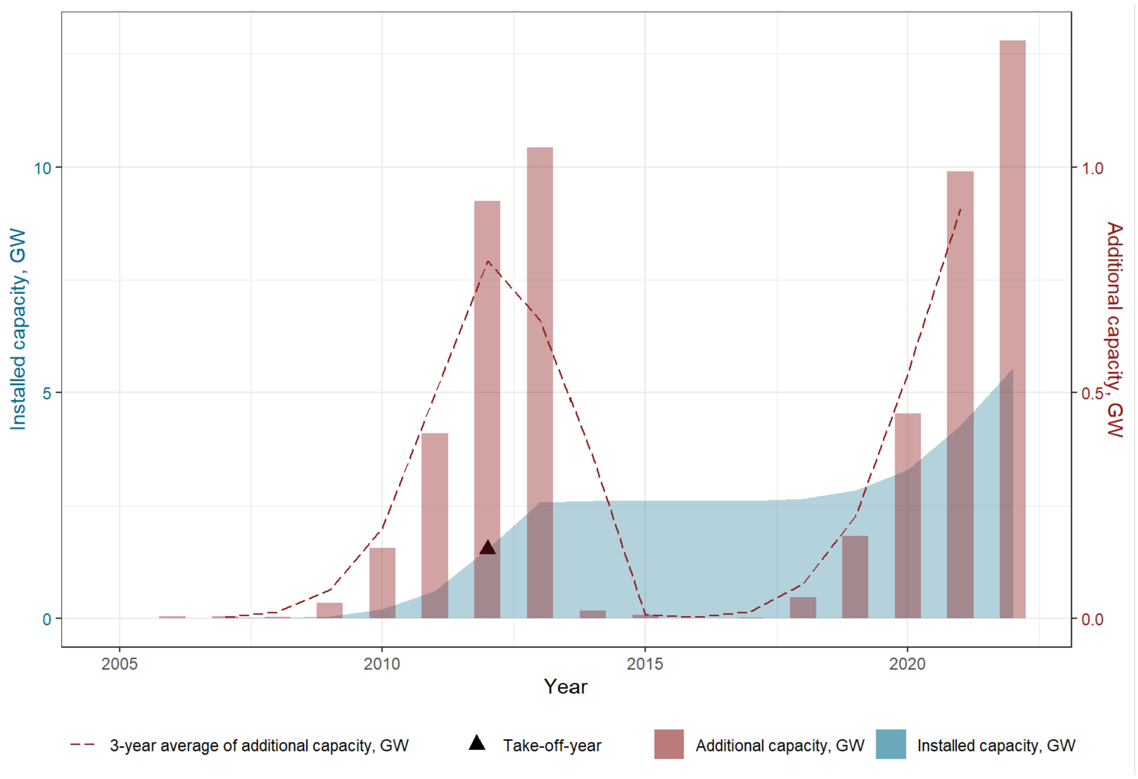


Figure 4.6: Change point diagnosis for solar PV in Greece.

Initial growth

The Greek legislature acknowledged the importance of renewable energy sources in the Greek energy landscape earlier than the broader European community. In 1994, significant legislative events unfolded. Internationally, Greece ratified the Climate Change Convention through Act 2205/1994. This pioneering legislation granted private entities the right to produce renewable energy and sell it to public power companies at a favorable tariff, aiming to boost renewable energy penetration [108].

Five years later, Act 2742/1999 recognized the need for a special spatial plan for renewables due to Greece's decentralized geography, particularly its islands. In the same year the integration of energy from renewables into the grid was prioritized for the first time. However, renewable energy development did not continue due to complex licensing procedures and the absence of a spatial plan [109].

In 2001, the European Parliament issued Directive 2001/77, urging member states to promote renewable energy investments. Greece incorporated this directive into law with Act 3468/2006. This legislation aimed to guarantee renewable energy grid connection and set a target for renewables to contribute at least 20% to the energy balance by 2010. Additionally, it introduced an FIT pricing system, spurring increased investor interest and the implementation of numerous renewable energy projects. Thus, Act 3468/2006 marked a significant shift in Greek energy policy towards renewable energy pricing and promotion [110].

Examining the growth curve depicted in Figure 4.6, it can be seen, that it took some time for the policies to show impacts, as the country had to go through the formative phase. Licensing procedures remained lengthy, spanning approximately three to four years, followed by a construction phase lasting around three years. Consequently, the peak years are observed to be 2012 and 2013 [110].

Act 3734/2009 changed Greece's renewable energy landscape significantly by introducing substantial reductions in FITs, amending the previous legislation of Act 3468/2006. The gradual decrease in FITs commenced in August 2009 and continued on a semester basis [110]. This law also extended the duration of the Power Purchase Agreements from 10 to 20 years and mandated that the contracted FIT would remain unchanged for 18 months from the date of signing the Power Purchase Agreement. However, if activation occurred after this 18-month period, the guaranteed tariff would no longer be maintained and would instead be set based on the provisions applicable in the equivalent semester of its activation, which causes an uncertainty for the renewable energy producers [111].

In 2010, Act 3851/2010 aligned Greece with the mandated European target for renewable energy, known as the 20-20-20 rule, which outlined ambitious goals for RES contributions to electricity generation, gross energy consumption, heating and cooling, and transportation by 2020. Moreover, the legislation aimed to simplify the licensing process, resulting in a surge of construction projects, as all the registered projects were permitted. Once more, the construction phase endured for approximately three years, thereby making 2013 the pivotal year when the impacts of this legislation became apparent [110].

Stagnation

The stagnation phase commenced in 2014, following concerns about the long-term financial sustainability of the Greek solar PV market, that led the government to implement new laws [112].

Through Law 4042/2012, an approximate 15% reduction in tariffs was imposed. These reductions were aligned with the initial tariffs set by Law 3468/2006, maintained for certain semesters as per Laws 3734/2009 and 3851/2010. A transitional period was established to ensure a smooth adjustment to the new rates. Subsequently, in August 2012, a further 28% reduction in tariffs was introduced, also accompanied by a transitional period [112].

Law 4093/2012, enacted in November 2012, introduced emergent measures to rationalize funding for renewable energy sources and PV station remuneration. It included a "solidarity surcharge" of 25–30% for energy generated between July 1, 2012, and June 30, 2014. The law stipulated that the guaranteed tariff would be based on the semester in which the PV station was activated, with exceptions for pre-existing Power Purchase Agreements. Additionally, PV stations were required to be activated within four months of the law's implementation, providing a short transitional period until March 2013 [111].

Subsequently, Law 4152/2013 modified the solidarity surcharge on PVs to 34–42% and introduced the concept of a minimum floor income from the wholesale market for the RES account, a special financial mechanism established to manage the funds related to RES. It ensured that compensation for renewables corresponded to avoided costs based on the weighted average variable cost of conventional thermal units [112].

Law 4254/2014 aimed to standardize economic returns for renewable energy projects over a 20-year period and stabilize the RES account. It included provisions to delete part of the accumulated deficit by requiring a compulsory credit invoice from RES producers [113].

Under Law 4254/2014, tariffs for the sale of operational RES projects were unilaterally and retroactively redefined, despite existing contracts, to ensure consistent economic returns across different technologies over a 20-year period. This aimed to stabilize the RES account and reduce its deficit. The disparity in economic returns, particularly for PV projects, stemmed from the rapid decrease in installation costs without corresponding reductions in FITs. Prior to Law 4093/2012, tariffs could be maintained for 18 to 36 months, depending on plant capacity, resulting in older, higher-cost tariffs being applied [113].

Re-acceleration

The re-acceleration, beginning in 2018, can be attributed to the implementation of a state aid scheme introduced by Law 4414/2016, which aims to boost investment in renewable energy sources and bring the Greek energy market in line with EU objectives [113]. During that time the electricity demand had another peak and the net imports were high.

Under the renewable energies state aid program, which is scheduled to run until 2025, eligible renewable energies projects may receive 20-year operating aid agreements in the form of Feed-in-Premium contracts. These contracts operate on the basis of contracts-for-difference between the market price of electricity and a fixed reference price, determined through competitive procedures conducted by the Regulatory Authority for Energy's, replacing the previous FIT system which proved ineffective [113].

Small-scale and demonstration projects are exempt from the Feed-in-Premium scheme, and instead, standard FIT contracts are arranged. According to Law 4643/2019 and Regulation 2019/943, as of January 1, 2020, renewable energy plants with a capacity equal to or greater than 400 kW are only eligible for Feed-in-Premium contracts awarded through bidding procedures. Additionally, they are required to undertake balancing obligations in the Hellenic Energy Exchange Market. This threshold is expected to be lowered to 200 kW by 2026 to comply with EU regulations [113].

Starting from November 1, 2019, renewables projects that have entered into Feed-in-Premium contracts are now participants in the day-ahead market, either directly or through a renewable energy sources aggregator. They are subject to clearance and settlement procedures, and must commit to accurately predicting the declared injected quantity of power. This is done following the implementation of intra-day and balancing markets, as part of their obligations under Feed-in-Premium contracts or the representation in the electricity wholesale market [113].

In essence, the stagnation ensued when the costs of PV installations declined, but the subsidies remained high, raising concerns about the long-term financial viability of the Greek PV market. Consequently, the government took measures in 2012 – after electricity demand and net electricity imports had declined for some years – to address this by reducing FITs and introducing a solidarity surcharge. As a transitional period was established to smooth the transition to the new rates, the effects only became evident in 2014, particularly after the retroactive adjustment of tariffs for the sale of operational renewable energy projects. The re-acceleration commenced in 2018 and can be attributed to the implementation of a competitive tendering system introduced in 2016, after some years of increasing electricity demand and net imports. This system ensures a feed-in-premium on top of the market price for 20 years of operation. All the pivotal laws are depicted in Figure 4.7.

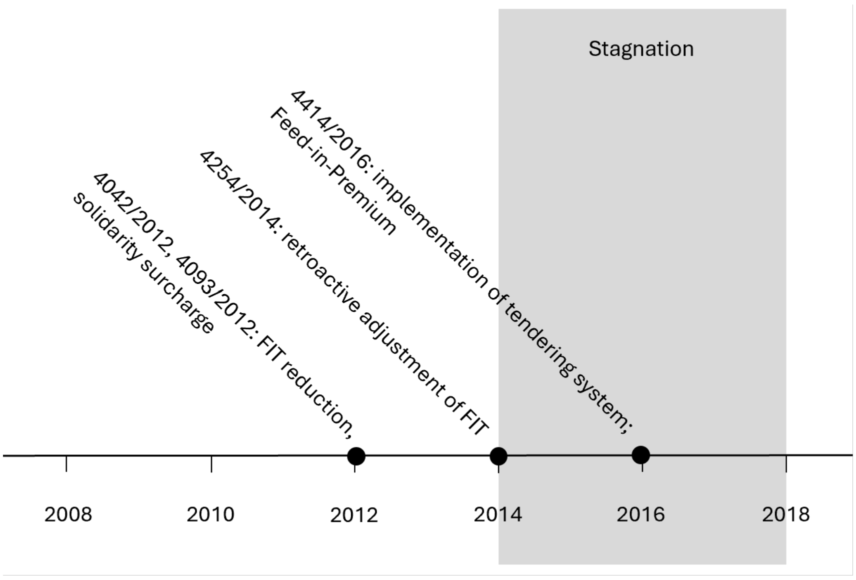


Figure 4.7: Timeline of pivotal Greek policies regarding solar PV

4.4 Spain solar PV

Spain stands out as a prominent case in both the solar PV and onshore wind energy sectors, capitalizing on its advantageous climate and geographical features to lead substantial advancements in renewable energy generation.

General power supply and demand trends
As depicted in Figure 4.8, there was an almost linear increase in demand from 1997 until 2008, driven by economic growth, initially met primarily by a rise in natural gas consumption, which was entirely imported. Starting from 2004, there was

also a significant contribution from wind energy. However, from 2008 to 2013, the global economic crisis and the Spanish financial crisis caused a decline in demand. This decline in demand, alongside the rising wind sector and the emergence of solar PV generation, resulted in reduced coal and oil consumption and imports. Furthermore, from 2004 until 2013, Spain was a net electricity exporter. However, from 2013 to 2018, total demand saw a slight increase as Spain rebounded from its financial downturn, leading to electricity imports due to the unpreparedness of the electricity system. Notably, this transition from exporting to importing electricity coincided with the beginning of onshore wind stagnation and persisted until 2020, suggesting a correlation between the re-acceleration of onshore wind and solar PV, beginning both in 2018, and the end of electricity imports. It's plausible that the government aimed to curtail import dependency by enhancing conditions for renewables, including solar PV. Post-2018, electricity demand began to decrease once more. The growing renewables sector mainly substituted imported coal and oil, with a slight increase in gas consumption. Consequently, since 2009, Spain's self-sufficiency ratio has significantly increased due to the rising share of renewables, which have mainly replaced imported fossil fuels. However, as shown in Figure 4.8, alongside the growth of renewables, the diversity of the electricity mix decreased from 2010 onwards and will continue to decrease with the complete phase-out of coal and the ongoing process of nuclear phase-out. This, combined with the intermittency of renewables, poses a challenge for energy security [114].

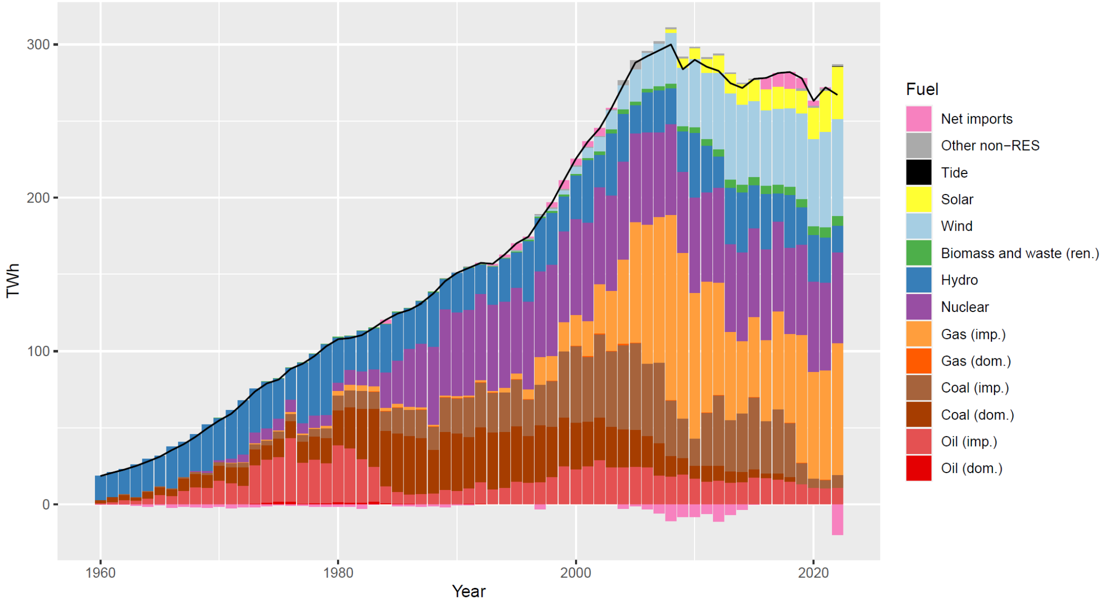


Figure 4.8: Electricity supply in Spain by fuel type and domestic or imported. Data: IEA Energy Balances [78], graph by V. Vinichenko.

Grid condition and interconnection

Spain's electricity grid was essentially isolated, with limited interconnection and trading with neighboring countries. Only about 3% of the electricity demand was imported in 2011 [115]. This lack of interconnection, coupled with the inability to store electricity, meant that all electricity produced had to be consumed within Spain. Spain's electricity system had a significant excess generation capacity. In 2009, the installed capacity was 93,000 MW, while peak demand was only 44,000 MW [116].

Manufacturing

In comparison to Germany, Spain did not have a large solar PV manufacturing industry. The few manufacturers they had could not withstand the international price competition triggered by China's mass production starting in 2008, leading to the crash of the Spanish solar PV market in 2009 [48].

Solar potential

The conditions for solar PV production in Spain are generally favorable. Spain receives abundant sunlight throughout the year, especially in southern regions such as Andalusia, Extremadura, and Murcia. The levels of solar irradiance are among the highest in Europe, as shown in Appendix A.4, which makes Spain an ideal location for solar PV installations [117]. Spain has a diverse climate, ranging from Mediterranean in the south to maritime in the north. The southern regions experience hot, dry summers with a lot of sunshine, while the northern regions have milder temperatures and higher precipitation. Spain experiences around 300 days of sunshine every year, which is equivalent to over 3,000 hours of potential generation [118]. Overall, the climate conditions in Spain are conducive to solar PV production, particularly in the sunnier southern regions. Spain's geographical location in the Iberian Peninsula provides sufficient land area for solar PV installations, including both ground-mounted solar farms and rooftop installations. Large parts of Spain, particularly arid and undeveloped regions like Aragón, are ideal for utility-scale solar projects due to their ample sunlight and flat terrain [118].

Stagnation and re-acceleration points

Figure 4.9 illustrates both the total and annually installed capacity, aiding in the identification of stagnation and re-acceleration points, as discussed in Chapter 3. The stagnation period begins abruptly in 2009 following a year of exceptionally high growth. The take-off year also occurs in 2009, immediately after the significant deployment boom. However, there was nearly a complete halt in deployment in 2009, with deployment levels reaching those of 2007 only in 2010 again. Despite this, growth did not rebound, and from 2013, annual deployment decreased until it came to a complete stop from 2014 to 2018. The re-acceleration phase commenced in 2019, also abruptly, with deployment in that year surpassing even that of 2008. Although there was a slight slowdown in 2020, deployment recovered in 2021 and 2022. The average 3-year growth rate has a maximum value of $3.84\frac{MW}{TWh}$ before stagnation and $11.51\frac{MW}{TWh}$ afterwards. The maximum growth rate for the fitted curve can not be told, as the growth is still accelerating with its inflection point far in the future. Growths rates cannot be reliably estimated when the inflection point is too far in the future, which is indicated by a maturity of less than 0.5, in this case with 0.0008 much less.

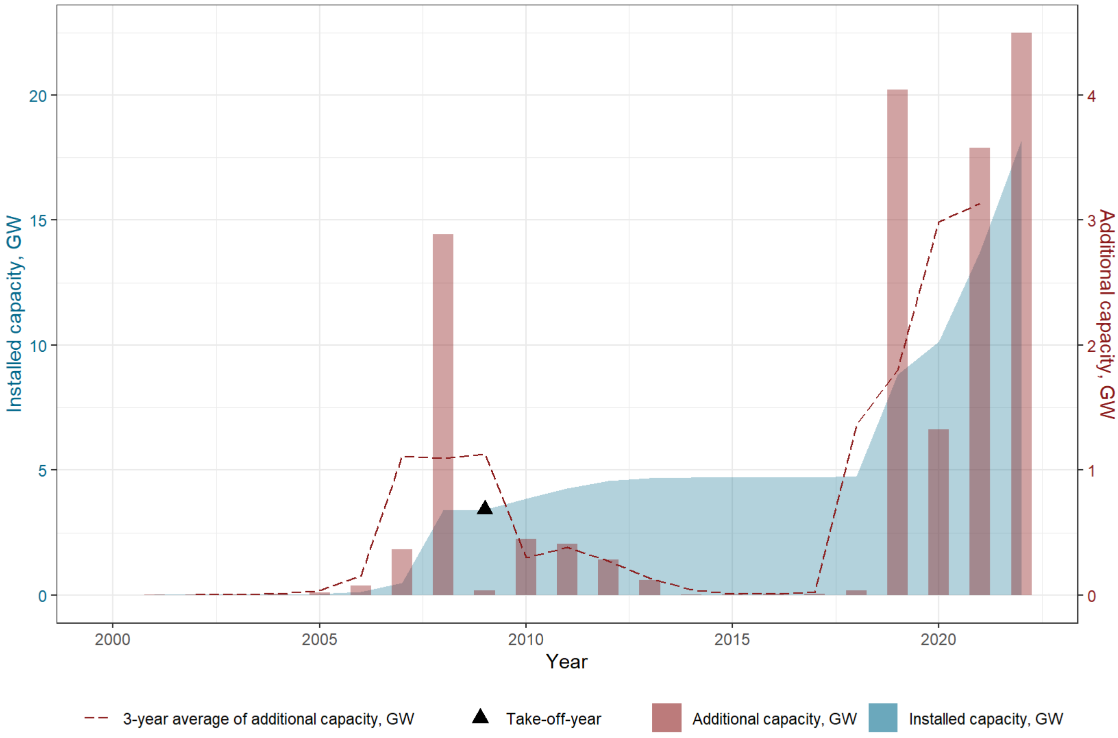


Figure 4.9: Change point diagnosis for solar PV in Spain.

Initial growth
The solar PV deployment in Spain experienced a notable boom only within a brief timeframe, from 2007 to 2008, as illustrated in Figure 4.9. During this period, significant factors drove the surge in installations. Firstly, the costs for PV installations witnessed a sharp decline, primarily due to the commencement of Chinese mass production, coupled with advancements in solar panel efficiency. Secondly, access to credit was relatively easy owing to low interest rates, particularly after Spain joined the Euro currency zone in 2006. Concurrently, the FIT rates were set at notably high levels [119].

Spain had already introduced FITs in 1997 (Law 54/1997), allowing investors to opt for either a fixed FIT rate or a fixed premium on top of the electricity market price [119]. However, concerns were raised regarding the annual adjustment of FIT rates, which was deemed non-transparent and posed risks to investors. Consequently, Royal Decree 436/2004 established a target of 150 MW for solar PV, which needed to be achieved before any adjustment to FIT rates. While this regulation improved circumstances for solar PV investors, it fell short of incorporating best-practice FIT design elements such as degressive FIT rates [120].

The pivotal shift occurred with Royal Decree 661/2007, which significantly impacted Spain's solar PV sector [120]. Under this decree, solar PV investors were mandated to accept the fixed FIT rate, eliminating the option for choosing a premium. Revision of these FIT rates was scheduled every four years, commencing in 2010 or upon reaching a capacity target of 371 MW for PV generation. Additionally, renewable energies were granted prioritized access to the electricity grid, and renewable plants with capacities exceeding 10 MW were required to connect to a generation control center. The FIT rate for installations ranging from 100 kW to 10 MW was nearly doubled. The Renewable Energy Plan for 2011 to 2020 was further developed to reassure investors of continued support beyond 2010. Furthermore, a cap-and-floor price system was introduced, stipulating that if the market price plus the FIT rate exceeded the cap, renewable energy generators would receive only the cap price, while if it fell below the floor level, they would receive this price [121].

These measures made investments in solar PV plants, especially those with capacities between 100 kW and 10 MW, highly attractive. Investors capitalized on these incentives by constructing small-sized plants in close proximity rather than building larger ones. Consequently, large-scale systems were able to benefit from the FIT rates intended for smaller, more expensive systems [120]. Despite these advantages, various loopholes existed for investors and operators, such as "repowering" existing plants to fall under the better regulations of Royal Decree 661/2007. Additionally, the FIT rates, besides being too high, failed to adjust to the decreasing costs resulting from Chinese mass production. The policy change was simply too slow to halt the boom and the corresponding costs for the government. Although the draft of the new Royal Decree was published in September 2007, it only entered into force in September 2008 [120].

Stagnation
As previously mentioned, a new Royal Decree was enacted in September 2008 to manage solar PV deployment and implement cost-containment measures. RD 1578/2008 categorized PV installations into facades- or roof-mounted and ground-mounted systems. It introduced capacity quotas, limiting the number of new solar PV installations eligible for subsidy support each quarter of the year. These quotas operated on a first-come-first-serve basis and were linked to the FIT rate. If less than 75% of the quota was utilized, the current FIT level remained unchanged; however, exceeding 75% led to a reduction in the FIT rate [122].

Furthermore, the already reduced feed-in-tariffs faced additional cuts through another Royal Decree in 2010 [123]. Between 2008 and the end of 2011, these tariffs were decreased by a total of 19% to 61%, varying depending on the type of installation [120].

To manage subsidy costs during the financial crisis, that additionally led to decreasing demand, RD 1578/2008 reduced the duration of financial support for new solar PV plants to 25 years [122]. Subsequently, RD 1565/2010 extended this 25-year cap retroactively to all solar PV plants developed under RD 661/2007, which were originally promised subsidies across their entire operating lifetime [121], [123]. Later, RDL 14/2010 increased the support period to 28 years [123]. However, it also introduced a cap on operating hours for most existing solar PV plants. This meant that any electricity generated beyond this cap had to be sold at the pool electricity price instead of the relevant FIT rate [120]. Additionally, RD 14/2010 closed the repowering loophole by stipulating that all repowering must involve the use of new equipment, preventing developers from updating systems with outdated modules [123].

Furthermore, RDL 1/2012, introduced a moratorium on new projects, deferring the registration of pre-allocation applicants for an indefinite period and abolishing all types of tariffs and premiums for new projects. Calls for new solar PV installations were completely suspended [124]. Additionally, RDL 2/2013 introduced a special tax on all sources of electricity generation, including solar PV plants. Feed-in tariffs would be annually adjusted using the core inflation rate as a reference, leading to a freeze of FIT in 2013 and likely reductions in the future.

These government measures aimed at reducing costs and installation rates resulted in lower demand and, consequently, decreased deployment of solar PV. They also reduced job opportunities in the solar PV sector and eroded confidence in Spain as an investment environment with a stable regulatory framework for renewable energies. This uncertainty led to increased capital costs for lending institutions. However, the public was shielded from these changes as the Spanish government regulated electricity prices, thereby maintaining consumer living costs [120].

Re-acceleration
The re-acceleration began in 2019, when Spain witnessed the installation of 261.7 MW of new solar power, with approximately 10% of this capacity being connected to the grid, while the remaining 90% comprised self-generating installations for self-consumption [125]. Self-consumption entails utilizing all produced energy for personal use or storing any surplus energy for later use, with the option to sell excess energy either directly to a supplier at a price defined by the supply contract or through a reference dealer at a rate based on average hourly prices, typically lower than purchased energy costs [126]. This surge in self-consumption installations in 2018 was propelled by regulatory changes, notably RDL 15/2018 and RD 224/2019, which enhanced economic conditions, simplified administrative processes, and permitted shared self-consumption in community settings [127]. Furthermore, self-consumption PV systems with capacities below 10 kW were exempt from variable fees associated with backup network usage [128]. The introduction of these regulations also abolished the "sun tax" imposed by RD 900/2015, which had hindered low-power building installations [129].

The initiation of Spain's economy's decarbonization and an 80% reduction in solar PV energy costs over the past decade have attracted major companies to invest in large-scale PV power plants [130], [131]. Notably, many of these companies are new players, as the leading companies from the initial solar PV boom of 2004-2007 have either ceased to exist or experienced substantial declines in market share [129].

Furthermore, Royal Decree 357/2017 introduced a new compensation system for new renewable energy facilities, featuring competitive tendering procedures to allocate specific remuneration regimes based on various criteria [132]. The first governmental emergency energy auction in 2017, prompted by concerns about meeting European energy objectives for 2020, primarily allocated capacity to onshore wind energy, prompting criticism from the Spanish solar association. Consequently, a second auction was held, resulting in solar PV being awarded capacity for 4 GW [133]–[135].

In summary, the stagnation occurred because the government did not anticipate the rapid deployment rate driven by unexpected cost drops and high FITs. A further complete stop of solar deployment can be associated with electricity demand decline and the policy response to that decline. The re-acceleration ensued when the costs dropped further, while policies were adapted: conditions for self-consumption were enhanced, and the introduction of the auction system played a pivotal role. A certain electricity demand increase combined with coal phase-out led to demand for low-carbon power sources. A summary of the pivotal policies is illustrated in the following Figure 4.10.

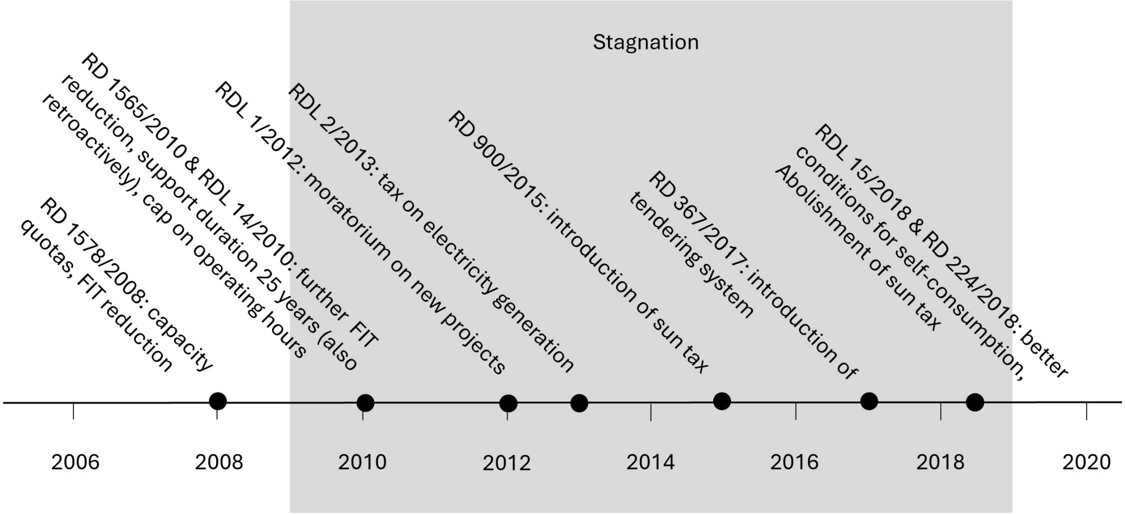


Figure 4.10: Timeline of pivotal Spanish policies regarding solar PV

4.5 Spain Onshore Wind

Spain has the second largest European wind energy market after Germany and the fourth largest installed capacity globally. Wind power has been a crucial technology in Spain, covering 24% of energy consumed and avoiding the emission of millions of tons of CO2 annually [136].

General power supply and demand trends, Grid condition
The general supply and demand trends and grid conditions are described in detail in section 4.4.

Manufacturing
Spain's wind manufacturing industry is substantial, boasting over 250 manufacturing centers scattered across 16 of the country's 17 regions [137]. The growth of this

sector was primarily propelled by the regional governments during the 1990s. These governments extended support to both domestic and foreign investors, encouraging them to establish manufacturing facilities within Spain's borders. This proactive stance towards local manufacturing played a pivotal role in augmenting Spain's installed wind capacity and nurturing the growth of its domestic wind industry [138].

Wind potential

Spain boasts favorable wind conditions for onshore wind turbines, especially in specific areas. Regions like Galicia, Castile and León, Aragon and Navarre in the northern and central parts of the country are known for their strong and steady winds, rendering them prime spots for wind energy projects. Coastal zones also benefit from consistently strong winds, further bolstering their suitability for wind turbine installations, which can also be seen in the Global Wind Atlas in Appendix A.5. Moreover, elevated landscapes such as mountainous regions contribute to accelerated wind velocities, creating additional prospects for wind power generation. Spain's varied topography presents a spectrum of wind conditions that favor the effective operation of onshore wind turbines, establishing the nation as a leading country in wind energy production [136].

Stagnation and re-acceleration points

Until 2009, Spain had a stable growth in wind deployment, although the annually added deployment fluctuated a lot between 2002 and 2009. From one year to another there were changes up to 1 GW capacity. Beginning from 2010, a downward trend in deployment became evident and in 2013 the addition was almost zero, remaining like this until 2018. In 2019, there was a huge increase in installations of 2 GW, but in the following year it decreased to around 1.2 GW and remained constant from that time on. The average 3-year growth rate has a maximum value of $8.63\frac{MW}{TWh}$ before stagnation and $5.42\frac{MW}{TWh}$ afterwards. The maximum growth rate for the fitted curve is $7.54\frac{MW}{TWh}$, which is plausible as the maturity is with 0.995 above 0.5, which means the inflection point has been passed.

It is striking, that the re-acceleration of onshore wind and solar PV was in 2019 and it both was a significant increase from almost zero in 2019 to 2 GW for wind and even 4 GW for solar PV.

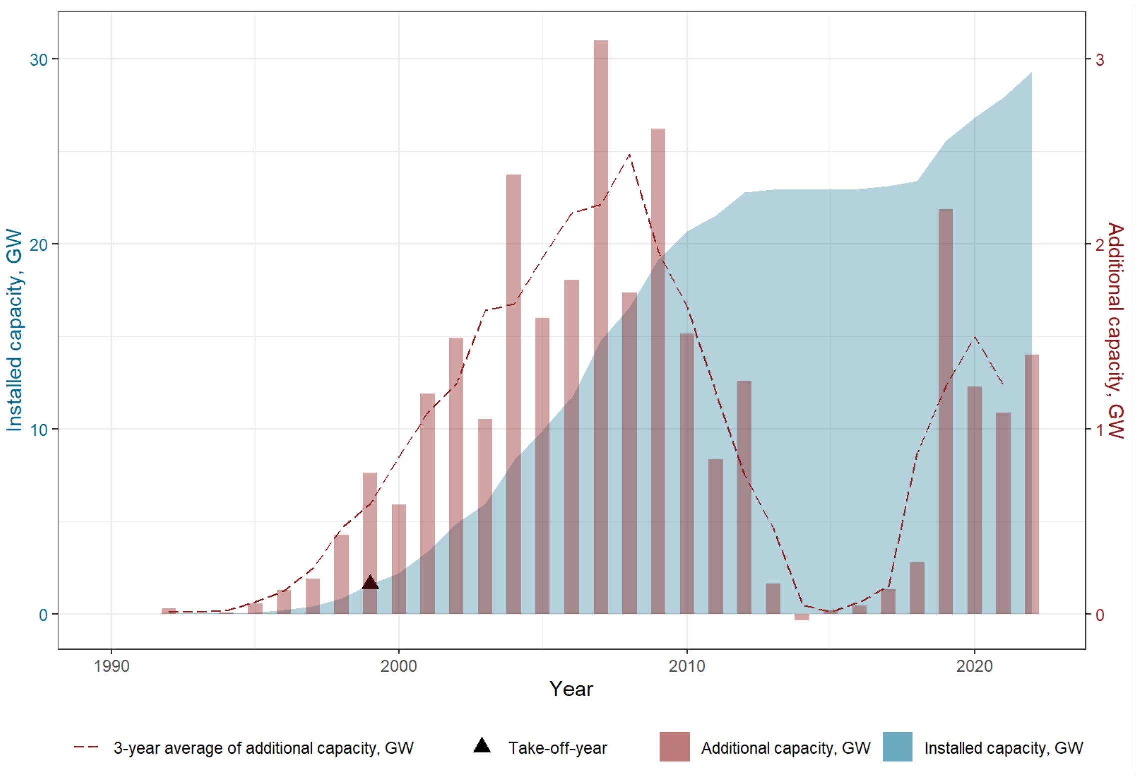


Figure 4.11: Change point diagnosis for Onshore Wind in Spain.

Initial growth

Spain was one of the early adopters of onshore wind technology. The country began investing in wind energy in the 1980s, making significant strides in the development and deployment of onshore wind turbines [138]. This was around the same time when the Spanish government decided to not build any new nuclear power but the electricity demand was still rising: In the early 1980s, construction of a third generation of five units was started, but after a moratorium was decided by the new socialist government in 1984, only two were completed [139].

The initial growth can be split in three phases:
Between 1980 and 1996, Spain enacted policies to enhance energy efficiency and promote renewable energy, including the Law of Energy Conservation in 1980 and Renewable Energy Plans (PER'86 and PER'89). In 1991, the National Energy Plan set targets for renewable energy production and incentivized cogeneration. Despite limited tariff support, Spain expanded its wind capacity and nurtured a local wind industry by actively supporting local manufacturing with policies. These policies encouraged foreign companies to establish manufacturing bases in Spain in return for access to the domestic market [140].

Between 1997 and 2000, Spain enacted vital policies to boost renewable energy. The Electric Power Act of 1997 established a "Special Scheme" mandating renewable energy incorporation into the grid, offering surplus energy sale options. The "Plan for the Promotion of Renewable Energies" aimed for 12% renewable energy by 2010. Under this Act, the electricity distributor had an obligation to buy all electricity produced from renewable sources. Royal Decree 2818/1998 regulated renewable energy production, allowing producers to sell all electricity to the grid at premium prices. Additional sets of incentives were introduced in 1999, including research budgets and a program for promoting renewable energy among the general public. Wind energy flourished, surpassing government targets, supported by regional incentives [138].

Between 2000 and 2010, Spain implemented significant measures to boost renewable energy, particularly through the 2005 Renewable Energy Plan devised by the Institute for Diversification and Saving of Energy (IDAE). This plan involved collaboration between governmental bodies and institutions and set revised capacity targets for 2010, including a wind target of 20,155 MW, replacing the previous plan from 1999 [141].

The 2005 plan primarily relied on private investment, with only a minor portion allocated for public investment aid. In 2007, the Spanish feed-in tariff system underwent alterations with Royal Decree 661/2007, introducing alternative remuneration options for wind power: Feed-in-tariffs, which means a guaranteed payment and feed-in-premiums, that are paid on top of the electricity market price [138].

Stagnation

In 2010, further revisions to the tariff system were made through Royal Decree 1614/2010, temporarily reducing the feed-in-premium and introducing measures to limit the number of qualifying operational hours for FITs for wind farms annually [138], which led to a downward trend in deployment.

On February 1, 2013, the government implemented a new Royal Decree (RD 2/2013) that eliminates the choice for renewable energy producers to sell energy at market price plus a premium. Instead, from that time on they were required to select either a fixed tariff or the prevailing market price. Previously, over 80% of Spanish wind farms utilized the market price plus a premium option, which was one of the incentives provided by Royal Decree 661/2007. With the introduction of the new decree, renewable energy producers are favoring the fixed tariff option due to the inadequacy of the current market price to support projects, as reported by the Spanish Wind Energy Association. Additionally, this decree is retroactive, necessitating project owners to completely revise the original conditions under which long-term investments were undertaken [142].

Moreover, RDL 1/2012 implemented a moratorium on new projects, postponing the registration of pre-allocation applicants indefinitely and eliminating all forms of tariffs and premiums for new projects. During that time, Spain exported more electricity than they imported. This could be a reason for the government's decision to implement this moratorium [124].

Re-acceleration

Re-acceleration began when the Royal Decree 359/2017 introduced a framework for granting a specific remuneration regime to renewable energy facilities operating within the Spanish peninsula's electricity grid. This decree included several key provisions:

Firstly, it mandated an official announcement for the allocation of this specific remuneration regime, exclusively applicable to facilities utilizing renewable energy sources.

Secondly, the allocation process was governed by competitive tendering procedures, allowing companies and investors to submit bids to secure remuneration for their facilities. The criteria for allocation were established during the tendering process.

Lastly, the decree outlined a unique method for determining the allocation of the specific remuneration system and the standard value of initial investments. This method, referred to as the "closed envelope auction with marginal system," involved participants submitting sealed bids, with remuneration being determined based on a marginal system that prioritized the lowest accepted bids [134].

In 2017, the first renewable energy auction was held for 3 GW, with the majority allocated to wind energy. Remarkably, the contracts were secured at an unprecedented rate of 43 EUR per MWh, marking the lowest level ever recorded in onshore wind energy. The reason behind such low prices lies in the government's offering of a guaranteed minimum income, which attracted investors and ensured competitive bidding, consequently driving down the prices. This underscores that revenue stabilization mechanisms, rather than subsidies, are key to reducing the costs of onshore wind energy [134].

However, there was a perceived bias against solar PV as only 1 GW was allotted to it. Consequently, the Spanish solar association raised concerns about discrimination, leading to a second auction. In this subsequent auction, solar was awarded 4 GW, while wind received 1 GW, resulting in a total allocation of 4 GW capacity for both sectors [135].

In summary the stagnation began in 2013 because Spain was a net electricity exporter and the demand declined, which led to the government's decision to implement a moratorium for all renewable energies projects, as they thought they were no longer needed. Additionally they switched from a premium system to fixed tariffs, even retroactively for already existing contracts. The re-acceleration started when a certain electricity demand increase combined with coal phase-out led to demand for low-carbon power sources. Therefore the policies were adapted and a tendering system was implemented. All the pivotal laws are depicted in Figure 4.12.

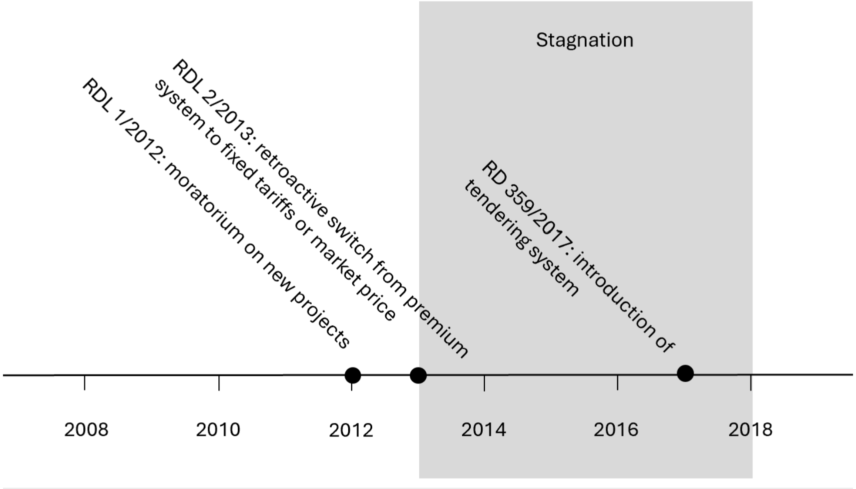


Figure 4.12: Timeline of pivotal Spanish policies regarding onshore wind

4.6 Denmark Onshore Wind

Denmark stands as the pioneering adopter of and a frontrunner in wind energy with a long history of deployment and a sizable manufacturing industry. The country recognized early, that renewable energies play a complementary role alongside traditional sources, rather than seeing them as alternatives [143]. In 2022, 55% of the electricity consumed in Denmark was sourced from wind power.

General power supply and demand trends

Figure 4.13 shows an almost linearly increasing demand until 1995, as the standards of living improved and so did the levels of energy consumption [144]. As oil was inexpensive, abundant and easy to transport in the 1960s, until 1972 Denmark's electricity production was highly dependent on imported oil, in fact, in the early 1970s more than 90% of the national energy consumption was imported from the unstable Middle East [145]–[148]. This changed after the first international oil crisis in 1973, as this crisis showed the extent of the import dependency [148]. From this year on Denmark phased out oil and instead relied on imported coal until 1995. Beginning from 1975, Denmark also net-imported electricity for almost two decades (apart from some exceptions). To reduce their import dependency, the energy-mix was diversified by scaling up domestic gas, wind energy and biomass. This led to a phase of net electricity exports. Since 1996 the efforts of diversifying the energy mix became obvious, as the share of coal also could be reduced since then. Additionally, the demand stagnated. However, from 2011 on Denmark has been dependent on electricity imports again, but the phase-out of coal is still ongoing and also the use of domestic gas has been decreasing again since 2010, while wind power and biomass have been growing and solar PV was implemented.

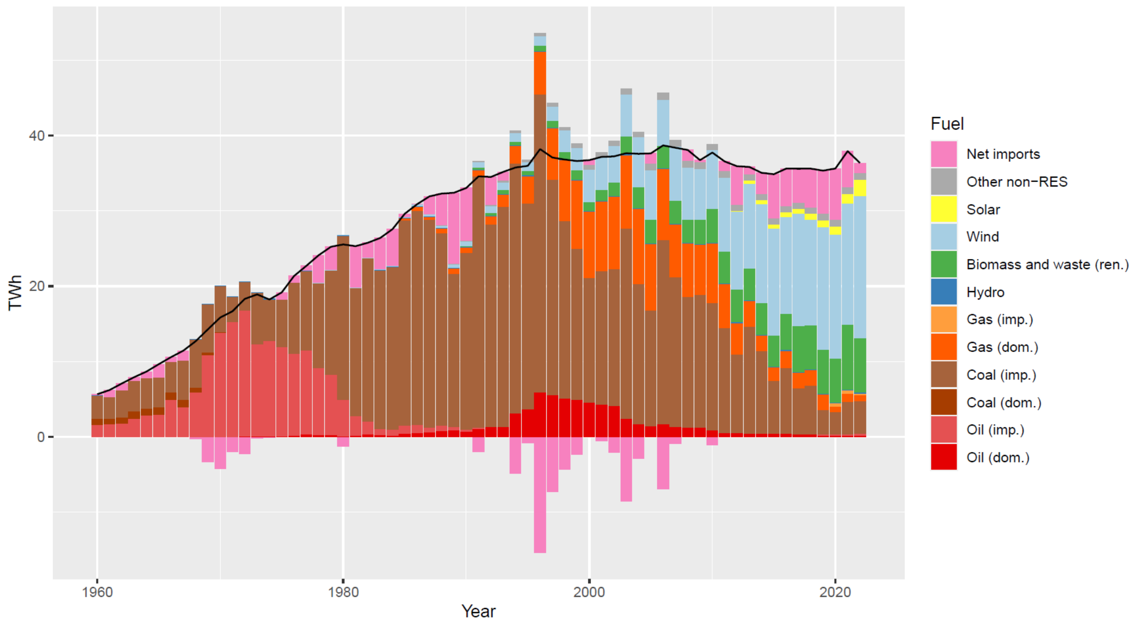


Figure 4.13: Electricity supply in Denmark by fuel type and domestic or imported. Data: IEA Energy Balances [78], graph by V. Vinichenko.

Grid condition and interconnection

Denmark offers the most reliable electric grid in Europe, with 99.997% uptime, despite its large share of fluctuating renewables [149]. The country has two separate transmission systems, of which the eastern one is synchronous with the Nordic countries and the western one with continental Europe [150]. Since 2010, the two systems are connected by the Great Belt Power Link[151], [152]. Denmark is located at an electricity crossroad between the larger electricity markets in Scandinavia and Germany, and facilitates power trade between these. Several cables connect the two Danish systems to neighboring countries. The western Danish power grid is connected to Norway and Sweden, the eastern grid is connected to Germany, and Jutland is connected to the Netherlands and England [153], [154].

Manufacturing

The Danish wind turbine industry is one of the world's largest with Vestas as Denmark's leading wind turbine manufacturer and a key player in the Danish wind power industry. The company is a major manufacturer, seller, installer and service provider worldwide and accounted for over 15% of the wind turbine commissioned capacity worldwide in 2021, the highest of any manufacturer [155]. The turnover from the Danish wind power industry was 115.1 billion Danish kroner in 2020 [156]. At the same time the exports of wind power technologies and services was 51.9 billion Danish kroner [157], which leads to an export percentage of 45%. This economic benefit is an important motivator for supporting the local industry.

Wind potential

The wind potential in Denmark is significant, as it can be seen in Appendix A.6. The country experiences strong and consistent winds, especially in coastal areas. These winds are largely driven by the temperature differences between land and sea, as well as by the prevailing westerly winds from the North Sea [158]. The country is relatively flat and has a long coastline, which ensures consistent wind flow across large areas and provides good opportunities for the installation of wind turbines.

Stagnation and re-acceleration points

Denmark's take-off year in wind power was in 1989, one decade earlier than any other country, which shows its emergence as an early adopter of this technology [3]. However, progress in deployment was modest in the subsequent years until a notable surge occurred in 1996, reaching a remarkable peak in 2000. The slow-down began in 2001, and by 2003, the deployment started to reach almost zero. A gradual re-acceleration commenced in 2008, leading to a peak year in 2013. Afterwards, the trajectory has been marked by fluctuations and an overall declining trend in the annual addition of capacity. The average 3-year growth rate has a maximum value of $11.00\frac{MW}{TWh}$ before stagnation and $5.83\frac{MW}{TWh}$ afterwards. The maximum growth rate for the fitted curve is $4.73\frac{MW}{TWh}$, which is plausible as the maturity is with 0.93 above 0.5, which means the inflection point has been passed.

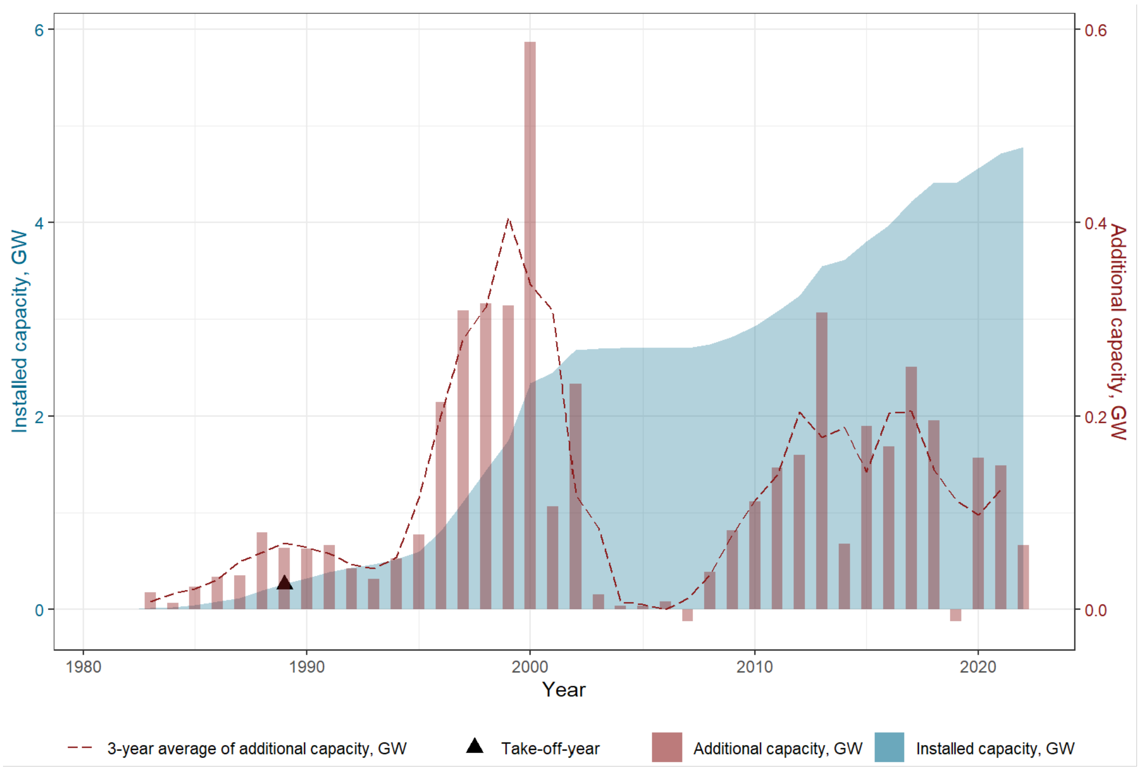


Figure 4.14: Change point diagnosis for onshore wind in Denmark.

Initial growth

After the first international oil crisis showed Denmark the consequences of their dependency on imported oil, the government reacted by introducing plans to reduce the vulnerability of national economy due to import dependency. This involved diversifying the energy mix and enhancing energy efficiency measures [159], [160].

In 1976, Denmark introduced its first Energy Plan (Danske Energipolitik), outlining various objectives. This included transitioning power plants from oil to coal and nuclear energy, as well as improving energy-efficiency in heating systems. The integration of renewable energy sources was also part of it, but only played a minor role [146], [147], [161], [162]. During the mid-1970s, however, energy taxes were imposed on electricity prices and were used for research and development in renewable energy sources [138]. In 1979, after the second oil crisis, Denmark created the Ministry of Energy and shifted its focus to ensuring a stable, accessible, and affordable energy supply for all. This objective was pursued through strategies aimed at minimizing energy consumption, maximizing energy efficiency, diversifying fuel sources, and leveraging locally available energy resources [145], [146], [159], [162].

During the 1970s, international anti-nuclear movements gained momentum, and in Denmark, it was particularly influential. This movement actively campaigned for the integration of RES [138], [163]. They were particular active in 1979 and their activism led to a parliamentary decision in 1985 to permanently exclude the option of nuclear power from the Danish energy system, leaving no other option to reach energy self sufficiency than concentrating on renewables [138], [145], [146], [162], [163]. Scientists and researchers in Denmark proposed two different alternative energy plans in 1976 and 1983, that suggested the integration of sustainable energy systems in Denmark highly relying on wind power [147]. These, in combination with energy efficiency and natural gas in decentralized co-generation plants, were planned as an alternative to nuclear and helped the anti-nuclear development [138].

During the 1970s, Danish wind power technology primarily relied on small-scale innovators, investor groups, and small companies, often operating with personal funds at personal risk, working from below [145], [148], [164]. Top-down, the government initiated a research program for larger wind turbines and introduced a 30% subsidy for the installation costs of wind turbines certified by a Danish test center in 1979, fostering collaboration between stakeholders and researchers [148], [164], [165]. These capital grants were gradually faded out until 1988 with the improvement of cost-effectiveness of the turbines [138]. However, as the size of wind turbines gradually grew, exceeding 55kW, costs escalated, which prompted local initiative groups to create wind farm cooperatives and jointly finance larger turbines to meet their own electricity consumption and sell excess energy to the grid [138]. By 2001, 86% of all turbines in Denmark were installed by wind turbine cooperatives, involving approximately 100,000 families. Additionally, utilities began investing in wind turbine installations [148], [165], [166].

The second Energy Plan (Energiplan81), implemented in 1981, introduced subsidies for the construction and operation of wind turbines, which significantly contributed to establishing a robust domestic market and local industry for wind energy. Additionally, the plan imposed taxes on coal and oil, increasing the competitiveness of renewable energy sources and offered tax incentives to families who generated electricity for their community [138].

During the 1980s, the development of a substantial renewable energy market in California presented a promising export opportunity for Danish wind manufacturers. However, this potential was reduced in 1985 when deployment in California ceased, resulting in declining overseas sales [138]. Nevertheless, the local wind industry received further support, indirectly through the parliamentary decision to not integrate nuclear power to the Danish electricity sector and directly through the implementation of the "100 MW Agreement" in 1985. This agreement aimed to deploy 100 MW of wind power between 1986 and 1990 [138], [167].

From the mid-1990s onward, state subsidies were implemented to encourage the replacement of older, smaller, and inefficient wind turbines with modern ones [168]. Additionally, successive Energy Plans introduced during this period included progressively ambitious climate goals.

In 1992, the renewable energies planning system was decentralized, which means municipal planning and site assessment of wind farms was encouraged. Municipal governments have large independence for policy design and get the financial means to drive renewables deployment, including provisions for public hearings to increase the acceptance. However, the policies have to be embedded in the strong national framework [169]. This initiative was accompanied by the introduction of fixed feed-in tariffs. These tariffs mandated that utilities prioritize wind-generated electricity and purchase it at a rate equivalent to 85% of the price paid by consumers and guaranteed wind energy projects connection to the grid [138]. Before, Danish utilities favored conventional, large-scale power plants, as they had little experience in handling dispersed, small-scale electricity systems. Furthermore, wind projects received a tax refund (environmental premium) of DKK 0.27 per kWh. In total this resulted in a typical remuneration of DKK 0.60 per kWh for wind power [170].

In 1999 the Danish government decided to liberalize the electricity market by 2002 to introduce competition into the electricity supply sector, that was in reality a monopoly [138], [169]

Stagnation

Stagnation started in 2001, when a right-wing government was in power, which led to a shift in environmental priorities from previous years. There was reduced support for renewable energy sources, resulting in the scaling back of various financial incentives. Feed-in-tariffs were replaced with feed-in-premiums, which were set at levels insufficient to continue growth and no longer ensured guaranteed interconnection [138], [143]. The support for certain R&D activities was also cut back. The uncertainty surrounding these policies held investors back from pursuing new installations. Additionally, research centers lost funding, which challenged their ability to continue their work [143], [148], [168]. Moreover, there was a restructuring of the power supply sector. This involved the privatization of power companies, leading to the establishment of independent sectors for power distribution, transmission, and production, each operating within its own framework [171].

The unstable and fluctuating electricity prices increased the risks associated with investment. Consequently, ownership of modern industrial-scale wind power plants shifted towards external developers, utilities, private investors, or public/private partnerships [145], [148]. This trend led to a decrease in the role and significance of the wind farm cooperative movement, which had been prominent since the early days of wind power in Denmark [172].

Resistance to local onshore wind farms grew and farm opposition groups mobilized, as the wind farms became increasingly prominent in the landscape and local ownership of turbines declined, so there was no chance for financial profit from the revenue of the turbine [172], [173].

Re-acceleration

The re-acceleration began in 2008 with the negotiation of a broad coalition Energy Agreement, in which the government renewed its focus on energy efficiency, renewable energy sources, and wind farms. The drivers for this were rising energy security concerns due to increasing net-imports of electricity and declining domestic gas production. The agreement served as a roadmap and provided long-term planning guidelines for Danish energy policy, emphasizing the ongoing transition towards low-carbon energy [148]. The goal was to promote the utilization and integration of RES in the energy system while considering environmental and socioeconomic factors. It is crucial to acknowledge the increasing instances of resistance and social controversy about local wind farms to enhance local acceptance and engagement in such projects [168], [172]. To achieve this, incentives and a compensation scheme for local residents to allow onshore wind farms to be located in their area were introduced [60].

In 2009, the Promotion of Renewable Energy Act entered into force. The primary support mechanism for wind power remained a FIP scheme, but with higher premiums compared to the initial scheme introduced in 2001 (premium to market price of DKK 0.25 per kWh instead of DKK 0.10 per kWh for the first 22,000 peak load hours). This scheme provided stable revenues for wind power projects. All subsidy costs were transferred to consumers through an equal Public Service Obligation tariff on their overall electricity consumption [174]. For offshore wind farms, special tariffs were established based on competitive tenders [138]. The act also establishes a "loss of value scheme", that offers payment in case of loss of value to a property due to the erection of a wind turbine. In addition, individuals installing onshore wind turbines were required to offer at least 20% of the turbines ownership for sale for residents living up to 4.5 km away from the turbines to give them a chance to benefit financially from the revenue of the turbine [60].

In February 2011, the government published its Energy Strategy 2050, with the primary objective of achieving independence from coal, oil, and gas by 2050. Additionally, an interim goal was set to reach a 30% share of renewables in the final energy demand [138].

In 2011, a new government was elected with big targets for renewable energies. In March 2012, a broad Energy Agreement was published for the period until 2020. According to this agreement, wind energy was projected to account for 50% of electricity consumption by 2020, while greenhouse gas emissions from the Danish energy sector would be decreased by 34% compared to 1990 levels. The plan also aimed to install 3.3 GW of new wind power capacity. The expansion of the electricity grids should be financed through a Public Service Obligation scheme, like the FIP are [175].

In summary, stagnation occurred due to shifting priorities following the election of a right-wing government in 2001. This government implemented significant cutbacks to incentives for wind deployment, which led to political uncertainty. Feed-in tariffs were replaced by feed-in premiums, with the premiums being insufficiently high to economically justify the construction of new wind turbines. Additionally, Research and Development spending was reduced. Furthermore, opposition groups against onshore wind formed, as wind turbines became more prominent in the landscape and local ownership of turbines declined, so there was no chance for financial profit from the revenue of the turbine. The starter for re-acceleration was the broad coalition Energy Agreement of 2008. The driver for this agreement were rising energy security concerns because of the increasing electricity imports. The agreement redirected the focus back to renewable energy sources and established long-term plans for a sustainable energy transition. As part of this shift, the premiums of the FIP scheme were increased. Additionally, measures to overcome public resistance were introduced. All pivotal policy changes are illustrated in Figure 4.15.

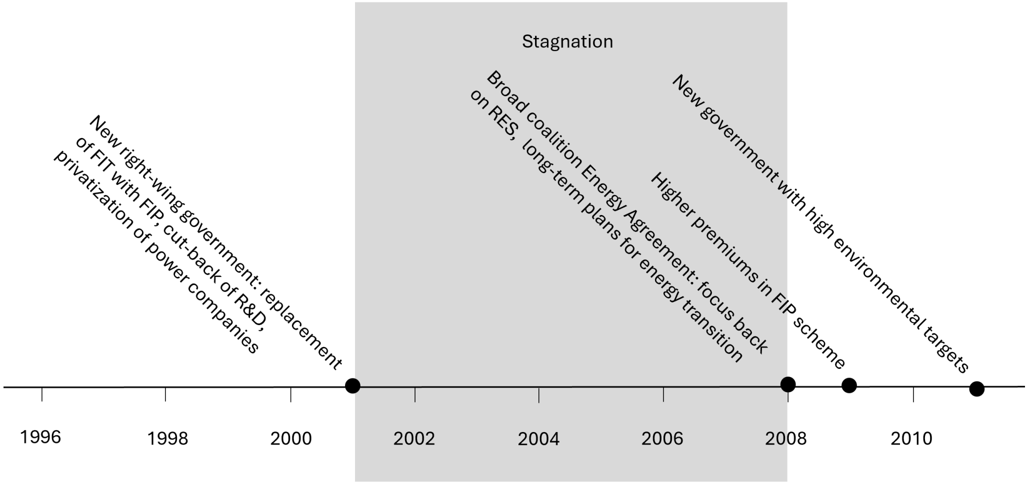


Figure 4.15: Timeline of pivotal Danish policies regarding onshore wind

4.7 Austria Onshore Wind

Austria has considerable potential for wind power in specific regions, complemented by a grid infrastructure capable of storing surplus electricity in pumped hydro storage facilities. Furthermore, Austria has successfully overcome two periods of stagnation in wind turbine deployment.

General power supply and demand trends

Austria's electricity demand has been steadily increasing over time, with a noticeable slowdown of the growth rate observed around 2008, as illustrated in Figure 4.16. There were two distinct demand drops in 2009, after the global economic crisis and in 2020 because of Covid-19. From the beginning on, hydro power has consistently represented the largest share of Austria's electricity production. Until the early 2000s the capacity for hydro power generation increased, but in subsequent years, the potential for further expansion of hydro power production became largely exhausted. As the demand continued to grow, surpassing its domestic production capacity, Austria transitioned from being a net exporter to a net importer of electricity. Consequently, the amount of imported gas in the electricity mix grew. Noticeably, the early 2000s marked a significant increase in wind deployment in Austria. This shift leads to the presumption, that Austria was forced to focus on other renewables as a means to reduce import dependency and further develop towards a low-carbon electricity system. With the increasing contribution of wind power to the energy mix, Austria successfully decreased the reliance on imported coal in its electricity production. However, they are still a net-importer of electricity.

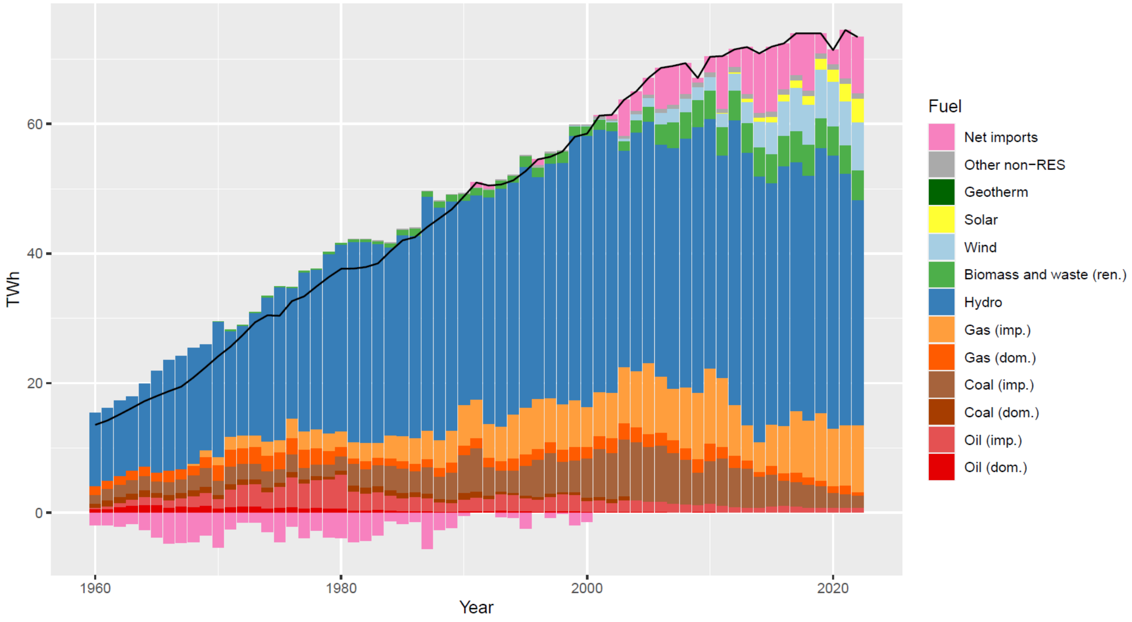


Figure 4.16: Electricity supply in Austria by fuel type and domestic or imported. Data: IEA Energy Balances [78], graph by V. Vinichenko.

Grid condition and interconnection

Austria has a robust electricity grid infrastructure. The country has a transmission network capable of transporting electricity across the country. Notably, wind turbines located in the eastern regions of Austria are interconnected with pumped hydro storage facilities in the western parts. This strategic setup aids in mitigating the fluctuations of renewable energies by converting and storing excess electricity when available. Additionally, Austria's grid is interconnected with neighboring countries, allowing the import and export of electricity to ensure reliable and secure energy supply [176].

Manufacturing
The Austrian industry for wind turbines is especially known for their supply sector, that produces core components for onshore and offshore wind turbines, like control systems, wind power generators, wind turbine design or high-tech materials. Recent studies assume an estimated export share of 90%. Technology originating from Austria is integrated into nearly every wind turbine worldwide. Some of the suppliers in Austria's wind turbine industry are "hidden champions", and a few of them even hold leading positions in the global market. To maintain their status at the top of the world market, R&D plays a crucial role. The wind industry is an important economic driver and adds high value to the country [177].

Wind potential
Austria's wind potential varies across the country, as it is influenced by the country's topography. There are windy corridors in the Eastern Alps and flat plains in the East of the country, that are ideal locations for wind turbines, which can also be seen in the Global Wind Atlas in Appendix A.7. These regions experience consistent wind speeds suitable for wind energy generation [178]. Other areas with good wind potential are regions with higher elevation, such as parts of Upper Austria, Styria, and Carinthia [179].

Stagnation and re-acceleration points
Figure 4.17 clearly illustrates that Austria has experienced two distinct phases of stagnation, each followed by periods of re-acceleration. The initial significant growth in Austria's wind energy sector started in 2002, with the take-off year occurring two years later in 2004. The first period of stagnation began in 2007 and the deployment of wind energy projects nearly halted for several years. Growth re-accelerated in 2011 and soon reached higher values of additionally installed capacity per year than before stagnation. However, this phase also came to a halt in 2016, when the deployment trend first decreased and then completely stopped in 2020. Unlike the previous stagnation, this slowdown was characterized by a more gradual decline, with only one year of no deployment. The re-acceleration began in 2021, with already high additionally installed capacity during that year and even more in 2022. The average 3-year growth rate has a maximum value of $3.71\frac{MW}{TWh}$ before the first stagnation and $4.88\frac{MW}{TWh}$ afterwards. After the second stagnation it is $2.31\frac{MW}{TWh}$, but it have been only two years since the re-acceleration began, so this rate is not meaningful yet. The maximum growth rate for the fitted curve is $3.26\frac{MW}{TWh}$, which is plausible as the maturity is with 0.82 above 0.5, which means the inflection point has been passed.

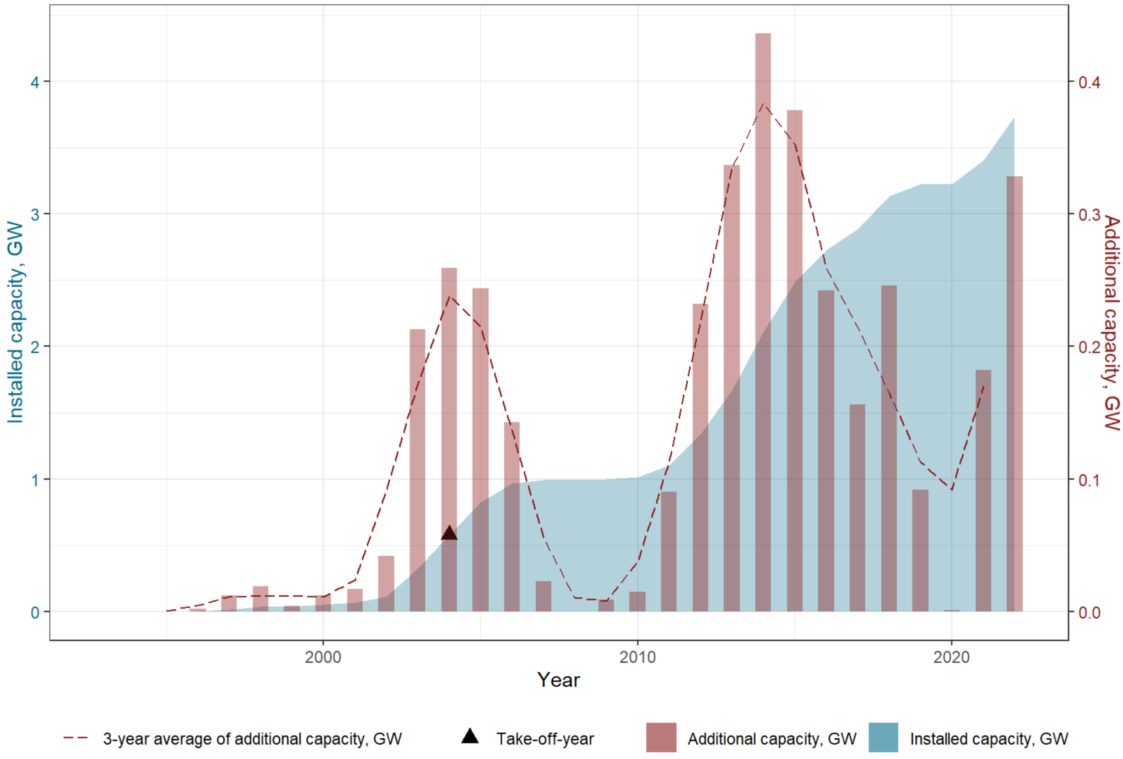


Figure 4.17: Change point diagnosis for onshore wind in Austria.

Initial growth

The first turbines in Austria were installed in 1994, when RES were promoted for the first time. During this period, wind power plants were offered double the market standard tariff for the first three years as an incentive. However, since this subsidy was limited until 1996 and no subsequent financing was evident, the expansion of wind energy did not experience significant growth [180], [181]. In 1998, the federal government reintroduced FITs. However, these tariffs were not consistently regulated on a national level, leading to variations between the states. By 2000, Austria's nine states advocated for a standardized subsidy scheme for RES and expressed willingness to transfer jurisdiction in energy policy from the regional to the federal level [181]. At that time, the deployment of hydro power started to stagnate, highlighting the necessity of expanding other renewable energy sources to maintain the trajectory towards carbon neutrality. The uniform subsidy came with the introduction of the Green Electricity Act (GEA) in 2002. It was the first legislation to regulate the purchase of green electricity and it introduced feed-in-tariffs of EUR cent 7.80 per kWh for all RES [180]. This FIT was financed by the Austrian electricity consumers through a clearance mechanism. The GEA also established a target to raise the proportion of "green" power from 70% (as of 1997) to an indicative target of 78.1% by 2010, aligning with the objectives outlined in EU Directive 2001/77/EC [182], [183].

Stagnation 2007

The first stagnation occurred in 2007 after a major amendment of the GEA. The FITs were reduced to EUR cent 7.55 per kWh and were configured to decrease gradually over time to reduce the burden on the Austrian electricity consumers. Additionally, the duration of guaranteed support was shortened to ten years, and a dedicated green power settlement agency, the OeMAG, was established. This agency has a maximum annual budget of EUR 17 million per year from 2007 to 2011 to purchase renewable electricity. consequently the unlimited payments for all RES power plants ceased. Instead, only renewable installations that received permits within the annual funding volume allocated by OeMAG were promoted and remunerated. Electricity distributors are mandated to purchase a certain amount of green electricity from OeMAG at a fixed price set by the Federal Ministry. This price is lower than the feed-in tariff. The difference between the feed-in tariff and the purchase price for electricity distributors is covered by Austrian electricity consumers, who contribute a fixed lump sum to OeMAG [182].

Re-acceleration 2011
In 2010, Austria implemented the National Renewable Action Plan in response to EU Directive 2009/28/EC, which mandated all member countries to outline their targets for the share of renewable energy in their electricity mix. Austria's target was to achieve 71% of its electricity demand met by electricity generated from renewable energy sources. To reach this goal, the growth of renewables, especially wind power had to accelerate again. In addition, the net-imports of electricity increased during that time. Therefore, in the same year, the Green Electricity Regulation (GER) was introduced, which raised the Feed-in Tariff (FIT) for wind energy to EUR cent 9.70 per kWh and extended the duration of support to 13 years. This new regulation drove the re-acceleration.

In 2012, there was also a reform of the Green Electricity Act, which implemented specific expansion targets for RES, particularly focusing on wind energy. The reform aimed to address the backlog of power plant operators on the waiting list, which had accumulated since 2007 due to the OeMAG's limited budget for FITs [182], [183].

Stagnation 2016
Starting in 2016, the yearly installation of wind turbines began to decline. This was due to the insufficient funding for support schemes dedicated to renewable energy initiatives, particularly for wind power projects. As a result, there was a backlog of permitted projects with a combined capacity exceeding 800 MW, all awaiting FITs [184]. Additionally, the GER was amended and feed-in-tariffs were reduced to EUR cent 8.95 per kWh. Deployment stagnated even more when the GER was amended another time in 2018 and the FITs were further reduced to EUR cent 8.12 per kWh [183]. However, this second stagnation period was more a slow down, as the deployment did not totally stop, except for 2020.

Re-acceleration 2021
The Renewable Energy Expansion Act was implemented in 2021 to re-accelerate the growth of renewables, particularly as net electricity imports began to rise once more, and electricity prices increased. Moreover, according to recent surveys, the public acceptance is growing, and in 2022 78% of Austrians surveyed appreciated wind tur-

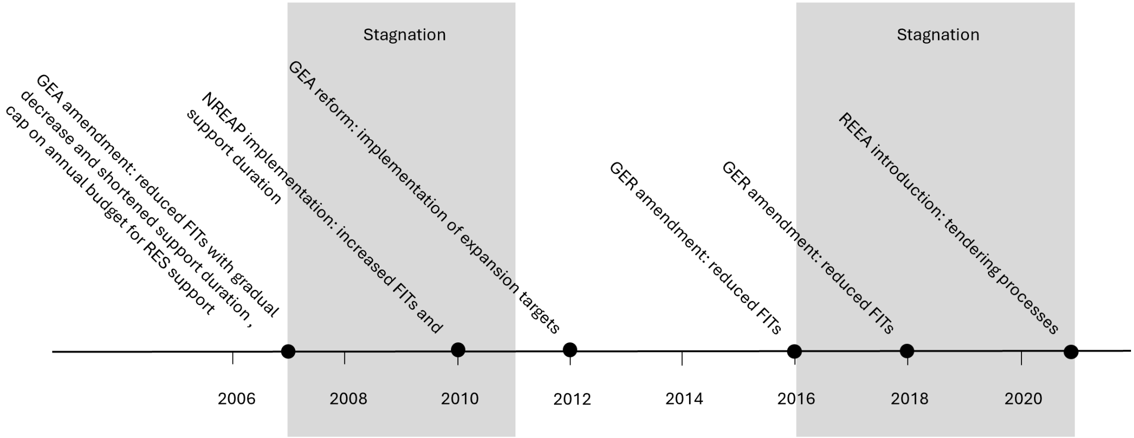


Figure 4.18: Timeline of pivotal Austrian policies regarding onshore wind

bine deployment in their region [185]. The Renewable Energy Expansion Act aims to increase annual electricity generation from renewable sources by 27 TWh, with a specific target of 10 TWh for wind energy. Additionally, tendering processes were implemented, with plans to tender a capacity of 190 MW in 2022 and an additional 400 MW each year thereafter. Another support option provided by the act is market premiums of EUR cent 7.98 per kWh for renewable energies [183].

In summary, Austria faced its first stagnation in wind turbine deployment in 2007, primarily due to the gradual reduction of feed-in tariffs and shortened support durations aimed at alleviating the burden on electricity consumers. Additionally, limited budget allocations for financial support resulted in the inability to approve all applications for wind turbine installations. In response to newly established environmental targets and rising net electricity imports, the government reinstated higher feed-in tariffs and extended support durations in 2011 to re-accelerate growth. However, by 2016, insufficient funding for support schemes, particularly for wind power projects, led to a backlog of permitted projects awaiting feed-in tariffs. Furthermore, the reduction of feed-in tariffs contributed to a slowdown in deployment. With net electricity imports on the rise again and electricity prices increasing, new targets for renewable electricity production were set. To achieve these goals, a tendering process was implemented in 2022 to drive re-acceleration in the renewable energy sector. An overview of the pivotal Austrian policies is given in Figure 4.18.

5

Discussion

This chapter aims to analyze and compare the different solar PV and onshore wind cases described in Chapter 4 with each other, respectively, to uncover similarities and differences in the mechanisms across the different countries. Furthermore, it compares solar PV and onshore wind to determine whether similar factors are responsible for the stagnation and re-acceleration of both energy sources. Additionally, comparisons are made between the growth rates before and after stagnation, as well as with the maximum fitting-based growth rate. Lastly, the regional and global growth curves are compared to the national ones to ascertain whether they exhibit similar or different behaviors.

5.1 Comparison of solar PV cases

For Greece and Germany, the stagnation phases exhibit striking similarities. In Greece, the stagnation phase begins just one year after Germany, starting in 2014 and ending in 2018 for both countries. Additionally, the growth patterns during the initial phase and the subsequent re-acceleration are comparable. In both countries, annual deployment gradually increases before experiencing a significant decrease to the level of stagnation. However, the level of deployment during stagnation differs between the two countries. In Germany, the annual deployment during stagnation slows down to approximately 25% of the annual deployment before stagnation, whereas in Greece, it nearly comes to a halt, hovering around zero. This is also observed in Spain, where annual deployment during the stagnation phase is also close to zero. In Spain, the stagnation phase commences in 2009 following a brief peak in deployment. Although there is a slight recovery in deployment in 2010, it gradually declines again until coming to a complete halt in 2014, coinciding with the beginning of stagnation in Greece. The re-acceleration in Spain begins around the same time as in the other two countries, starting in 2019. Notably, the stagnation phase in Spain is twice as long as the one in Germany. Table 5.1 provides an overview of the stagnation and re-acceleration times of the solar PV cases, along with the duration of their stagnation phases.

Table 5.1: Comparison of stagnation and re-acceleration of the solar PV cases

Country	Stagnation	Re-acceleration	Stagnation phase
Germany	2013	2018	5 years
Greece	2014	2018	4 years
Spain	2009	2019	10 years

The power supply and demand dynamics vary across the three countries. In Germany, demand decreased before and during stagnation, and the country remained a net exporter of electricity throughout this period. However, the decision to phase out nuclear power and the gradual decline of coal usage led to an increased demand for low-carbon electricity sources, potentially driving political motivations to re-accelerate solar growth. The decision to completely phase out coal by at latest 2038 was made in 2020 [186]. Germany's significant domestic coal resources and the influential lignite industry played a role in this decision-making process.

In Greece, prior to the onset of stagnation, there was a rapid decline in both demand and net electricity imports following the global financial crisis in 2008. However, from 2014 to 2016, both demand and net imports began to increase once more. During this period, there was also a notable reduction in the amount of domestic coal in the electricity mix, leading to a growing demand for low-carbon electricity sources. The decision to phase out coal by 2028, however, was only made in 2019 [186]. Similar to Germany, Greece also possesses domestic coal resources that were heavily relied upon in earlier years. The decreasing demand and reduced dependence on electricity imports may have influenced the government's decision to not further support renewables, particularly during a period of financial instability. However, as demand began to rise again, along with increased electricity imports, there was a renewed motivation to re-accelerate solar PV growth in 2016. This initiative aimed to enhance the country's self-sufficiency and reduce reliance on imported electricity.

In Spain, prior to the stagnation period, electricity demand experienced growth. However, during the first part of stagnation phase, there was a slight decrease in demand due to the global economic crisis and the Spanish financial crisis. Despite this, Spain remained a net exporter of electricity during this time. However, in the second part of stagnation phase, spanning from 2013 to 2018, there was a notable increase in electricity demand. This surge in demand was primarily met by electricity imports, as the Spanish electricity system was unprepared for that rise in consumption and not only solar PV but also onshore wind installations stagnated during this period. The end of electricity imports in 2020 suggests a correlation between the re-acceleration of onshore wind and solar PV, beginning in 2018 and 2019, respectively. It is plausible that the government took measures to re-accelerate renewables to enhance the country's self-sufficiency and reduce import dependency. Furthermore, in 2018 in its just transition strategy, the Spanish government made the decision to phase out coal and set the date to 2030 in 2021 by joining the PPCA [182], [186]. This led to a higher demand of low-carbon electricity sources and therefore presumably contributed to the re-acceleration. Unlike Germany and

Greece, Spain lacks significant domestic resources, which further underscores the importance of renewable energy sources for the country's energy security.

The policy trajectory across all three countries exhibits similarities, with the introduction of feed-in tariffs being the primary policy instrument for promoting solar PV. Additionally, to re-accelerate growth, all three countries transitioned to tendering processes. However, there are significant differences in the approach to FITs among the three countries. While Germany and Greece implemented gradual changes to FITs, in Spain they were very abrupt. This led to sudden peaks in annual deployment such as after the doubling of FITs in 2008, and the decision to only change them every four years, instead of changing them slightly and predictably with a degression rate like in Germany and Greece later. This resulted in a surge in deployment, also driven by declining prices, which substantially increased subsidy spending [119], [120]. However, Spain struggled to handle this sudden growth, failing to implement effective FIT policies. Instead, in response to the financial burden, they drastically cut FITs and support duration in 2008 [122]. They also imposed limits on PV installations for each quarter of the year, causing a halt of deployment in 2009. 2010 saw a slight recovery as the panel prices were dropping even further, however, FITs were reduced again, even retroactively [123]. With declining demand and net electricity exports, a moratorium on new projects came in 2012, causing a second decrease in installations until a complete stop in 2014, lasting until 2018 [124]. The abruptness of these measures created a highly uncertain investment environment for RES in Spain, portraying the country as an unfavorable destination for RES investments. Indeed, both Greece and Germany also reduced their FITs in 2012 and 2013 due to financial burdens and declining cell prices. However, unlike Spain a few years earlier, they implemented transitional phases with gradually decreasing FITs, incorporating degression rates that responded to actual deployment through an extension corridor [72], [110]. This approach allowed them a smoother transition and better management of the deployment pace. Interestingly, their stagnation occurred a few years after Spain's, indicating that they may have learned from Spain's mistakes and adjusted their policies accordingly to overcome similar issues like the financial burden of ineffective policies and demand decline. The trade barriers imposed by the European Commission in 2013, however, had an impact on all three countries, as they artificially increased the prices of solar panels while subsidies decreased. Consequently, this resulted in lower deployment rates [72]. However, in Germany, deployment did not drop to zero, potentially attributed to the presence of a domestic solar PV industry and market.

The immediate cause of the re-acceleration were reduced costs due to the abolishment of trade barriers in 2018 [100]. This was a response to the inability to save European solar PV industry and the rising demand of low-carbon electricity sources. Additionally, oversupply in China, resulting in decreased panel prices, played a role, as China could not sell as many panels to Europe as before. Another contributing factor to cost reduction was the implementation of tendering systems in all three countries. However, it's worth noting that the tendering systems in Germany and Spain differed. In Germany, successful bidders received their offer, while in Spain, all participants received the same offer. Moreover, in Germany, the tenders were technology-specific, whereas in Spain, all renewable technologies competed against each other [187]. This led to problems in the beginning, as the first tender predominantly allocated capacity to wind power, with minimal allocation to solar PV.

When it comes to grid conditions, all three countries show similarities, as they all have a good electricity grid, but face some challenges. Germany boasts a robust interconnection with neighboring countries, however, it struggles with a deficiency in transmission capacity from its windy northern regions to the industrial hubs in the south [79]. In Greece, interconnection with neighboring countries is generally strong, but some islands remain disconnected from the main grid [105]. In Spain, although interconnection with neighboring countries is still developing, it is steadily improving over time [116].

In terms of the manufacturing, the countries differ. Spain and Greece lack a substantial solar PV manufacturing industry. In contrast, Germany once had the world's largest industry, although it was surpassed by China in 2007 [48]. Spain experienced an emerging market during its initial boom, but faced a crash when China began mass production, as it was no longer competitive in the global market [48].

While Spain and Greece share similar solar potential, Germany's solar potential is notably lower. However, there is no indication that this difference has had a significant impact on deployment. This may be due to the substantial improvements in efficiency observed in recent years, averaging around 0.5% per year during the last 20 years [188]. It may also suggest that a high solar potential is not a prerequisite for being a leader in solar power deployment.

5.2 Comparison of onshore wind cases

The onshore wind cases exhibit different stagnation and re-acceleration timelines, as evident from Table 5.2. Moreover, the duration of the stagnation phase varies across cases. Austria and the first part of stagnation phase in Spain (until 2012) share similar patterns, characterized by a gradual decrease in annual deployment. This aligns with political decisions to gradually decrease FITs (Austria) or FIPs (Spain) [138], [182]. In contrast, Denmark and the latter part of stagnation phase in Spain since 2012 experienced more abrupt declines in annual deployment, coinciding with political decisions such as Denmark's shift from FITs to FIPs and the moratorium in Spain [124], [138]. Re-acceleration in Denmark and Austria during the first phase involves a gradual increase in annual deployment, while in Spain and Austria during the second phase, it occurs in a more significant step upwards in annual deployment. The common political decisions associated with gradually increasing annual deployment include the increase of FITs or FIPs [174], [182]. Conversely, the introduction of tendering processes corresponds to the abrupt surge in deployment [134], [183].

Table 5.2: Comparison of stagnation and re-acceleration of the solar PV cases

Country	Stagnation	Re-acceleration	Stagnation phase
Spain	2010	2019	9 years
Denmark	2001	2008	7 years
Austria	2007	2011	4 years
	2016	2021	5 years

Austria stands out among the three countries due to its consistent growth in electricity demand over time. Historically, hydro power has been the primary source of electricity, with its share steadily increasing until the early 2000s. However, further expansion in hydro power production reached a point of saturation, leading to stagnation in its growth. As Austria's electricity demand continued to rise, the country became increasingly reliant on importing electricity, and had to increase the share of imported gas in the electricity mix. This shift likely prompted Austria to diversify its renewable energy sources, thus initiating an initial acceleration in wind deployment as part of its transition towards a more self-sufficient electricity system. This hypothesis is confirmed by the fact that the stagnation in wind deployment coincided with a decrease in imported electricity, while measures for re-acceleration were introduced when imports increased once again. Despite efforts to expand domestic renewable energy sources, Austria remains dependent on electricity imports.

In Denmark, a stagnation in electricity demand occurred around 1995, possibly because of early initiatives aimed at enhancing energy efficiency. By 1970, Denmark relied heavily on imported oil, but the oil crisis prompted a rapid transition to coal. Within a decade, coal became the primary energy source, albeit still imported, alongside electricity imports [146]. To mitigate this import dependency, Denmark began to diversify its energy mix, incorporating domestic sources such as gas, wind, and biomass. This diversification facilitated a reduction in the reliance on coal, leading to a phase of net electricity exports as demand also stagnated. The stagnating demand and the declining import dependency of electricity supply might have contributed to the stagnation, as the political will to support RES deployment sank. Therefore, the pace of renewable energy deployment did not match the phase-out of coal, nor did it compensate for the decline in domestic gas production. Consequently, Denmark had to import electricity again by 2011. The decreasing amount of exported electricity by 2007 may have prompted efforts to re-accelerate renewable energy deployment.

In Spain, prior to the stagnation period, there was a period of electricity demand growth. However, during the initial phase of stagnation, spanning from the onset of the global economic crisis in 2008 to around 2012, there was a slight decline in demand attributed to both the global economic crisis and Spain's financial crisis. Notably, Spain maintained its status as a net exporter of electricity during this period. However, in the subsequent phase of stagnation, from 2013 to 2019, there was a notable increase in electricity demand. This surge in demand was primarily met by electricity imports, as the Spanish electricity system was unprepared for that rise in consumption, as installations of both solar PV and onshore wind stagnated during this period. The end of electricity imports in 2020 suggests a correlation with the subsequent re-acceleration of onshore wind and solar PV installations, beginning in 2018 and 2019, respectively. It is plausible that government actions aimed to re-accelerate renewables were motivated by a desire to improve the country's energy self-sufficiency and reduce import dependency. Additionally, Spain's commitment to phasing out coal, underscored by its inclusion in the Powering Past Coal Alliance (PPCA), further reinforces the push towards renewable energy transition [182], [186].

The policy trajectories in all three countries share similarities, as their instrument for policy promotion is a feed-in-tariff or in the case of Spain -premium. In Denmark and Spain, guaranteed purchase agreements were pivotal, while Denmark introduced an environmental premium, a tax refund to incentivize producers further [138], [170]. Notably, Denmark's wind farm cooperatives played an important role, allowing residents to meet their electricity needs and generate income from nearby turbines, which led to enhancing social acceptance [138]. Denmark and Austria both pivoted towards wind energy promotion due to similar circumstances. Denmark's decision to exclude the implementation of nuclear power steered the country towards wind energy, aligning with its pursuit of energy self-sufficiency [146]. Similarly, Austria's stagnant hydro power deployment led to a shift towards wind energy to advance its transition to a low-carbon energy landscape and maintain self-sufficiency, albeit with limited success. Spain diverged slightly by introducing FITs as an alternative remuneration option alongside its existing FIPs nine years after their introduction [138]. However, despite the availability of FITs, the majority of investors continued to favor FIPs as the preferred incentive mechanism [142].

The primary immediate cause of stagnation across all countries was the reduction of subsidies. In Austria and Denmark, these cuts were introduced by newly elected governments. Austria's new socio-democratic government reduced FITs and support duration to lower the financial burden on electricity consumers during the global financial crisis. Moreover, they imposed a cap on the budget for renewable energy support [183]. Denmark's right-wing government did not prioritize environmental concerns, which led to the introduction of FIPs with low premiums instead of the existing FIT scheme and a reduced research and development funding to save costs [138]. Similarly, in Spain, FIPs were reduced, and operational hours were capped, which led to a downward trend in annual deployment [138]. However, the complete stop of deployment commenced in 2013 following the introduction of a moratorium on new projects and the wholesale transition to FITs, despite the previous preference for FIPs by 80% of stakeholders [142]. Notably, both measures were implemented by newly elected governments. At the onset of stagnation, Spain and Denmark were net exporters of electricity, and Austria experienced a gradual reduction in import dependency.

For both, Austria in its first re-acceleration and Denmark the immediate cause for the re-acceleration were increased FITs and FIPs, respectively [174], [183]. In Denmark, this re-acceleration was prompted by a renewed environmental focus and rising energy security concerns – electricity imports surged while domestic gas production decreased. Likewise, Austria faced similar energy security concerns during this period, with high electricity imports leading to a reevaluation of their renewable energy strategy. During these initial re-acceleration phases, both countries witnessed a gradual increase in annual deployment. However, the second re-acceleration in Austria diverged from Denmark's trajectory. Austria's second re-acceleration was similar to the one in Spain, as both experienced a sudden increase in annual deployment. The approaches were also similar with the introduction of tendering systems driving deployment [134], [183]. In both cases, rising energy security concerns due to escalating electricity imports were the driver. Additionally, Austria's re-acceleration was compounded by increasing electricity prices.

The importance of social acceptance in wind energy deployment becomes obvious by looking at Denmark's approach. Initially, wind turbine cooperatives played an important role, with local initiative groups owning a significant majority of installed turbines until 2001 [148]. This high level of ownership fostered acceptance, as residents directly benefited financially. However, as turbines grew in size, prominence, and cost, ownership shifted to larger companies, leading to increased resistance from communities. To address this challenge and facilitate re-acceleration, the government prioritized socio-economic factors to regain local acceptance [168], [172]. Alongside financial subsidies, they implemented a requirement for investors in onshore wind turbines to offer at least 20% ownership for sale to residents. This initiative aimed to provide residents with an opportunity to benefit financially from the turbines, mitigating concerns and improving local support.

In terms of wind conditions and industry, all three countries share similarities, as they all have favorable conditions and industry presence. Denmark stands out with one of the world's largest wind turbine industries, while Spain also hosts a significant manufacturing sector [138], [155]. Austria, although not as prominent in manufacturing, boasts a sizable supply sector for the wind turbine industry [177]. Moreover, all three nations benefit from reliable grid infrastructure, ensuring efficient electricity distribution. However, Spain lags slightly in interconnectivity with neighboring countries compared to Denmark and Austria [116].

5.3 Overall comparison of solar PV and onshore wind

Unlike the solar PV cases, the stagnation and re-acceleration periods for onshore wind show significant variation, with differing dates and durations of stagnation. This discrepancy probably comes from the absence of a global wind market crash similar to the one experienced by solar PV. Additionally, there was no EU-wide policy equivalent to the trade barriers imposed on solar PV.

Binz and Truffer [189] classify global innovation systems (GIS) for individual technologies into several categories. In particular, they characterize the GIS's for mature solar PV and onshore wind as "footlose" and "production-anchored" respectively. This indicates that the mode of innovation characteristic for wind power is largely grounded in local learning-by-doing, while for solar PV, innovation relies more on universal scientific principles and research that is not connected to any specific location. This may be a part of explanation why the deployment of solar power in individual countries is more sensitive to global market developments.

Energy security concerns and dynamic electricity demand are significant factors influencing the deployment of both solar PV and onshore wind technologies. As renewable energy sources, they contribute to improving self-sufficiency and meeting higher demand of low-carbon sources. However, promoting their deployment can cause financial burden for countries. Consequently, if there is no immediate need for additional generation capacity or if demand is not increasing, governments may be less willing to provide extensive support for deployment compared to periods of growth and rising demand.

In the wind sector, social acceptance is more important due to the prominent visibility of wind turbines in the landscape compared to solar PV installations, which can often be discreetly placed on rooftops without utilizing additional land. The development also started earlier, which leads to higher levels in deployment. Wind turbines also generate noise as their blades rotate, which potentially causes disturbance to nearby residents. Moreover, there are concerns about the impact on wildlife and property values, with residents fearing potential decreases in property value. These factors contribute to the importance of addressing social acceptance in wind energy projects [190].

By comparing the solar PV and onshore wind cases in Spain, some other parallels between the two technologies become obvious. The decline in deployment of onshore wind turbines began shortly after the crash in solar PV deployment in 2009. Both instances of reduced deployment were prompted by cuts in financial support mechanisms [122], [138]. The cause for these cuts were demand decline and growing financial burden. However, the decision to cut FITs for solar PV was more urgent due to rapid growth in deployment and significant financial burden on the country. Conversely, the decision to reduce support for wind energy was more deliberate and driven by a decline in electricity demand. Deployment in both technologies came to a halt in 2014 and only began to re-accelerate in 2018 for wind (with a significant increase in 2019) and in 2019 for solar PV. This complete stop in deployment for both technologies stemmed from Spain's introduction of a moratorium on new projects in 2012, driven by ongoing decreases in electricity demand and the country's status as a net electricity exporter [124]. The re-acceleration of both wind and solar PV was driven by the introduction of competitive tender processes in 2017 in response to rising electricity demand and therefore electricity imports. However, wind energy experienced a somewhat earlier re-acceleration, as the tenders were not technology specific, which led to most of the capacity being allocated to wind energy in the initial tender. This resulted in protests from the solar PV sector and subsequent adjustments to the tender process [134], [135]. Both re-accelerations were marked by abrupt increases in annual deployment. Overall, the similarities between the trajectories of solar PV and wind in Spain demonstrate the role of national context in addition to technology-specific factors.

5.4 Growth rates comparison

An essential aspect to analyze is whether the growth rate before or after the stagnation period was higher. To check whether the S-curve methodology is reliable, it is also important to investigate what factors may have influenced this. The following Table 5.3 provides an overview of the maximum 3-year average growth rates before and after stagnation, with the higher rate highlighted in red. All growth rates are normalized to the system size in the respective year to ensure comparability. The rates are calculated based on the equations outlined in Section 3.5. The meaningfulness of the maximum growth rate of the fitted curve is dependent on the maturity level of the technology within the respective country. When the maturity level is significantly below 0.5, indicating that the inflection point is still in the future, the maximum growth rate cannot be reliably determined [3]. This scenario applies to solar PV in Spain, where the maturity level is 0.0008. For solar PV in Greece, although the maturity level is also below 0.5, it is in close proximity, making the maximum growth rate feasible for analysis.

Table 5.3: Overview of the normalized maximum 3-year average growth rates before and after stagnation in $\frac{MW}{TWh}$. The higher rates are colored orange.

Country, Fuel	3-year average growth rate max. before stagnation	 max. after stagnation	ratio before/after
Germany solar PV	13.28	10.46	1.28
Greece solar PV	12.98	16.28	0.80
Spain solar PV	3.84	11.51	0.33
Spain wind	8.63	5.42	1.59
Denmark wind	11.00	5.83	1.89
Austria wind	3.71	4.88	0.76

Table 5.3 shows that Germany's solar PV, Spain's wind, and Denmark's wind experienced higher maximum 3-year-average growth rates before stagnation. Conversely, Greece's solar PV, Spain's solar PV, and Austria's wind showed higher growth rates after stagnation. However, for Austria, only the first stagnation is considered, as there is insufficient data for the second re-acceleration, which began in 2021 and data is only available until 2022. Consequently, the number of cases with higher maximum 3-year-average growth rates before and after stagnation is balanced. If the growth rate is higher before or after the stagnation could be dependent on whether the initial or re-accelerated growth period is (so far) longer. In Germany for solar PV and Denmark and Spain for wind, the initial growth period was longer then the

re-accelerated growth. For the other cases this was different. Their initial growth was shorter than their re-accelerated growth. Overall, the growth rates before and after stagnation are usually comparable. Significant exceptions are Spain were stagnation happened early in the deployment process and the renewed growth was three times faster, and Denmark where stagnation happened after a long period of mature growth, and the renewed growth was almost two times slower.

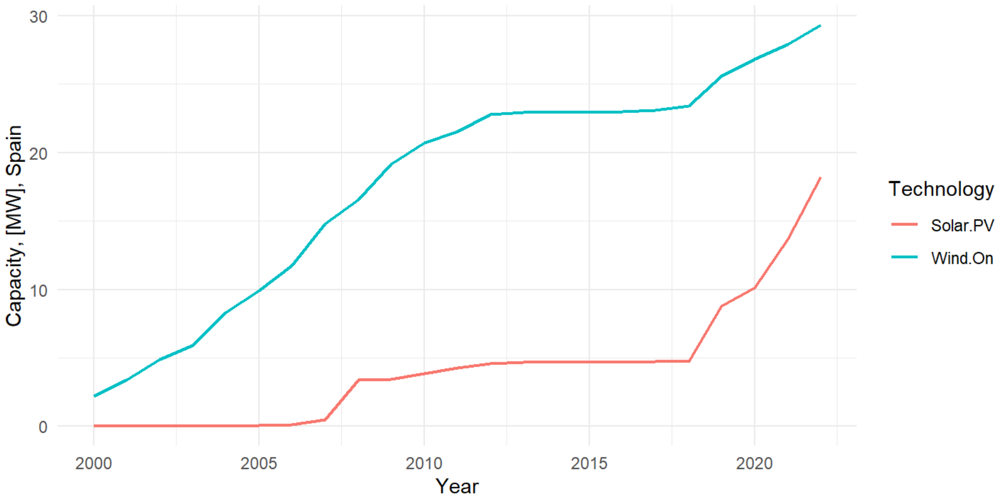
Table 5.4: Overview of the normalized maximum 3-year average growth rates and the normalized maximum growth rates according to the fitted curve in $\frac{MW}{TWh}$ with respect to feasibility of these rates. The higher rates are colored orange.

Country, Fuel	max. growth rate		ratio average/fitted
	3-year average	fitting-based	
Germany solar PV	13.28	8.03	1.65
Greece solar PV	16.28	9.15	1.78
Spain solar PV	11.51	no accurate rate measurable	-
Spain wind	8.63	7.54	1.14
Denmark wind	11.00	4.73	2.33
Austria wind	4.88	3.26	1.50

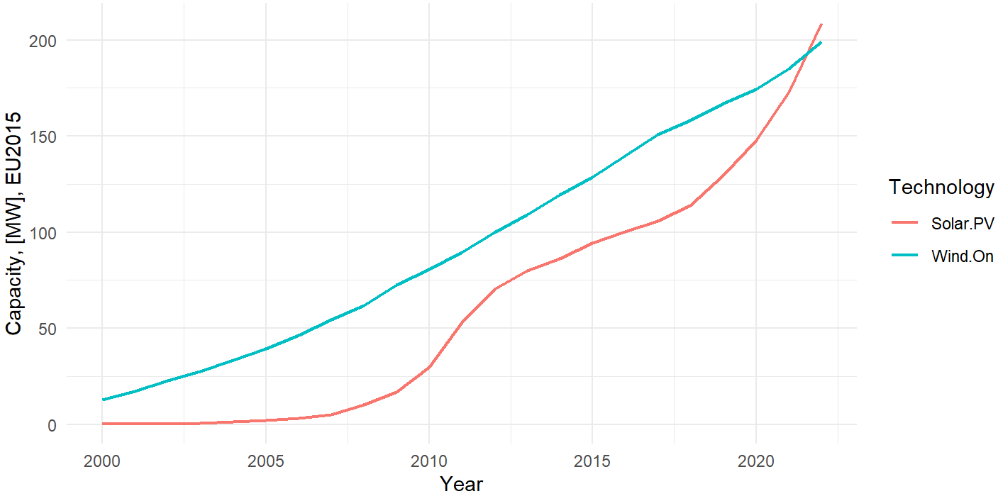
Table 5.4 shows that the maximum fitting-based growth rate – as far as it can be determined – consistently is lower than the actual maximum 3-year average growth rate. This discrepancy arises because the stagnation period is not taken into account in the fitted curves. Consequently, the curve is treated as a single S-shaped curve rater than a series of curves, resulting in a lower slope and hence a lower 3-year-short-term estimate of the growth rate. While this implies that the maximum fitting-based growth rate may not precisely reflect the maximum growth observed in the near future, it does offer better reliability for long-term growth estimations.

5.5 Global and regional comparison

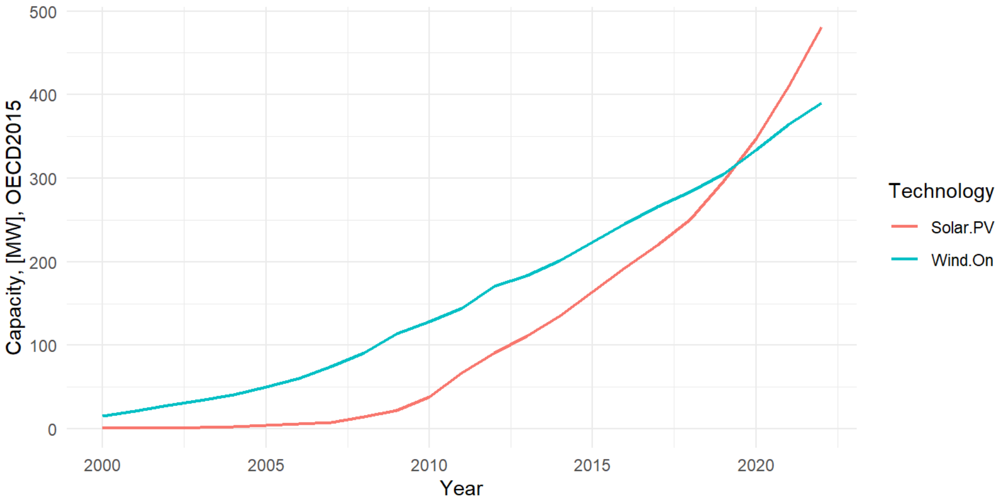
Now that we understand how growth curves look at the national level, the question arises whether similar growth patterns exist at the regional or global level. This section will delve into this analysis. The following Figure 5.1 shows growth curves of solar PV and onshore wind in different regions or country groupings in the world from one country to the whole world. The cumulative capacity is plotted over the time, beginning in the year 2000. It starts with Spain, where the stagnation periods of both technologies are very clear. For the EU member countries of 2015, the different periods of the S-curve and a subsequent re-acceleration are only recognizable for solar PV, however the stagnation is more of a slow-down. For wind it is an almost linear growth. The solar PV capacity overtook the wind capacity around 2022. The OECD countries as a whole didn't experience a stagnation phase in neither one of the technologies. Onshore wind deployment is slowly accelerating, while for solar PV the acceleration is quicker and it overtook wind capacity around 2019. A similar, but even more clear course shows the global capacity.



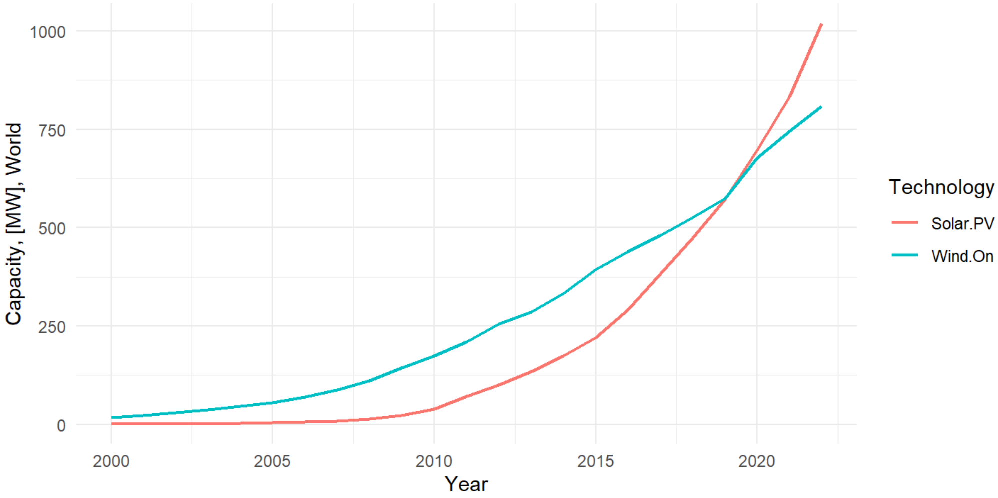
(a) Spain



(b) EU countries status 2015



(c) OECD countries status 2015



(d) World

Figure 5.1: Deployment curves of solar PV and onshore wind over time in different regions and unions beginning from 2000.

This illustrates that globally, there is not stagnation but rather a redistribution of growth, which contributes to an overall increasing and rapidly accelerating deployment of wind and solar PV technologies. This observation aligns with the theory proposed by Breetz et al. [52], which suggests that different countries play different roles in different stages of the learning curve, influenced by technological spillovers. In essence, certain political systems may excel in promoting early demonstration and niche adoption, while others are better suited for supporting large-scale deployment or system evolution [52]. Global learning, particularly in the case of solar PV, holds considerable significance. Countries seeking to restart their RES growth can take advantage of the technological advancements and cost reductions achieved through the global learning progress.

Moreover, it indicates, that while individual countries may have experience in re-accelerating renewable growth, but there is no experience on a broader regional and global level, as the deployment of solar PV and onshore wind is still accelerating there. The national experience, however, has limited applicability at broader levels, as it contains national legislation, driven by national concerns and goals.

5.6 Overall Conclusions and Learnings

The comparison of various renewable energy deployment cases and policy trajectories gives valuable insights that contribute to the existing literature on energy transition, although the experience of stagnation and re-acceleration in different national contexts is limited.

Changes in **electricity demand and import dependency** have significantly influenced policy decisions regarding RES. When demand decreases and a country becomes a net exporter of electricity, energy security concerns decrease and the government's will to support RES decreases. This is because the surplus electricity suggests that additional generation capacity is not immediately required, leading policymakers to prioritize other concerns over renewable energy promotion. Conversely, when demand for electricity increases and a country becomes dependent on electricity imports, this drives policymakers to take measures to enhance the country's self-sufficiency. In such scenarios, the government is more inclined to re-accelerate renewables, viewing them as a means to mitigate import dependency and improve domestic energy security. However, it is noteworthy that also the presence of domestic resources, particularly coal, also influences investment decisions in renewable energies. The existence of domestic resources, including coal, has a positive impact on energy security, which in turn can affect the willingness to invest in renewable energy sources. In essence, shifts in electricity demand and import-export dynamics are indicators for energy security concerns, which in turn are key drivers for shaping government policies related to renewable energy.

The **reduction and eventual phase-out of coal**, that all investigated countries decided, and in Germany additionally the phase-out of nuclear power, have notable implications for the demand for low-carbon electricity sources. As coal reduction measures take effect, there is a higher need for low-carbon energy sources. This shift aligns with broader international, regional and local policies within the European Union, like described in Section 4.1.2.

A significant aspect to consider is **policy learning**, which has been evident in the evolution of renewable energy support mechanisms. FITs have proven effective in promoting the initial growth of emerging renewable energy sources. However, it has become apparent that FITs need to be flexible and responsive to actual deployment rates and changing market dynamics, particularly in response to fluctuations in cell prices. Otherwise this leads to uncontrolled deployment and therefore a financial burden to the country, like it was the case in Spain. This leads to another key lesson learned – the importance of implementing transitional phases and adjustments to support mechanisms. For instance, Greece and Germany, in contrast to Spain, have proactively adapted their FIT structures by introducing degression rates that are dependent on an extension corridor. This approach allows a smoother transition and better alignment with the evolving market conditions, thereby reducing the risk of FITs becoming financially burdensome. As both countries had their stagnation phase a few years after Spain, it can be assumed, that they learned from Spain's political mistakes, that inconsistent policies lead to uncertainty and make a bad investment environment for RES. Tendering processes have emerged as an effective mechanism for re-accelerating growth in renewable energy deployment. These processes offer a competitive framework that can drive down costs and encourage innovation. Looking ahead, the implementation of tenders can be an effective measure to immediately re-accelerate growth or in the best case replace FITs when they become cost-ineffective without triggering a stagnation.

These learnings align with a theory proposed by Breetz et al. [52], which suggests that different policy instruments are suitable for different stages along the experience curve of renewable energy technologies and shows that transitions are not smooth and linear, especially for frontrunners.

There are also some noteworthy insights specifically relevant to solar PV deployment. One key observation is the potential **impact of having a domestic solar PV manufacturing industry** on deployment trends during periods of trade barriers implementation. Countries with a domestic industry may experience less drastic decreases in deployment due to the presence of a domestic market. This dynamic is particularly evident when trade barriers coincide with decreasing FITs. In cases where FITs remain high, deployment may even continue to increase or remain stable. For instance, China maintained high levels of deployment during trade barriers imposed by Europe, as they could redirect their surplus production to their domestic market, supported by robust FITs.

The German experience highlights another important lesson: trade barriers combined with reduced subsidies are not an effective strategy for protecting domestic industries. In response to recent challenges faced by their domestic solar PV industry, Germany is now considering a different approach. Rather than resorting to trade barriers, they are thinking about introducing a "Resilienzbonus". Under this scheme, investors have the flexibility to choose between purchasing Chinese panels and continuing to receive standard financing terms, or opting for panels manufactured in Germany and receiving a premium of up to EUR cent 3.5 per kWh for 20 years additionally to the standard financing terms, with gradual reductions in the premium until 2030 [191]. This approach aims to support domestic industry.

In the realm of onshore wind power, several noteworthy factors come into play. It's particularly significant to observe that **policy shifts** triggering stagnation frequently stem from newly elected administrations. In Austria, for instance, the incoming socio-democratic government aimed to alleviate the financial strain on electricity consumers. Similarly, Denmark's right-wing government deprioritized environmental concerns. Both countries illustrate how priorities regarding RES, particularly wind energy, can differ among political parties. A change in government direction consequently leads to a shift in priorities and support schemes, particularly for wind energy, which tends to be a more contentious energy source.

Resistance to wind energy tends to be stronger than for solar PV, despite an overall positive attitude towards it among the general public [192]–[195]. The primary driver of this support is the environmental benefits associated with renewable energy. However, when individuals are faced with the prospect of wind turbines being erected near their homes, opposition often arises. This phenomenon, commonly referred to as the "Not in my backyard" (NIMBY) theory [196], suggests that selfish concerns about visual impact and noise may contribute to local resistance. Another theory posits that the mere announcement of a wind turbine project triggers a thinking process leading to opposition [190]. Regardless of the underlying reasons, addressing local opposition is crucial. Denmark's experience highlights the effectiveness of involving residents in wind energy projects, whether through wind turbine cooperatives or requirements for investor ownership. This aligns with existing research of Wolsink [190] and O'Hare [196] emphasizing the importance of public engagement and information dissemination for the success of wind power initiatives.

The insights discussed above confirm the theory proposed by Kulmer et al. [29], which posits that critical events serve as "turning points" in the deployment of low-carbon energy. These events are understood as a focal point in one of the three perspectives. They can stem from either the supply or demand side, encompassing changes in electricity demand, shifts in national and international policies, and social aspects.

To conclude, there are indeed multiple causes in all three perspectives for stagnation and subsequent re-acceleration. Within the techno-economic perspective, the demand dynamics play the most important role for both technologies. The global market situation only had impact on the solar PV sector. Policies are within the political perspective. However, they are the immediate causes for subsidized growth, that are themselves driven by other factors and national interests like energy security concerns and global trends like the financial crisis. Policy learning is an intersection between the political and socio-technical perspective, as the action of learning is a social phenomenon. Other mechanisms within the socio-technical perspective are the prominence of manufacturing industry in the country and social resistance, which is more important in the onshore wind sector. The most important factors associated with stagnation and re-acceleration and their prominence in different cases are summarized in Table 5.5 and Table 5.6 respectively.

Table 5.5: Summary of the most important factors associated with stagnation and their prominence in the different cases.

	Source	Demand decline/ stagnation prior to stagnation	Decline of import dependence of el. supply prior to stagnation	Generous support policies leading to major spending	Change of the ruling party	Social resistance
Germany	S		+	+		
Greece	S	+	+	+		
Spain	S	+		++		
Spain	W	+	+			
Denmark	W	+	+		+	+
Austria (1)	W		+		+	+
Austria (2)	W					+

Table 5.6: Summary of the most important factors associated with re-acceleration and their prominence in the different cases (*also phase-out of nuclear power).

	Source	Demand growth prior to re-acceleration	Growth of import dependence of el. supply prior to stagnation	Introduction of more flexible support policies e.g. tenders	Change of the ruling party	Policies addressing social resistance	Coal phase-out
Germany	S			+			+*
Greece	S	+	+	+			+
Spain	S	+	+	+			+
Spain	W	+	+	+			+
Denmark	W		+		+	+	
Austria (1)	W	+					
Austria (2)	W			+			

6

Conclusion

This thesis has identified cases and periods of stagnation followed by re-acceleration in renewable growth. It has provided insights into the underlying mechanisms behind these growth patterns, aiming to equip policymakers with valuable knowledge to accelerate the transition towards a low-carbon future. Additionally, it has examined whether growth rates post-stagnation outpace or lag behind those observed prior to the stagnation.

By visually analyzing the growth curves of solar PV and onshore wind installations in various countries, this study identified instances characterized by a period of stagnation followed by re-acceleration. From these cases, six were chosen for a detailed analysis. Factors such as policy shifts, market conditions, technological progress, and external influences were scrutinized to uncover the reasons behind the periods of stagnation and subsequent re-acceleration.

Causes for both stagnation and re-acceleration in RES technologies are often directly influenced by policy decisions. Policies, which may not be appropriate for the current stage of technological development, such as FITs becoming financially burdensome after rapid deployment, can lead to stagnation. Re-acceleration typically occurs through policy learning; for instance, the use of tenders can effectively stimulate RES deployment while managing costs.

Another influential factor is electricity demand. Stagnation in RES deployment often accompanies stagnating or declining demand, as there is no immediate need for additional electricity generation. Conversely, growth in demand, particularly for low-carbon electricity driven by international or EU policies, tends to re-accelerate RES deployment. Similarly, import dependence of electricity supply plays a role. When a country has low import dependence and maybe even is a net exporter of electricity, concerns about energy security may diminish, leading to decreased political support for RES deployment and subsequent stagnation. Conversely, if a country relies on imports of electricity or fossil fuels used in generating it, energy security concerns may prompt increased support for RES deployment to enhance self-sufficiency. These factors are summarized in Figure 6.1.

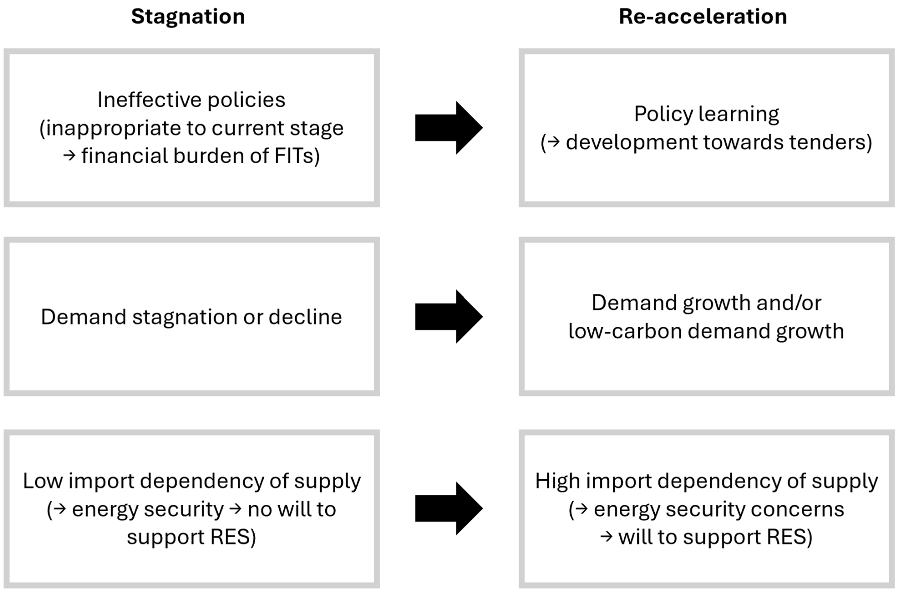


Figure 6.1: Overview of the technology comprehensive reasons for turning points.

There are also technology specific reasons for the stagnation. For solar PV, the global market shock triggered by the onset of Chinese mass production caused the stagnation. Due to the mass production there was a sharp decline in panel prices, leading to unmanageable deployment rates and a heavy financial burden because of the FITs, which led to their reduction. Additionally, trade barriers imposed by the European Commission caused panel prices to rise again, contributing to the stagnation of solar PV deployment.

In contrast, for onshore wind deployment, social acceptance is a critical factor, as wind deployment is less synchronized than solar PV deployment. Local resistance often arises when individuals are confronted with the prospect of wind turbines being installed near their homes. To address this, involving residents through wind turbine cooperatives or implementing requirements for investor ownership can be effective strategies in mitigating opposition.

The number of cases with higher actual maximum 3-year-average growth rates before and after stagnation appears to be balanced, suggesting that the height of the growth rate is not influenced by whether stagnation has occurred or not. However, it's evident that the fitting-based maximum growth rate consistently falls below the actual maximum 3-year average growth rate. This is because the fitted curve is treated as a single S-shape, which may not accurately reflect the maximum growth observed in the near future. While this implies that the maximum fitting-based growth rate may not precisely capture the peak growth experienced, it does provide greater reliability for long-term growth estimations.

An additional finding is that although individual countries may possess expertise in re-accelerating renewable growth, there is none in broader regional and global contexts, as the acceleration of solar PV and onshore wind deployment is still ongoing at these levels. The experience gained at the national level has limited applicability at broader scales due to the direct influence of national legislation, which is shaped by distinct national concerns and goals.

The research presented in this thesis has several limitations. One challenge lies in the limited number of cases that were investigated. Therefore, the findings may lack generalizability, and difficulties in drawing conclusions that can be applied to other contexts may arise. There is a higher risk of bias or outliers influencing the results. Furthermore, the limited amount of cases may restrict the ability to detect patterns, trends, or relationships, which might constrain the robustness of the study's conclusions.

Furthermore, all the cases analyzed in this this thesis represent the same country group, which also may limit the generalizability of the findings. This mainly arises from the fact that only early adopters, primarily EU members and OECD countries with the financial means, drive the initial adoption and expansion of newly developed technologies. Therefore these countries have a longer history of the specific technology and it is more likely that they already faced phases of stagnation and subsequent re-acceleration.

In this thesis, only countries that faced stagnation with a subsequent re-acceleration were investigated. At the same time, for some countries similar external factors (e.g. financial crisis, the solar PV market crash) did not lead to lead to a stagnation and a subsequent re-acceleration. A systematic comparison between these two groups can provide a deeper insight into causes of stagnation and re-acceleration, and should be prioritized as a task for future research.

Bibliography

[1] Intergovernmental Panel on Climate Change - IPCC, *Climate Change 2022 - Mitigation of Climate Change*. Cambridge University Press, 2023.

[2] D. Gielen, F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, and R. Gorini, "The role of renewable energy in the global energy transformation," *Energy Strategy Reviews*, vol. 24, pp. 38–50, 2019.

[3] A. Cherp, V. Vinichenko, J. Tosun, J. A. Gordon, and J. Jewell, "National growth dynamics of wind and solar power compared to the growth required for global climate targets," *Nature Energy*, vol. 6, no. 7, pp. 742–754, 2021.

[4] V. Vinichenko, J. Jewell, J. Jacobsson, and A. Cherp, "Historical diffusion of nuclear, wind and solar power in different national contexts: Implications for climate mitigation pathways," *Environmental Research Letters*, vol. 18, no. 9, p. 094 066, 2023.

[5] R. Way, M. C. Ives, P. Mealy, and J. D. Farmer, "Empirically grounded technology forecasts and the energy transition," *Joule*, vol. 6, no. 9, pp. 2057–2082, 2022.

[6] F. Creutzig, P. Agoston, J. C. Goldschmidt, G. Luderer, G. Nemet, and R. C. Pietzcker, "The underestimated potential of solar energy to mitigate climate change," *Nature Energy*, vol. 2, no. 9, 2017.

[7] European Commission, *Repowereu*, 25.04.2024.

[8] COP28, *Cop28: Global renewables and energy efficiency pledge*, 25.04.2024.

[9] V. Vinichenko, M. Vetier, J. Jewell, L. Nacke, and A. Cherp, "Phasing out coal for 2 °c target requires worldwide replication of most ambitious national plans despite security and fairness concerns," *Environmental Research Letters*, vol. 18, no. 1, p. 014 031, 2023.

[10] A. Grübler, "Time for a change: On the patterns of diffusion of innovation," *Daedalus*, vol. 125, no. 3, pp. 19–42, 1996.

[11] A. Sood and G. J. Tellis, "Technological evolution and radical innovation," *Journal of Marketing*, vol. 69, no. 3, pp. 152–168, 2005.

[12] A. Cherp, V. Vinichenko, J. Jewell, E. Brutschin, and B. Sovacool, "Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework," *Energy Research & Social Science*, vol. 37, pp. 175–190, 2018.

[13] A. L. George and A. Bennett, *Case studies and theory development in the social sciences* (BCSIA studies in international security), [Nachdr.] Cambridge, Mass.: MIT Press, 2004.

[14] B. Gompertz, "On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies.,"

Abstracts of the Papers Printed in the Philosophical Transactions of the Royal Society of London, vol. 2, pp. 252–253, 1833.

[15] E. M. Rogers, *Diffusion of innovations*, 3. ed. New York, NY: Free Press, 1983.

[16] S. Jacobsson and A. Johnson, “The diffusion of renewable energy technology: An analytical framework and key issues for research,” *Energy Policy*, vol. 28, no. 9, pp. 625–640, 2000.

[17] J. Markard, “The next phase of the energy transition and its implications for research and policy,” *Nature Energy*, vol. 3, no. 8, pp. 628–633, 2018.

[18] N. Bento, C. Wilson, and L. D. Anadon, “Time to get ready: Conceptualizing the temporal and spatial dynamics of formative phases for energy technologies,” *Energy Policy*, vol. 119, pp. 282–293, 2018.

[19] T. Napp, D. Bernie, R. Thomas, J. Lowe, A. Hawkes, and A. Gambhir, “Exploring the feasibility of low-carbon scenarios using historical energy transitions analysis,” *Energies*, vol. 10, no. 1, p. 116, 2017.

[20] J. Rotmans, R. Kemp, and M. van Asselt, “More evolution than revolution: Transition management in public policy,” *Foresight*, vol. 3, no. 1, pp. 15–31, 2001.

[21] S. Jacobsson, “Transforming the energy sector: The evolution of technological systems in renewable energy technology,” *Industrial and Corporate Change*, vol. 13, no. 5, pp. 815–849, 2004.

[22] W. B. Arthur, *Increasing returns and path dependence in the economy* (Economics, cognition, and society). Ann Arbor: University of Michigan Press, 1994.

[23] V. Vinichenko, *Measuring and diagnosing energy transitions.* 7.11.2023.

[24] J. Blazquez, R. Fuentes-Bracamontes, C. A. Bollino, and N. Nezamuddin, “The renewable energy policy paradox,” *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 1–5, 2018.

[25] B. Wanner, *Is exponential growth of solar pv the obvious conclusion?* 2019.

[26] E. Martinot, “Grid integration of renewable energy: Flexibility, innovation, and experience,” *Annual Review of Environment and Resources*, vol. 41, no. 1, pp. 223–251, 2016.

[27] L. Bird, M. Milligan, and D. Lew, *Integrating variable renewable energy: Challenges and solutions*, 2013.

[28] G. J. Kramer and M. Haigh, “No quick switch to low-carbon energy,” *Nature*, vol. 462, no. 7273, pp. 568–569, 2009.

[29] V. Kulmer, S. Seebauer, H. Hinterreither, D. Kortschak, M. C. Theurl, and W. Haas, “Transforming the s-shape: Identifying and explaining turning points in market diffusion curves of low-carbon technologies in austria,” *Research Policy*, vol. 51, no. 1, p. 104 371, 2022.

[30] C. Dong, R. Wiser, and V. Rai, “Incentive pass-through for residential solar systems in california,” *Energy Economics*, vol. 72, pp. 154–165, 2018.

[31] M. J. van der Kam, A. Meelen, W. van Sark, and F. Alkemade, “Diffusion of solar photovoltaic systems and electric vehicles among dutch consumers: Implications for the energy transition,” *Energy Research & Social Science*, vol. 46, pp. 68–85, 2018.

[32] J. Kingdon, *Agendas, alternatives, and public policies.* 1984.

[33] T. Wright, *Learning curve.* Journal of the Aeronautical Sciences, 1936.

[34] T. Skocpol, *States and Social Revolutions: A Comparative Analysis of France, Russia and China.* 1979.

[35] S. D. Krasner, *Defending the National Interest: Raw Materials Investments and U.S. Foreign Policy.* 1978.

[36] J. Dryzek, D. Downes, C. Hunold, D. Schlosberg, and H. K. Hernes, *Green States and Social Movements.* 2003.

[37] D. Helm, "Energy policy: Security of supply, sustainability and competition," *Energy Policy*, vol. 30, no. 3, pp. 173–184, 2002.

[38] Yergin. 1991.

[39] Keohane, "Cooperation and discord in global climate policy," *Nat. Clim. Change*, p. 1, 2016.

[40] F. Dobbin, B. Simmons, and G. Garrett, "The global diffusion of public policies: Social construction, coercion, competition, or learning?" *Annual Review of Sociology*, vol. 33, no. 1, pp. 449–472, 2007.

[41] K. Holzinger and C. Knill, "Causes and conditions of cross-national policy convergence," *Journal of European Public Policy*, vol. 12, no. 5, pp. 775–796, 2005.

[42] L. M. Schaffer and T. Bernauer, "Explaining government choices for promoting renewable energy," *Energy Policy*, vol. 68, pp. 15–27, 2014.

[43] A. Cherp, V. Vinichenko, J. Jewell, M. Suzuki, and M. Antal, "Comparing electricity transitions: A historical analysis of nuclear, wind and solar power in germany and japan," *Energy Policy*, vol. 101, pp. 612–628, 2017.

[44] J. Byrne and L. Kurdgelashvili, *Handbook of photovoltaic science and engineering*, A. Luque López and S. Hegedus, Eds., Chichester, 2011.

[45] Intergovernmental Panel on Climate Change, *Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change; chapter 11: Policy financing and implementation*, 2012.

[46] G. R. Timilsina, L. Kurdgelashvili, and P. A. Narbel, *A review of solar energy: Markets, economics and policies*, 2011.

[47] D. Finon, *L'inadéquation du mode de subvention du photovoltaïque à sa maturité technologique.* CIRED&Gis LARSEN Working Paper, Ed., 2008.

[48] H. J. J. Yu, N. Popiolek, and P. Geoffron, "Solar photovoltaic energy policy and globalization: A multiperspective approach with case studies of germany, japan, and china," *Progress in Photovoltaics: Research and Applications*, vol. 24, no. 4, pp. 458–476, 2016.

[49] IRENA, *Global Status of Wind Power in 2012.* 2012.

[50] Intergovernmental Panel on Climate Change (IPCC) Working Group III., *Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change. chapter 1 p. 197.* 2011.

[51] D. Jacobs and B. K. Sovacool, "Feed-in tariffs and other support mechanisms for solar pv promotion," in *Comprehensive renewable energy*, A. Sayigh, Ed., Amsterdam: Elsevier, 2012, pp. 73–109.

[52] H. Breetz, M. Mildenberger, and L. Stokes, "The political logics of clean energy transitions," *Business and Politics*, vol. 20, no. 4, pp. 492–522, 2018.

[53] M. Vetier, *Policies for energy transitions*, 28.11.2023.
[54] P. A. Sabatier, *Policy change over a decade or more.* 1993.
[55] C. Meseguer, “Rational learning and bounded learning in the diffusion of policy innovations,” *Rationality and Society*, vol. 18, no. 1, pp. 35–66, 2006.
[56] J. S. Levy, “Case studies: Types, designs, and logics of inference,” *Conflict Management and Peace Science*, vol. 25, no. 1, pp. 1–18, 2008.
[57] D. Collier, *APSA-CP Newsletter Winter*, p. 1, 1999.
[58] H. E. Brady, *Rethinking social inquiry: Diverse tools, shared standards.* 2004.
[59] C. H. Achen and D. Snidal, “Rational deterrence theory and comparative case studies,” *World Politics*, vol. 41, no. 2, pp. 143–169, 1989.
[60] IEA, *Iea - international energy agency*, 25.03.2024.
[61] IRENA, *Irena – international renewable energy agency*, 25.03.2024.
[62] V. Vinichenko, “Mechanisms of energy transitions: National cases and the worldwide uptake of wind and solar power,” Ph.D. dissertation, 2018.
[63] International Energy Agency - Photovoltaic Power Systems Programme, “National survey report of pv power applications in germany 2002 to 2011.,” 2002 to 2011.
[64] International Energy Agency - Photovoltaic Power Systems Programme, *National survey report of pv power applications in japan 2002 to 2012.* 2002 to 2012.
[65] International Energy Agency - Photovoltaic Power Systems Programme, *Trends in photovoltaic applications 2010.* 2010.
[66] International Energy Agency - Photovoltaic Power Systems Programme, *Trends in photovoltaic applications 2013*, 2013.
[67] EUR-Lex, *Kyoto protocol on climate change.* 2011.
[68] UNFCCC, *What is the kyoto protocol?* 20.04.2024.
[69] European Parliament, *Directive - 2001/77 - en - eur-lex*, 2001.
[70] The Carbon Trust, *Eu emissions trading scheme (eu ets)*, 2020.
[71] European Environment Agency, “Climate action and renewable energy package a major step forward,” 2008.
[72] Clean Energy Wire, *End of eu of trade controls for chinese solar panels sparks fears of glut on market*, 2018.
[73] UNFCCC, *The paris agreement*, 25.04.2024.
[74] PPCA, “Our story - ppca,” *Powering Past Coal Alliance*, 2.08.2022.
[75] European Parliament, *Energy transition in the eu.* 2023.
[76] K. Appunn, *Coal in germany*, Clean Energy Wire, Ed., 2013.
[77] BDEW Bundesverband der Energie- und Wasserwirtschaft, “Die energieversorgung 2023 – jahresbericht.,” 2023.
[78] IEA, *World energy balances - data product - iea*, 14.05.2024.
[79] J. Deign, “Germany’s maxed-out grid is causing trouble across europe,” *Greentech Media*, 31.03.2020.
[80] M. Boxwell, *Solar electricity handbook: A simple, practical guide to solar energy - designing and installing photovoltaic solar electric systems*, 2010 ed., 3. ed. Ryton on Dunsmore, Warwickshire, U.K.: Greenstream Publishing, 2010.
[81] BMWK Energiewende, *The energy transition across the german länder.* 2018.

[82] U.S. Energy Information Administration, *Where solar is found*, 2023.

[83] H. Wirth, "Aktuelle fakten zur photovoltaik in deutschland.," 2024.

[84] S. Jacobsson and V. Lauber, "The politics and policy of energy system transformation—explaining the german diffusion of renewable energy technology," *Energy Policy*, vol. 34, no. 3, pp. 256–276, 2006.

[85] T. Grau, M. Huo, and K. Neuhoff, "Survey of photovoltaic industry and policy in germany and china," *Energy Policy*, vol. 51, pp. 20–37, 2012.

[86] C.-J. Yang, "Reconsidering solar grid parity," *Energy Policy*, vol. 38, no. 7, pp. 3270–3273, 2010.

[87] V. Lauber and L. Mez, "Three decades of renewable electricity policies in germany," *Energy & Environment*, vol. 15, no. 4, pp. 599–623, 2004.

[88] International Energy Agency - Photovoltaic Power Systems Programme, "Trends in photovoltaic applications 2002 to 2013," 2002 to 2013.

[89] P. Mints, "The history and future of incentives and the photovoltaic industry and how demand is driven," *Progress in Photovoltaics: Research and Applications*, vol. 20, no. 6, pp. 711–716, 2012.

[90] International Energy Agency - Photovoltaic Power Systems Programme, *Annual report 2005.* 2005.

[91] R. Bhandari and I. Stadler, "Grid parity analysis of solar photovoltaic systems in germany using experience curves," *Solar Energy*, vol. 83, no. 9, pp. 1634–1644, 2009.

[92] I. Alloisio, *The policy drivers of pv industry growth. paper presented at the 26th european photovoltaic solar energy conference (eu–pvsec).* Hamburg, Germany, 2011.

[93] International Energy Agency - Photovoltaic Power Systems Programme, *National survey report of pv power applications in germany 2003 and 2006.* 2003 and 2006.

[94] European Commission, "Energy economic developments in europe," *European Economy*, vol. 1, 2014.

[95] Federal Ministry for the Environment Nature Conservation and Nuclear Safety, *Report on the environmental economy 2009 fact & figures for germany.* 2009.

[96] A. de La Tour and M. Glachant, *How do solar photovoltaic feed–in tariffs interact with solar panel and silicon prices? an empirical study.* CERNA Working paper, Ed., 2013.

[97] Umweltbundesamt, *Erneuerbare-energien-gesetz*, 1.03.2024.

[98] Bundesverband Solarwirtschaft -BSW Solar, *Photovoltaik | bundesverband solarwirtschaft*, 29.02.2024.

[99] S. Enkhardt, "Photovoltaik-zubau in deutschland erreicht nach jahresendrallye knapp drei gigawatt 2018," *pv magazine*, 2019.

[100] Y. Rack, *Price drop fueled 68% increase in german solar buildout in 2018.* 2019.

[101] B. Wehrmann, *Solar power in germany – output, business & perspectives*, Clean Energy Wire, Ed., 2018.

[102] K. Appunn, *Eeg reform 2016 – switching to auctions for renewables*, Clean Energy Wire, Ed., 2016.

[103] T. Spangenberg, “Deutschland wird zum solarland: Branche freut sich über volle auftragsbücher ,” *Fuldaer Zeitung*, 2023.

[104] HELLENIC REPUBLIC Ministry of the Environment and Energy, *National energy and climate plan*, 2019.

[105] IEA, *Executive summary – greece 2023 – analysis - iea*, 11.03.2024.

[106] Mordor Intelligence, *Solar energy greece market - companies & report*.

[107] ESMAP, *Global photovoltaic power potential by country.* World Bank, Ed., Washington, DC, 2020.

[108] Mouratian, “Simplification of licensing procedure for energy plants,” *Energy Law Rev*, vol. 4, p. 19, 2005.

[109] Karageorgou, “Confrontation of climate changes and res—the european and greek perspective,” *Energy Law Rev*, vol. 5, p. 5, 2006.

[110] E. Giannini, A. Moropoulou, Z. Maroulis, and G. Siouti, “Penetration of photovoltaics in greece,” *Energies*, vol. 8, no. 7, pp. 6497–6508, 2015.

[111] P. Anagnostopoulos, N.-A. Spyridaki, and A. Flamos, “A “new-deal” for the development of photovoltaic investments in greece? a parametric techno-economic assessment,” *Energies*, vol. 10, no. 8, p. 1173, 2017.

[112] S. Loumakis, E. Giannini, and Z. Maroulis, “Renewable energy sources penetration in greece: Characteristics and seasonal variation of the electricity demand share covering,” *Energies*, vol. 12, no. 12, p. 2441, 2019.

[113] Y. Seiradakis and E. Stazilova, “Energy laws and regulations 2024 | greece,” 8.12.2023.

[114] IEA, *Spain electricity security policy – analysis - iea*, 27.02.2024.

[115] Red Eléctrica de España, *El sistema eléctrico español 2011.* 2012.

[116] J. Bilbao, E. Bravo, O. Garcia, C. Verala, M. Rodriguez, and Gonzalez P, *ELECTRIC SYSTEM IN SPAIN: GENERATION CAPACITY, ELECTRICITY PRODUCTION AND MARKET SHARES.* 2011.

[117] A. Pérez-Burgos, J. Bilbao, A. de Miguel, and R. Román, “Analysis of solar direct irradiance in spain,” *Energy Procedia*, vol. 57, pp. 1070–1076, 2014.

[118] Rapid Transitions Alliance, *Solar power surges in spain.* 2022.

[119] P. Del Río González, “Ten years of renewable electricity policies in spain: An analysis of successive feed-in tariff reforms,” *Energy Policy*, vol. 36, no. 8, pp. 2917–2929, 2008.

[120] Pablo del Río and Pere Mir-Artigues, *A Cautionary Tale: Spain’s Solar PV Investment Bubble.* IISD: International Institute for Sustainable Development, 2014.

[121] Government of Spain, *Real decreto 661/2007, de 25 de mayo, sobre la regulación de la actividad de producció de energía eléctrica en régimen especial. rd 661/2007*, 2007.

[122] Government of Spain, *Real decreto 1578/2008, de 26 de septiembre, sobre la retribución de la actividad de producción de energía eléctrica mediante tecnología solar fotovoltaica para instalaciones posteriores a la fecha de vigencia de la retribución del real decreto 661/2007, de 25 de mayo. rd 1578/2008*, 2008.

[123] Government of Spain, *Real decreto-ley 14/2010, de 23 de diciembre, por el que se establecen medidas urgentes para la corrección del déficit tarifario del sector eléctrico: Rdl 14/2010*, 2010.

[124] Government of Spain, *Real decreto-ley 1/2012, de 27 de enero, por el que se procede a la supresión de los procedimientos de preasignación de retribución y a la supresión de los incentivos económicos para nuevas instalaciones de producción de energía eléctrica a partir de cogeneración, fuentes de energía renovables y residuos: Rdl 1/2012*, 2012.

[125] A. Burger, "Spain's second solar boom, and possible market failure?" *Solar Magazine*, 19.09.2019.

[126] A. Colasante, I. D'Adamo, and P. Morone, "What drives the solar energy transition? the effect of policies, incentives and behavior in a cross-country comparison," *Energy Research & Social Science*, vol. 85, p. 102 405, 2022.

[127] J. López Prol and K. W. Steininger, "Photovoltaic self-consumption is now profitable in spain: Effects of the new regulation on prosumers' internal rate of return," *Energy Policy*, vol. 146, p. 111 793, 2020.

[128] P. Escobar, E. Martínez, J. C. Saenz-Díez, E. Jiménez, and J. Blanco, "Profitability of self-consumption solar pv system in spanish households: A perspective based on european regulations," *Renewable Energy*, vol. 160, pp. 746–755, 2020.

[129] R. Fernández-González, E. Arce, and D. Garza-Gil, "How political decisions affect the economy of a sector: The example of photovoltaic energy in spain," *Energy Reports*, vol. 7, pp. 2940–2949, 2021.

[130] A. Ibarloza, I. Heras-Saizarbitoria, E. Allur, and A. Larrea, "Regulatory cuts and economic and financial performance of spanish solar power companies: An empirical review," *Renewable and Sustainable Energy Reviews*, vol. 92, pp. 784–793, 2018.

[131] E. Bullich-Massagué, F.-J. Cifuentes-García, I. Glenny-Crende, M. Cheah-Mañé, M. Aragüés-Peñalba, F. Díaz-González, and O. Gomis-Bellmunt, "A review of energy storage technologies for large scale photovoltaic power plants," *Applied Energy*, vol. 274, p. 115 213, 2020.

[132] Government of Spain, *Real decreto 359/2017, de 31 de marzo, por el que se establece una convocatoria para el otorgamiento del régimen retributivo específico a nuevas instalaciones de producción de energía eléctrica a partir de fuentes de energía renovables en el sistema eléctrico peninsular. rd 359/2017*, 2017.

[133] K. Gürtler, R. Postpischil, and R. Quitzow, "The dismantling of renewable energy policies: The cases of spain and the czech republic," *Energy Policy*, vol. 133, p. 110 881, 2019.

[134] J. S. Hill, "European energy auctions yield ever-lower wind energy prices in germany & spain," *CleanTechnica*, 22.05.2017.

[135] J. S. Hill, "Spain awards 4 gigawatts solar & 1 gigawatt wind in renewables auction," *CleanTechnica*, 28.07.2017.

[136] Ministerio de Economía, Comercio y Empresa, *Renewable energy in spain*, 6.03.2024.

[137] Asociación Empresarial Eólica, *Wind energy in spain - asociación empresarial eólica*, 15.02.2024.

[138] IRENA, “30 years of policies for wind energy: Lessons from 12 wind energy markets,” 2013.

[139] World Nuclear Association, *Nuclear power in spain | spanish nuclear energy*, 8.03.2024.

[140] J. Lewis, *A comparison of wind power industry development strategies in Spain, India and China.* 2007.

[141] European Renewable Energy Council - EREC, “Spain: Renewable energy policy review,” 2009.

[142] IEA, *Royal decree 617/2013 on professional certificates in the renewable energy sector*, 2013.

[143] J. Lipp, “Lessons for effective renewable electricity policy from denmark, germany and the united kingdom,” *Energy Policy*, vol. 35, no. 11, pp. 5481–5495, 2007.

[144] K. Johansen, “Blowing in the wind: A brief history of wind energy and wind power technologies in denmark,” *Energy Policy*, vol. 152, p. 112 139, 2021.

[145] F. Petersen, *Vindmøllehistorien 1978-2018.* 2018.

[146] M. Rüdiger, “From import dependence to self-sufficiency in denmark, 1945−2000,” *Energy Policy*, vol. 125, pp. 82–89, 2019.

[147] Danish Energy Agency, *Danmarks Energifortider. Hovedbegivenheder På Energiområdet.* 2016.

[148] K. M. Araújo, *Low Carbon Energy Transitions.* 2018.

[149] Denmark.dk, *Infrastructure in denmark | advanced and well-functioning*, 28.03.2024.

[150] T. Skødt, *Electricity interconnections*, 2013.

[151] K. Tornbech, *The queen plugged in the great belt power link*, 2010.

[152] Nordic Competition Authorities, *Capacity for competition: Investing for an efficient nordic electricity market*, 2007.

[153] TenneT, *Cobracable*, 28.03.2024.

[154] Viking Link, *Viking link interconnector*, 28.03.2024.

[155] L. Fernández, “Wind energy in denmark - statistics & facts,” *Statista*, 10.01.2024.

[156] L. Fernández, *Denmark: Turnover from wind power industry | statista*, 27.07.2023.

[157] Danskindustri.dk, *Eksport af energiteknologi og -service 2021*, 2021.

[158] NOAA, *The jet stream*, 20.09.2023.

[159] B. Mortensen, P. A. Truelsen, and L. Christensen, *In: Varmeforsyningsloven Med Kommentarer.* 2018.

[160] Quartz+co, *Energiindustriens Historiske Omstilling Og Betydning for Danmark.* 2015.

[161] Energinetdk and Rambøll, *Sejerø Bugt Havmøllepark. VVM-redegørelse og miljørapport. Del 4: sammenfatning og konklusion. 8.06.2015.* 2015.

[162] State of Green, *District energy explained.* 2018.

[163] The Energy Movement Ooa, *Energibevægelsen OOA - organisationen til oplysning om atomkraft.* 1994.

[164] F. Hvelplund, P. A. Østergaard, and N. I. Meyer, “Incentives and barriers for wind power expansion and system integration in denmark,” *Energy Policy*, vol. 107, pp. 573–584, 2017.

[165] Danmarks Vindmølleforening, *Vindmøllernes historie.* 2013.

[166] S. Krohn, *Wind Energy Policy in Denmark: 25 years of Success–What Now.* 2002.

[167] Organization for Economic Co-Operation and Development, *Regulatory reform in denmark*, 2000.

[168] K. Sperling, F. Hvelplund, and B. V. Mathiesen, “Evaluation of wind power planning in denmark – towards an integrated perspective,” *Energy*, vol. 35, no. 12, pp. 5443–5454, 2010.

[169] M. Oteman, M. Wiering, and J.-K. Helderman, “The institutional space of community initiatives for renewable energy: A comparative case study of the netherlands, germany and denmark,” *Energy, Sustainability and Society*, vol. 4, no. 1, pp. 1–17, 2014.

[170] N. I. Meyer, “Learning from wind energy policy in the eu: Lessons from denmark, sweden and spain,” *European Environment*, vol. 17, no. 5, pp. 347–362, 2007.

[171] P. Maegaard, *Danish renewable energy policy.* 2009.

[172] H. T. Anker and M. L. Jørgensen, *Mapping of the Legal Framework for Siting of Wind Turbines.* 2015.

[173] B. K. Sovacool, *ENERGY and ETHICS. Justice and the Global Energy Challenge.* 2013.

[174] M. Rathmann, T. Winkel, E. Stricker, M. Ragwitz, A. Held, B. Pfluger, G. Resch, C. Panzer, S. Busch, I. Konstantinaviciute, and et al., *Renewable energy policy country profiles. 2009 version. Based on information available in October 2009.* European Commission, 2009.

[175] Danish Ministry of Climate, Energy and Building, *Dk energy agreement, march 22 2012*, 2012.

[176] Austrian Power Grid AG, *Stromnetz österreich.*

[177] IG Windkraft supported by BMK, *Wind energy - industry in austria*, 2024.

[178] SKF Wind News - Wind industry news, insights and conversations, *Harnessing the alpine breeze - skf wind news*, 2023.

[179] Austrian Wind Potential Analysis, *Windatlas österreich*, 31.01.2022.

[180] N. Schneider and A. Rinscheid, “The (de-)construction of technology legitimacy: Contending storylines surrounding wind energy in austria and switzerland,” *Technological Forecasting and Social Change*, vol. 198, p. 122 929, 2024.

[181] N. Wenz, “Energy governance in austria,” in *Handbook of energy governance in Europe*, ser. Springer Nature Reference, M. Knodt and J. Kemmerzell, Eds., Cham, Switzerland: Springer, 2022, pp. 455–482.

[182] IEA, *Policy database – data & statistics - iea*, 11.04.2024.

[183] OeMAG, *Gesetze & regelwerk*, 12.04.2024.

[184] IEA Wind, *Tcp report 2021*, 2021.

[185] IG Windkraft, *Umfrage belegt: Bevölkerung will mehr windkraft*, 13.04.2024.

[186] Beyond Fossil Fuels, *Europe’s coal exit - beyond fossil fuels*, 31.01.2024.

[187] J. López Prol, “Regulation, profitability and diffusion of photovoltaic grid-connected systems: A comparative analysis of germany and spain,” *Renewable and Sustainable Energy Reviews*, vol. 91, pp. 1170–1181, 2018.

[188] Fraunhofer-Institut für Solare Energiesysteme ISE, *Klimaneutrales energiesystem bis 2050: Kontinuierlicher pv-ausbau während der nächsten 10 jahre erforderlich - fraunhofer ise*, 17.04.2024.

[189] C. Binz and B. Truffer, “Global innovation systems—a conceptual framework for innovation dynamics in transnational contexts,” *Research Policy*, vol. 46, no. 7, pp. 1284–1298, 2017.

[190] M. Wolsink, “Wind power implementation: The nature of public attitudes: Equity and fairness instead of ‘backyard motives’,” *Renewable and Sustainable Energy Reviews*, vol. 11, no. 6, pp. 1188–1207, 2007.

[191] 1komma5grad, *Resilienzbonus - hintergrund & auswirkung auf solaranlagen*, 24.04.2024.

[192] M. Wolsink, “Attitudes and expectancies about wind turbines and wind farms,” *Wind Eng*, vol. 13, p. 196, 1989.

[193] G. Walker, “Renewable energy and the public,” *Land Use Policy*, vol. 12, no. 1, pp. 49–59, 1995.

[194] P. Devine–Wright, “Beyond nimbyism: Towards an integrated framework for understanding public perceptions of wind energy,” *Wind Energy*, vol. 8, no. 2, pp. 125–139, 2005.

[195] M. Wolsink, *Maatschappelijke acceptatie van windenergie.* 1990.

[196] M. O’Hare, *Not on my block you don’t - facilities siting and the strategic importance of compensation*, 1977.

[197] Solargis, *Global solar atlas*, 29.01.2024.

[198] Global Wind Atlas, 8.03.2024.

A

Appendix

A.1 Import dependency of the investigated countries

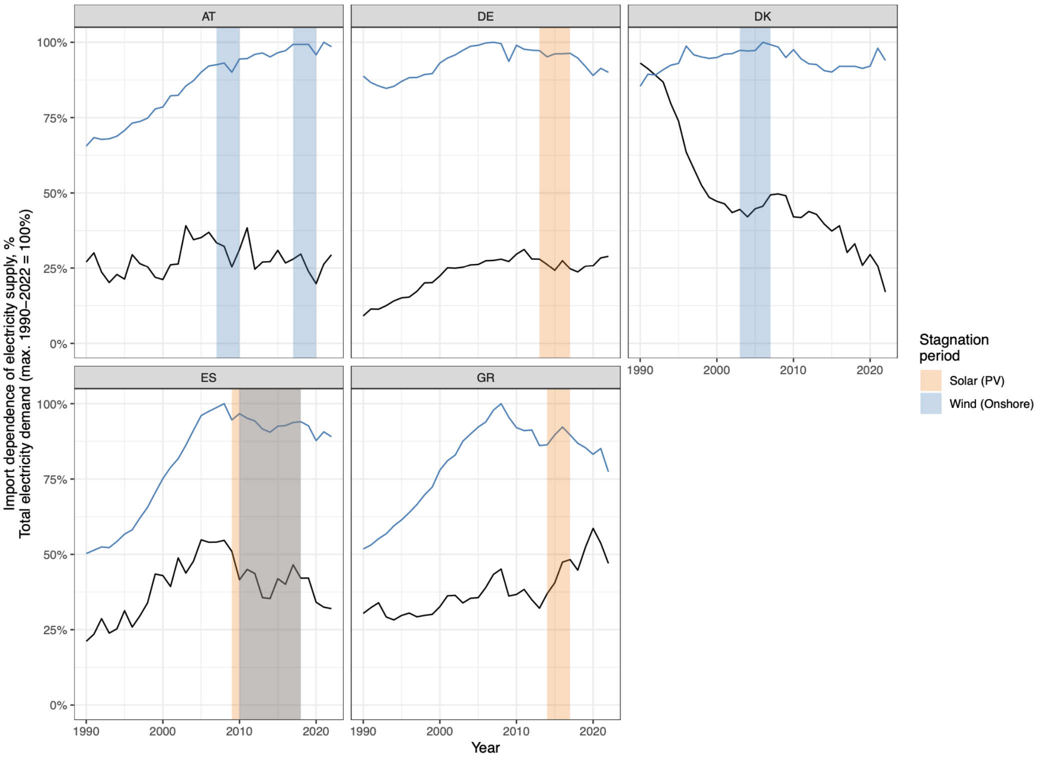


Figure A.1: Import dependency of electricity supply of the investigated countries; plot by V. Vinichenko.

A.2 Germany solar irradiation map

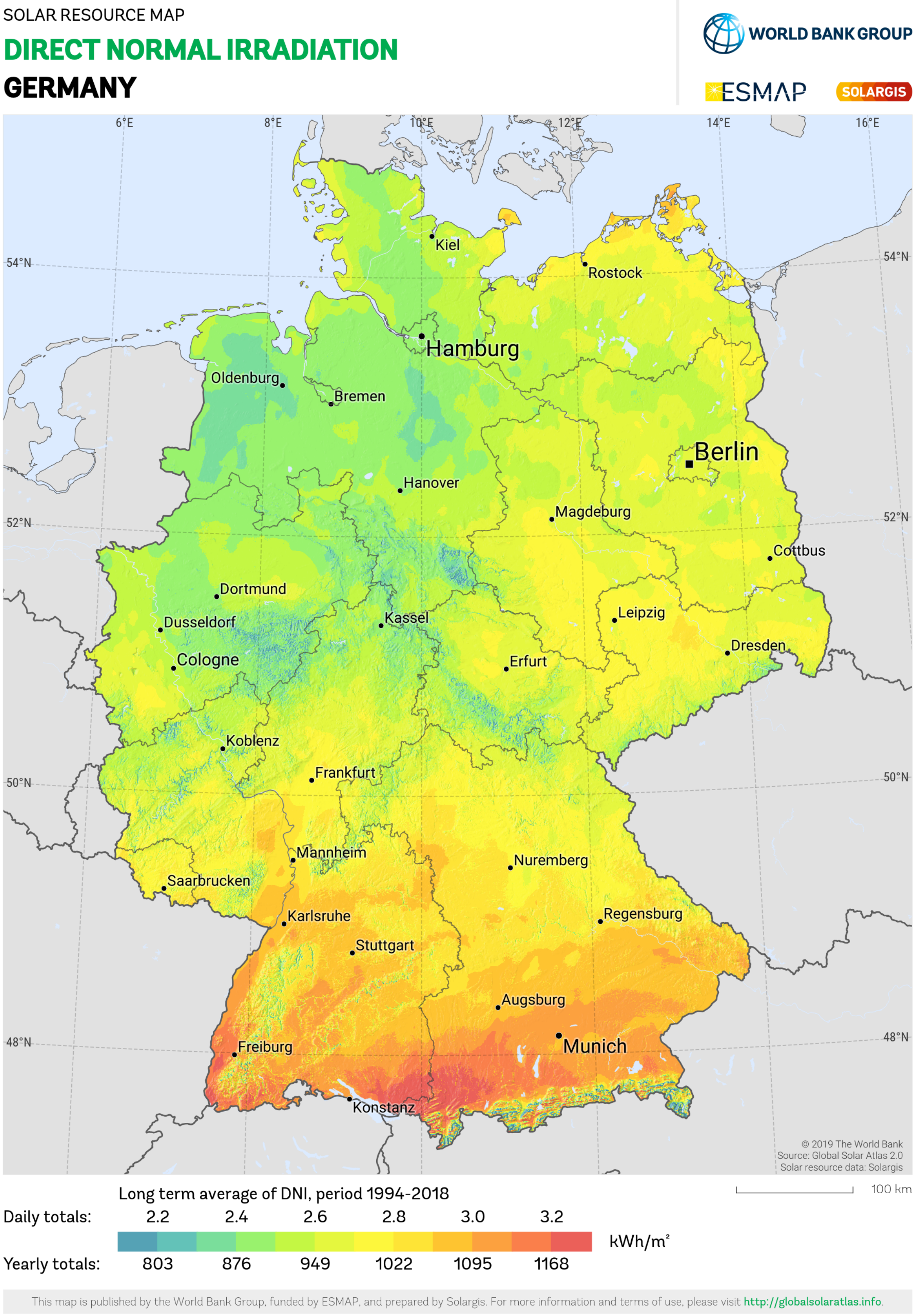


Figure A.2: Solar irradiation map for Germany [197].

A.3 Greece solar irradiation map

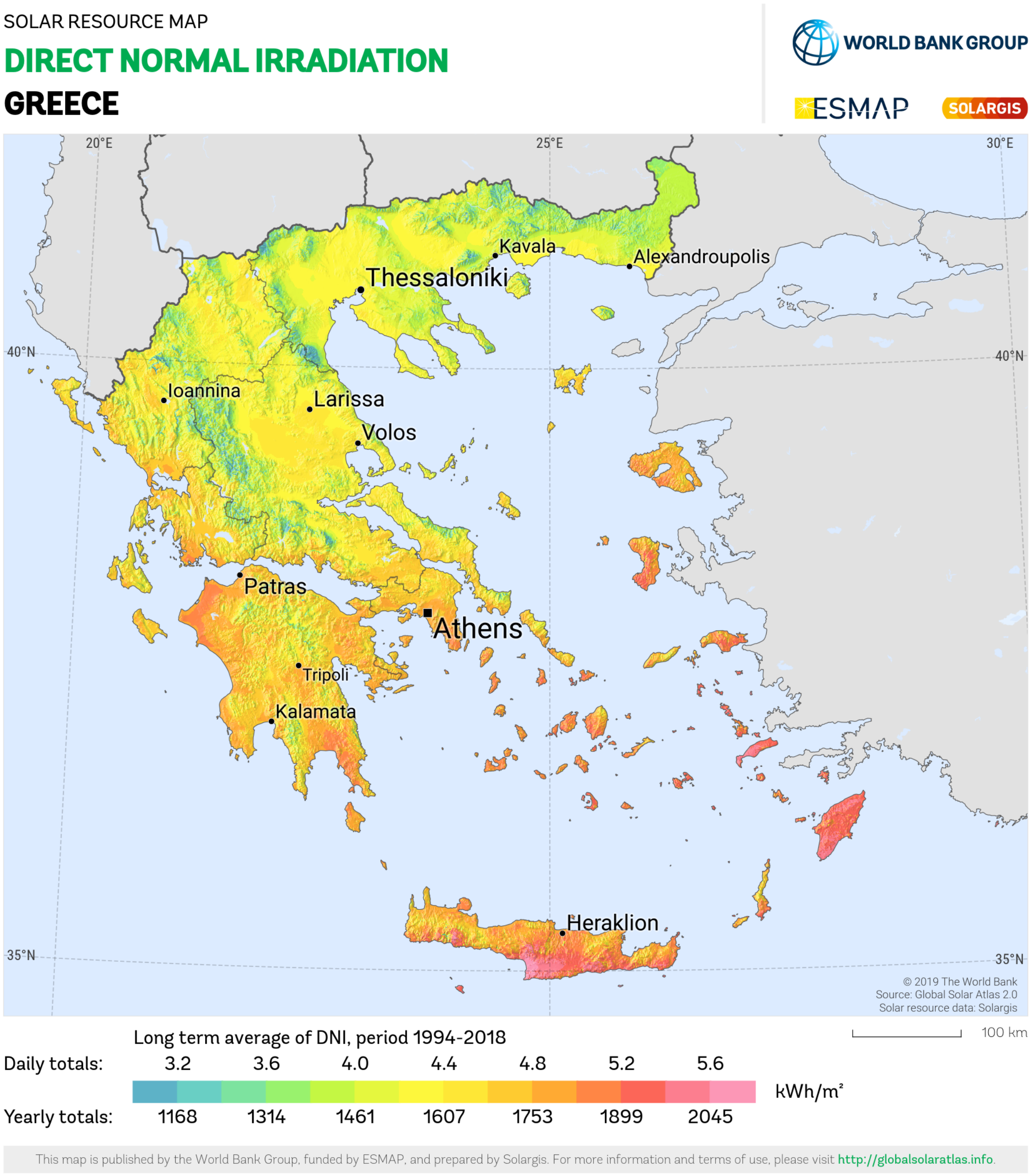


Figure A.3: Solar irradiation map for Greece [197].

A.4 Spain solar irradiation map

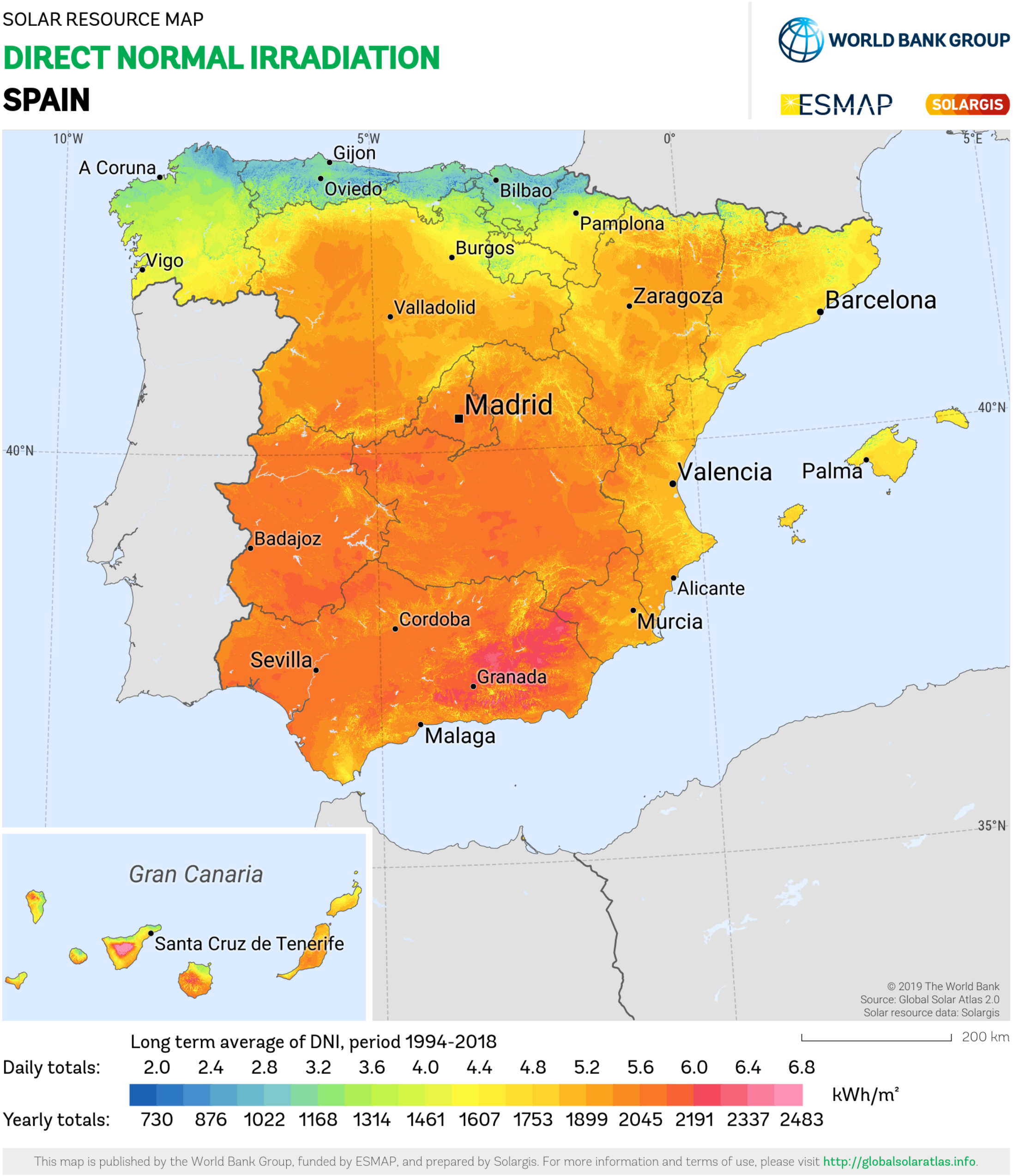


Figure A.4: Solar irradiation map for Spain [197].

A.5 Spain Global Wind Atlas map

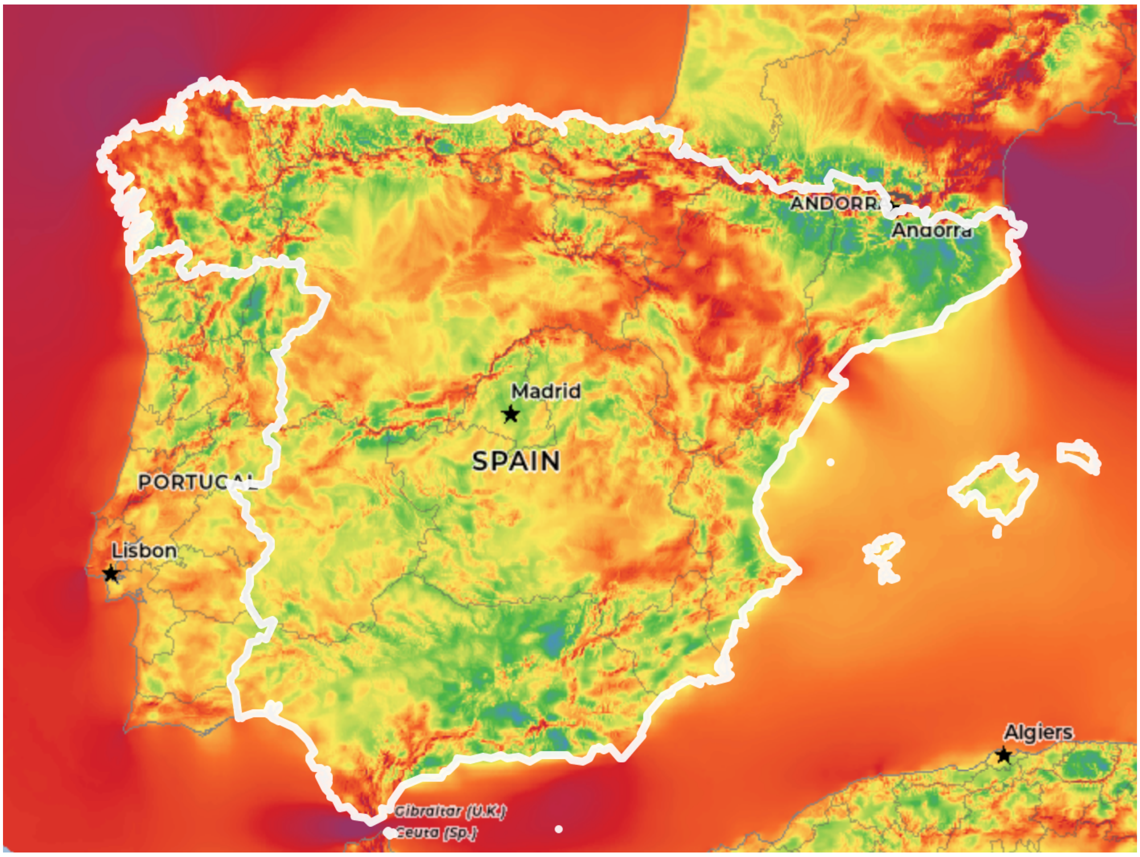


Figure A.5: Global Wind Atlas map for Spain [198].

A.6 Denmark Global Wind Atlas map

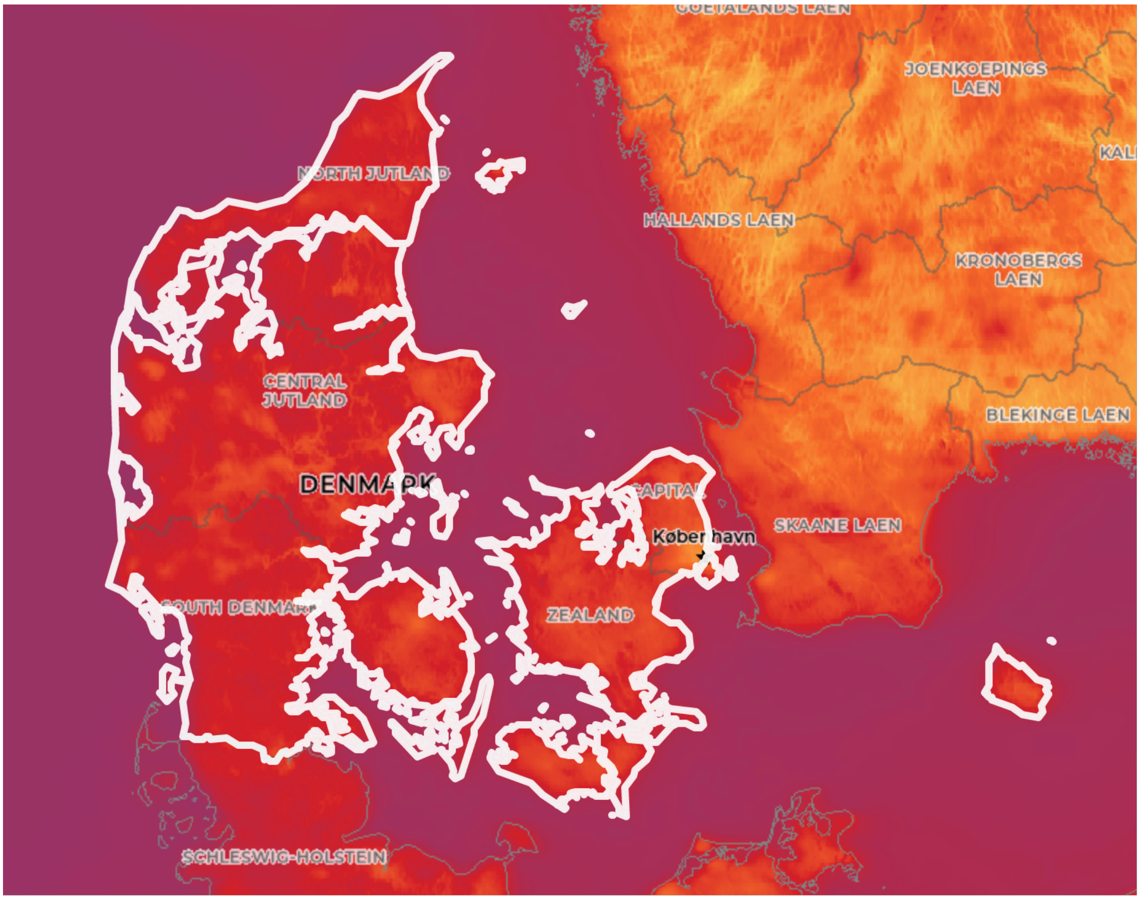


Figure A.6: Global Wind Atlas map for Denmark [198].

A.7 Austria Global Wind Atlas map

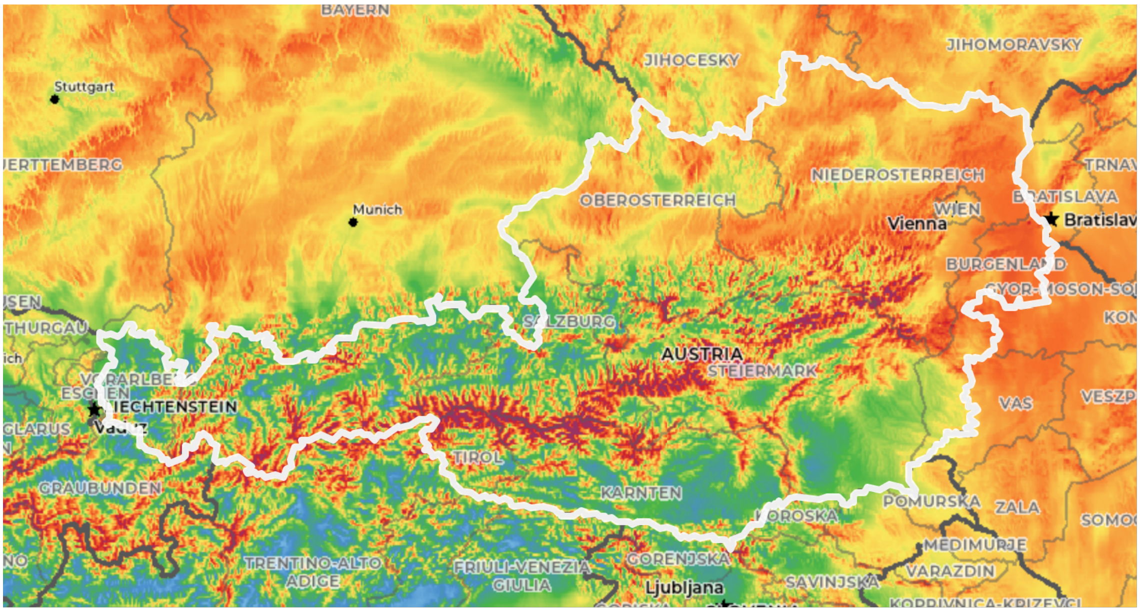


Figure A.7: Global Wind Atlas map for Austria [198].

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