Accelerating technology growth through policy interventions

The case of onshore wind in Germany

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Introduction

There is general consensus that climate change mitigation requires sustained and rapid growth of renewables such as wind and solar PV to decarbonise electricity systems(1,2). This is mirrored in recent policy commitments, such as the goal to triple global renewabels deployment(3), or national targets such as Germany's ambition to triple the speed of renewables deployment (4). A natural question following from such targets is: How difficult (or easy) is it to achieve and sustain such rapid renewables growth – what type and strength of policy interventions are required?

However, the literature on renewables growth to date gives conflicting answers. A first strand of literature expects exponential growth of renewables in the near- to medium-term future, enabled mainly by cost reductions resulting from larger scale of deployment (5,6,7). While a "tapering off" of renewables growth may eventually occur as markets become saturated, this is not expected to happen soon(5). A second strand of literature disagrees with the assumption that exponential growth is likely over an extended period of time but instead that growth will stop accelerating because of natural resource constraints, grid or market integration, or limits of social acceptance (8,9,10,11) . This second strand observes such slow-down in countries or regions with advanced renewables deployment such as the EU, and cautions that renewables growth may already be nearing market saturation (11,12).

It is clear that challenges remain in estimating likely future renewables growth pathways, and the limited understanding of and accounting for the the role of policies has been highlighted as one major challenge(13). Neither of the two strands systematically assess policies related to technology diffusion, but make implicit (and sometimes explicit) assumptions about the role of policies: for the first strand, policies do not play a large role as cost reductions render renewables competitive even in contexts with little to no policy support(6) – at most, policies may be needed to encourage continued exponential growth, but required efforts are expected to decline as technology costs decrease (5). In the second strand, which sees early signs of stagnation of technology growth, policies are considered unlikely to be able to prolong or significantly speed up exponential growth (8,9), and may even provide signals limiting growth, if policy support is withdrawn over time (12).

The assumptions from both strands can be summarised under three main hypotheses: (1) Less policies are required as renewables deployment progresses due to its declining cost (mainly arising from the first strand). (2) Policies other than financial support become more important over time, as cost of onshore wind increases, but other constraining mechanisms emerge (mainly from the second strand). (3) The amount of financial support decreases over time as wind deployment increases (arising from both strands).

Here, we test these hypotheses by studying the case of onshore wind deployment in Germany, which has far surpassed early stages of growth, and is thus an ideal case to explore for how long different growth trajectories can be sustained, and what the role of policies has been over time. We draw on approaches and concepts from the socio-technical transitions and policy mix literature to understand feedbacks between policy interventions and renewables growth. We bridge these insights with a quantitative assessment of growth regimes of onshore wind over time.

We first review relevant literature on renewables growth, as well as on policy mixes in relation to renewabels growth, based on which we develop an approach to assessing changes in the growth regime for onshore wind in Germany over time. We then identify and classify wind-related policies over time, which we map to the idenfied growth regimes. Finally, we also map policy developments to cost developments of onshore wind.

Conceptual background

Phases, growth rates and mechanisms of technology diffusion

There is general consensus that, following patterns of technological diffusion, renewables growth occurs along S-curves and contain several phases of growth(5,10,12,14). As technologies are first introduced, there is typically a period characterized by high uncertainty and learning, when technology costs are high and growth rates are unstable(15). The end of the formative phase is usually called "take-off"(10,16) – technology costs become lower, adoption increases, and growth rates steady. The take-off point is usually identified once the technology has captured a significant share of the market (which may be considered at different limits, usually between 0.2%-2.5% percent of market share (refs)).

The next phase is often called the "growth phase" (10,17), but how growth evolves throughout this phase is contested.

Some argue that growth is expected to remain "exponential" for an extended period of time before rapidly "tapering off", meaning that it is expected that growth rates to remain constant which leads to increasing overall deployment (5,18). Mechanisms enabling such growth are that after being taken up by the market, increased deployment of renewables enables cost reductions according to Wright's law, likely due to increasing experience and learning as a result of renewables deployment which could render for example the production of components to become less expensive, and components to function better. (5,6,7,18). This is in turn assumed to facilitate further uptake of the technology especially as it becomes cost-competitive with fossil fuels (6). The data underlying these projections and assumptions typically are renewables deployment and cost developments at global level (5,6). Policies are not systematically assessed in this strand of the literature, but Way et al mention that policies may be important to expand the exponential growth phase as long as possible, so that cost reductions can be achieved more quickly (though the amount of effort needed overtime is expected to decline, as technology costs are expected to decrease) (5). Creutzig et al(6) argue that currently, renewables are already succeeding “even in markets with no carbon price or other climate policy”, indicating that little to no policy support may be needed in addition to self-reinforcing mechanisms of cost reduction.

Others argue that growth is expected to follow a logistic, rather than exponential, curve (9,11). The growth stops accelerating at the inflection point after a short ‘quasi-explonential’ phase. Kramer and Haigh (8) call the threshold after which growth stops accelerating “materiality”, which they estimate on global level to be achieved once a technology has reached 1% of the world’s energy mix, and they argue that this pattern remains constant across technologies. Mechanisms related to expected declines in growth rates relate to social opposition, natural resource constraints, and challenges related to grid and market integration that can impede the profitability of renewables despite cost declines (8,9,19). The role of policies in this strand of the literature may be considered as limited - while there is recognition that policies adapted to the deployment stage of a technology can support technology growth, constraints are difficult to overcome: learning by doing takes time and cannot be accelerated indefinitely (8); or policies may not be sustainable throughout the technology diffusion due to their cost (12). Policies may thus be expected to have only limited success when it comes to re-accelerating growth after it has begun to “taper off” and growth rates have begun to decline.

However, instead of such stagnation, one may also expect growth to continue for a prolonged period of time at a slower rate (10). One may also expect growth to fluctuate over time, with periods of acceleration and deceleration (20). Kulmer et al(20) map the growth of photovoltaics, residential heat pumps, and electric vehicles in Austria, and find several turning points in the growth regimes of these technologies, and argue that these may have partly been influenced by policy interventions. However, Kulmer et al(20) do not consider the concept of technology “take-off”, which may mean that some of the observed turning points arose due to high uncertainties and erratic growth in the formative phase of the technology. Here, we build on and expand this approach by applying it to a technology in an advanced stage of deployment, namely onshore wind in Germany.

Policy mixes for technology diffusion and sustainability transitions

To assess and map the evolution of policy interventions in relation to onshore wind deployment, we also draw on several strands within the literature that has assessed policies in relation to technology diffusion, or sustainability transitions in general.

First, there is a strand of literature which has focused on assessing individual policy interventions that address different types of barriers in support of technology deployment, such as (1) subsidies or feed-in tariffs to facilitate diffusion and cost reductions (20,21,22,23,24,25); (2) nature protection rules, siting rules or financial compensation may to address both bureaucratic issues regarding the placement of renewables and acceptance-related issues (26,27,28); and (3) rules to help with the integration of renewables into existing physical and non-physical systems, such as facilitating grid expansion, or reforming electricity markets (23,28).

Second, we draw on the concept of policy density, which assesses the evolution of the amount of policies over time in relation to whether policy outcomes are achieved. Literature on policy density has observed an increasing number of policies over time; across different countries and different policy areas (29,30,31). There is an ongoing debate regarding whether this should be considered a measure of “ambition”, i.e. more policies indicate higher political ambition to address an issue (31), or whether this is a “malfunction” of democracies where policies cannot be removed because this is politically more difficult, and continuous policy additions lead to bureaucratic overburdening (30).

Third, there is a strand of literature which has systematically assessed the evolution of combinations of different instrument types over time using different metrics. Oberthür and von Homeyer (32), for example, found an increasing diversity of policy instruments in the climate policy mix of the EU over time which they interpret as an increasing “thickness” of the policy mix, likely attributed to increasing efficiency. Contrastingly, Schmidt and Sewering (33) assess “policy mix balance” and find that the dispersion of policy instruments across different instrument types as a share of the overall policy mix is negatively correlated to renewables growth.

There are also many different metrics that assess content-related aspects of policies, for example their “intensity” (29), “strength”, “stringency”, or “specificity” (33)(Schmidt and Sewerin 2019). However, when measuring policies along such metrics, it becomes difficult to balance between metrics that measure nuances relevnant to the policy outcome to be studied, while at the same time being comparable across policies, and measurable by available data (31). In this paper, we quantify one type of policy only, namley economic support, which can be quantified relatively easily in monetary terms.

While the above literature mainly focuses on effects of policy interventions on technological change, there is also recognition in the literature that policy interventions themselves are affected by technological growth – as technology deployment evolves, policy priorities can shift from primarily focusing on facilitating low-carbon technology diffusion, to decreasing system costs, or to securing a functioning energy supply(34). Policies likely will adapt to these new challenges and barriers, in turn affecting how technological deployment evolves, and thus “co-evolving” together with technology diffusion (35). Lauber and Jacobsson (23)have studied the case of Germany’s renewables regulation over time, observing that discourses among policymakers change as renewables technologies diffuse and new challenges emerge, leading to adjustments and changes in policies, in turn affecting renewables deployment.

Summary

The insights from the policy literature highlight the relevance of better understanding the relationship between policy interventions and growth regimes of renewables technologies. Technologies do not diffuse in a vacuum, but are influenced by many different policies that may either support their diffusion, or potentially hinder it. The continous feedbacks between technology deployment and policy interventions may thus be expected to lead to periods of acceleration of policy deployment, where growth rates increase, and deceleration, where growth rates decline. Technology diffusion literature does to date not systematically and explicitly consider such interactions between the policy and technology systems. Here, we capture three hypotheses from our review of technology diffusion literature to date, which we will test by systematically quantifying and classifying policy interventions for onshore wind in Germany, and mapping these to growth trajectories of onshore wind deployment over time:

(1) **There are less policies over time as wind deployment increases**. This hypothesis arises from technology diffusion literature which assumes technology cost to decrease with increasing deployment, making it as cheap or cheaper as conventional fuel sources, which in turn facilitates its deployment with little to no policy support (5,6). Another reason for policy support to decrease stems from the concern that policy costs may increase with increasing technology deployment, potentially leading for policies to be withdrawn (12).

(2) **Non-economic policies become more important over time, as cost of onshore wind increases, but other constraining mechanisms emerge.** This hypothesis stems from literature warning that there are barriers other than technology cost, that may hinder its deployment (9,10). If technology cost decreaes over time and becomes a less important barrier, other barriers may gain (relative) importance and be reflected in policies. This is also reflected in some of the policy mix literature (34,35).

(3) **The amount of financial support decreases over time as wind deployment increases.** This hypothesis stems from the same assumption in the literature, especially that, as deployment increases experience with and knowledge about a specific technology, less R&D funding, and less effort are required to support its diffusion (5).

Approach and methods

We test these hypotheses using a single case study, focusing on onshore wind power in Germany. This case is thus ideally suited as onshore wind power is in an advanced phase of diffusion clearly having surpassed the formative phase (10). Additionally, there is rich primary data available on German onshore wind-related policies, as well as a large amount of prior studies (23,25,26,28,36,37,38,39) to triangulate primary data collection with.

Identifying turning points of growth regimes

We start by identifying the take-off point for onshore wind power in Germany – this is the point at which the formative phase ends during which we expect erratic and unstable growth rates, and the growth phase begins, during which we expect to identify more stable growth regimes.

In prior literature, different thresholds have been defined for the "take-off" point of a technology, ranging from 0.2%-2.5% of final market share (8,15,40,41). Here, we define final market share as total domestic electricity generation. We identify a possible range of years for technology take-off, beginning with the first year when onshore wind reached more than 0.2% of final market share, and ending with the last year in which onshore wind was below 2.5% of total market share. We then identify the average of both as the central estimate for the take-off of onshore wind in Germany. This method allows us to identify a best estimate for the take-off year of onshore wind in Germany, acknowledging the reality that both electricity generation from onshore wind, and total electricity generation, may fluctuate from year to year.

Following the take-off point, based on previous literature, one may expect to see either (1) prolonged exponential growth, (2) growth along an S-curve such as projected by a logistic function, or (3) growth that does not match either of these two models. We use a hindcasting approach (41) to test the performance of several growth models on curtailed historical data of onshore wind deployment for Germany. We test the performance of projecting wind power growth based on the exponential growth model; the logistic growth model, the logistic-linear growth model and the Gompertz-model (41).

We compare empirically observed wind power deployment with modelled growth trajectories, and find that since the take-off point, there have been several periods of acceleration and deceleration of growth, that are not captured by growth models assuming prolonged growth according to a singular growth regime and may lead to either over- or under-estimating growth.

We thus take inspiration from the approach of Kulmer et al(20), who identify turning points at which growth regimes of technologies change, to better understand when turning points occur, and to be able to map these to ongoing changes in the policy system, and to technology cost. We adapt the method of Kulmer et al(20) by only identifying turning points after technology take-off has occurred. Using the software "R", we fit different combinations of possible growth models (logistic or linear functions) to all available data points for GW onshore wind installed, ranging from the take-off year, until the most recent year for which data is available (2023). One constraint to different model combinations is that there needs to be a minimum of five data points between two 'function change' years; as well as between a 'function change' year and the start and end of the curve respectively. This ensures that there are enough datapoints for each curve to be properly fitted, but it results in the fact that very late turning points - e.g. in 2021 for a timeseries that ends in 2023- would not be captured by this method. All of the different potential fit combinations are compared using the Aikaike Information Criterion (AIC) - this measure compares "goodness of fit" while at the same time punishing for adding extra parameters and thus avoiding "overfitting" using too many different models. The best fit combination ranked by AIC is then used to identify turning points.

Identifying and classifying policy interventions relevant for onshore wind

Identifying wind-relevant policies in Germany

Combinations of different policy interventions are often called "policy mixes" in the literature. Policy mixes, in turn, are often defined as consisting of two elements: overarching aims, goals or strategies; and concrete tools, interventions or instruments to achieve these aims (33,42,43,44,45). To identify the relevant elements of the "focal policy mix" in a given case, Ossenbrink et al(45) outline three different approaches: a top-down approach, a bottom-up approach, and a combined approach. Our approach is most similar to the "bottom up" approach, since our starting point is the choice of a specific "impact domain", rather of one explicit policy area. Our aim is to capture relevant policies that may have affected the diffusion of onshore wind power, even those that are not necessarily explicitly aimed at expanding wind power. Nature protection regulations, for example, may affect where wind power can be placed, without explicitly following the goal of expanding onshore wind deployment. This approach allows us to capture policies even as priorities or 'strategic intents' shift over time (34). We focus on one governance level, namely policies at the national level.

To identify the relevant policies, we consult the policy database of the Clearingstelle EEG/KWKG"(46). This is an agency which has been established by the Environment Ministry (BMU) in 2007, and was transferred to Ministry for economy and climate protection (BMWK) in 2013. Its main mandate is to offer advice and mediation on issues related to the German Renewables Directive (EEG) and other energy-relevant directives. In addition to these services, the Clearingstelle also hosts a database on German energy legislation. We search among all documents under the section "Political Programmes" (dt.: "Politische Programme"), which contain documents mainly published by public institutions regarding renewables regulations. The database includes different types of laws and regulations, strategies and programmes such as the "Onshore Wind Strategy", informative documents that outline how certain laws should be interpreted or implemented, as well as monitoring reports. There are a total of 170 "Political Programmes". Of these 170 documents, we capture 82 documents for further analysis which contain the term "wind"; the earliest one was published in 2005, the latest one published in 2023. We then review the downloaded documents, and capture information on (1) the names, (2) contents (e.g. feed-in-tariff, nature protection, minimum distance regulation), and (3) start and end dates of any policies that are mentioned in relation to wind.

We supplement these findings with policies from literature identified on renewables policies and wind deployment in Germany. We do this for two reasons: first, because the documents from the Clearingstelle only start form 2005, and we can thus not be sure that these documents contain all relevnat policies that had been in place before 2005. Second, because this enables us to triangulate our findings and potentially add any policies that have not been linked to wind deployment in political documents, but have been found to be relevant in previous scientific literature.

Classifying and quantifying wind-relevant policies in Germany

Our aim is to map both the density, i.e. the amount of policies over time, as well as policy types, to onshore wind deployment over time. We thus classify policies by policy priorities, which may capture the overall intent, priorities or goals that are part of the policy mix beyond the diffusion of onshore wind, which may help indicate types of barriers or constraints that arise for onshore wind diffusion over time.

We take an iterative approach to develop our classification system for policy priorities that are likely to be relevant for onshore wind power: first, we collect likely relevant policy priorities from existing literature reviewed in the literature review section. We then conduct a first round of policy classification using the original classification system, which we then aggregate, refine, and re-classify policies according to the refined system. Our finalised classification system differentiates between:

- **Domestic manufacturing:** supporting or regulating domestic component manufacturing; budget allocation to *domestic* companies (e.g. subsidies, R&D funding)

- **Market creation:** Enabling diffusion of the technology through feed-in-tariffs, subsidies, targets, auctions, …

- **System-integration**: integration of technology into non-physical institutions and processes, such as electricity markets, curtailment regulations, interactions between actors, grid connectivity rules, any sector regulations etc.

- **Complementary technology and grid infrastructure**: any physical additions to the system that are needed such as storage, grid lines, experimentative /hybrid-technologies etc.

- **Land use and acceptance**: Policies that affect the placement of the technology locally, for example rules around land use, minimum distance regulations, acceptance/compensation, etc.

We also classify policies by instrument type - here, we also use an iterative process, starting from existing classification systems in climate policy databases like the New Climate policy database, which we then aggregate and refine throughout the coding process. We differentiate between

- **Regulatory policies** which include for example mandatory requirements, mandatory product standards, inspection schemes or mandatory reporting or data collection requirements
- **Economic policies** which include feed-in-tariffs, R&D funding, or tax rebates
- **Targets**, which include targets for renewables or wind deployment included in laws and regulations

- **Strategic policy support**, which includes measures such as institution creation (for example, the creation of the "competency centre for nature protection and energy transition" or the formation of the "Fachagentur Wind"; or the recent measures making renewables, energy storage and grid expansion part of the "Overriding Public Interest"; affecting the weighting of the expansion of these technologies with other public interests)

Since we are interested in temporal dynamics of policy mixes, we also capture the start and end dates of policies. For some policies, there are no end dates in the documents previously identified, so in these cases additional analysis is conducted in the German legal database to understand whether the policy is still active, and if not, when it was discontinued.

Finally, we also count policies to establish "policy density" over time. Here, our overarching category of a "policy" means a law, regulation, or other policy measure such as the creation of a new agency – each policy, regulation, or mesaure is counted as "1" for our measure of policy density.

Each of these laws and regulations may then contain several policy instrument types, or be coded according to several mechanisms. For example, especially later versions of the renewables law (EEG) contain not only regulations around the feed-in-tarriff (or auction systems), but also contain specifications around nature protection; monitoring regulations, regulations around night illumination, specifications that onshore wind now is in the overriding public interest, etc. If one policy, such as the EEG, contains multiple policy instruments, these are given equal weights – e.g., "Market creation" receives a weight of 0.5, and "Grid infrastructure and complementary technologies" receives a weight of 0.5, so that together, the entire policy counts as "1". The reason each of the instrument types is given equal weight is that it is not systematically possible to assign weights, since there is no empirical evidence to indicate whether one instrument type is more important than the other.

Quantifying financial support for onshore wind power over time

Here, we look at two main types of financial policy support for onshore wind.

First, financial support for electricity generation from renewables. The feed-in-tariff system was first introduced with the feed-in-law from 1991, where feed-in amounts were linked to electricity prices (ref) - for the amounts from the years between 1991 and 1999, there are no data from official government documents, but there are estimates in academic literature for the feed in tariff per kWh (e.g. Hitaj and Löschel). The feed-in-law from 1991 was replaced by the renewables law (dt. "Erneuerbare Energien Gesetz; in short: EEG) - the law contains many amendments over time, including a swith from the original feed-in tariff to a market premium in 2012, and finaly to an auction system in 2017. To capture all of these different version, we here use the term "EEG-support". For the years from 2000 to 2023, we retrieve data on how much EEG-support is paid to onshore wind producers both in total per year, and in cent per kWh, from government documents. There is one important distinction to make when quantifying EEG-support to onshore wind plant operators, namely between (1) support paid in each respective year to existing wind plant operators, and (2) support levels pledged to be paid to new wind plants that will start operating in a given year for the coming 20 years. Support paid in a given year to some extent provides information about the “financial burden” or “financial effort” associated with supporting onshore wind (it is important to note that the EEG suport all renewables, and that the EEG-fee paid by consumers up until 2023 is not differentiated by technology, so the share of money paid to wind power is not known by the consumer). This measure however conflates feed-in-tariff levels over the past 20 years, since this is the timespan over which a certain tariff level is guaranteed for plant operators - so the total amount paid in 2015 also includes feed-in and premium-levels from the early 2000s. The support promised to new wind plants that will start operating in a given year provides information about the level of support that wind operators expect to receive for the coming 20 years, and thus likely influences investors’ or operators’ decisions to add new capacity to the grid in a given year.

The second type of financial support we capture is public research funding from onshore wind, which we capture from the IEA database.

Mapping policy mix and financial support to onshore wind growth and turning points over time

In addition to mapping policies to wind deployment, we also conduct a qualitative document analysis in order to arrive at a more in-depth understanding of policy changes around turning points, and whether feedbacks from one may have prompted the other to change. To this end, we read the policy documents we identified from the Clearingstelle EEG which contain not only policy documents but also policy evaluations, monitoring reports, and strategies for the development of new policies.

Results

Database of onshore wind policies in Germany

We consolidate a database of policies we identify as being relevant to the diffusion of onshore wind power growth over time. In line with our bottom-up approach, the policies identified include both policies directly applicable to renewables and wind power (such as the “renewables law”, or the “onshore wind energy law”) - but they also include nature protection regulations, grid-expansion regulations, etc. See Table 1 for a summary of the major policies identified; the years in which the policy was active, and the major priorities and policy instruments identified as being contained in each policy. The detailed database, including a short description of each policy, its German name, and notes on coding, is available upon request. Here, our overarching category of a “policy” means a law, regulation, or other policy measure such as the creation of a new agency - each of these laws and regulations may contain several policy instrument types, or be coded according to several mechanisms. For example, especially later versions of the renewables law (EEG) contain not only regulations around the feed-in-tariff (or auction systems), but also contain specifications around nature protection; Monitoring regulations, regulations around night illumination, specifications that onshore wind now is in the overriding public interest, etc.

Table 1 Main policies, policy priorities and policy instruments identifed as relevant for onshore wind

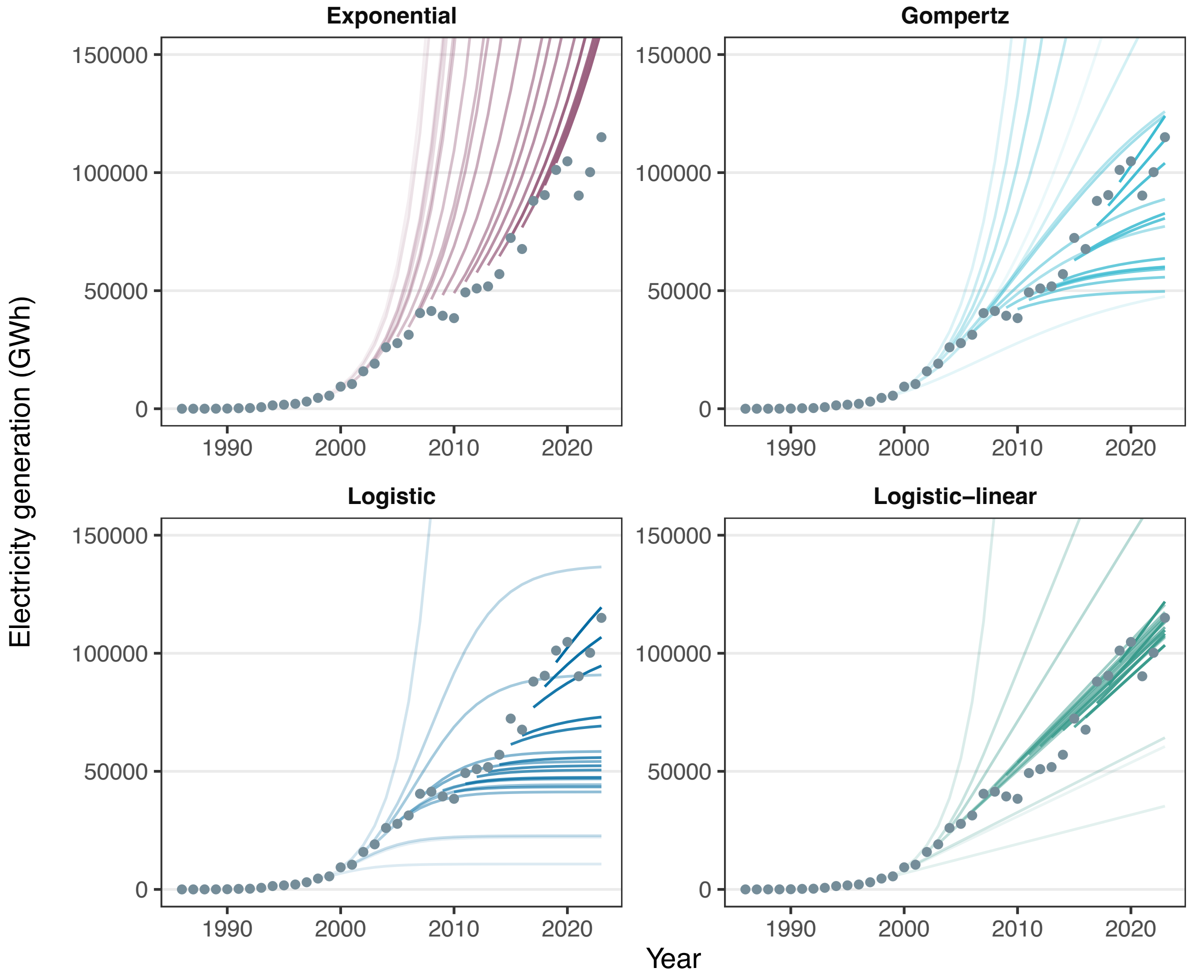
Policy name	Year(s) active & relevant to onshore wind	Major policy priorities	Major policy instruments
GROWIAN	1974-1985	Domestic manufacturing	Strategic policy support
R&D and energy research funding	1974-2024	Domestic manufacturing	Economic support
Federal air pollution and noise regulation	1974-2024	Land use and acceptance	Regulatory instrument
Federal nature protection regulation	1977-2024	Land use and acceptance	Regulatory instrument
Renewables purchasing requirement	1979-1990	Market creation (indirect)	Economic support
100/250 MW wind programme	1989-1995	Market creation; Domestic manufacturing	Economic support
Feed-in law	1990-2000	Market creation	Regulatory instrument and Economic support
Environmental Impact Assessment Regulation	1990-2024	System integration	Regulatory instrument
Land use regulation	1990-2024	Land use and acceptance	Regulatory instrument
Federal zoning law	1997-2024	Land use and acceptance	Regulatory instrument
Energy Industry Law	1998-2024	Market creation; Grid integration and complementary technologies	Economic support; Strategic Policy support
Renewables law (different amendments)	2000-2024	Market creation, Land use and acceptance, System integration, Grid integration and complementary technologies	Regulatory instrument, Economic support, Target
Regional zoning law	2008-2024	Land use and acceptance	Regulatory instrument
Tax law	2009-2024	Land use and acceptance	Economic support
Grid expansion legislation	2011-2024	Grid integration and complementary technologies	Strategic policy support
System stabilisation	2015-2024	Grid integration and complementary technologies	Regulatory instrument
Renewables regulation (EEV)	2016-2024	System integration	Strategic policy support, Economic support
Electricity market regulation	2017-2024	System integration	Strategic policy support
Collective energy amendment legislation	2018-2024	Market creation, Land use and acceptance	Regulatory instrument
Etablishment of renewables register	2018-2024	System integration	Strategic policy support
Invesmtent acceleration law	2020-2024	System integration	Regulatory instrument
Information campaign on energy transition	2022-2024	Land use and acceptance	Strategic policy support
Onshore wind acceleration law	2022-2024	Land use and acceptance, System integration	Target, Regulatory instrument

Take-off, growth model fits and turning points for onshore wind growth in Germany

The central take-off point for onshore is estimated for 1998 – the first year in which wind reached more than 0.2% of electricity generation in Germany was 1994, and the last year in which it was below 2.5% of electricity generation was in 2001.

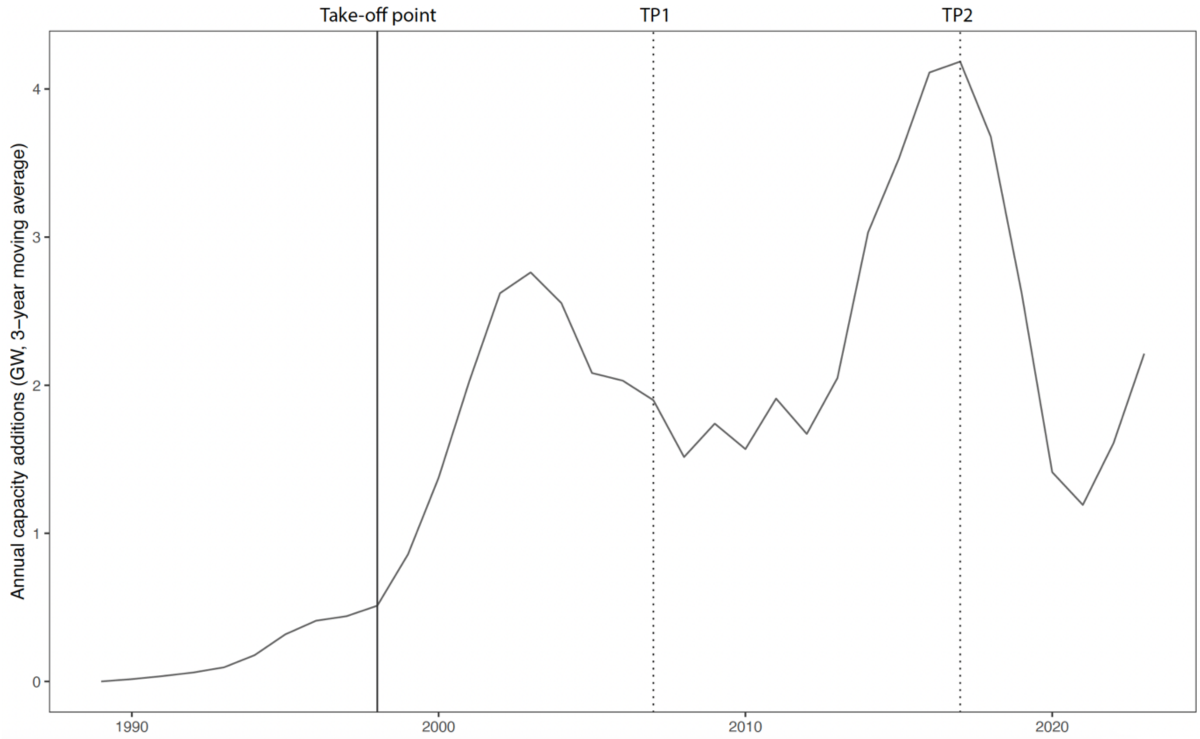
When fitting different growth models to curtailed data of onshore wind growth from 1998 onwards, it becomes obvious that since the take-off point growth regimes since then must have changed – while the exponential model regularly overestimates the speed and scale of observed onshore wind growth, it performs relatively well over brief periods of time, for example in the early 2000s, and again from ~2015 onwards until ~2017. The Gompertz and logistic models, which project S-shaped-growth, also perform relatively well for part of the data, up until the ~2010s when growth stagnates, but they cannot capture re-acceleration of growth after 2015. The logistic-linear function seems to perform overall best, with most projections roughly in line with current deployment – however, some years fall outside of the projection range, especially also around 2010-2015.

***Figure 1 Hindcasted onshore wind power generation based on four growth models. Data** for electricity generation for onshore wind from X, hindcasting done in line with the appraoch in Jakhmola et al. Hindcasting begins after the take-off of onshore wind growth in 1998, and ends in 2019 after which there are too few datapoints to continue fitting the growth models.*



This indicates that a mix of different growth regimes, approximated by different growth models, may provide the best fit for onshore wind growth in Germany. Testing the range of all possible fit combinations, and selecting the one with the highest ranking according to the Aikaike Information Criterion, shows that major turning points occurred in 2008 and 2017, when growth regimes significantly changed: first, growth begins to taper off after 2002, which using an S-curve model may indicate stagnating growth – this is why the logisitc and Gompertz models underestimate growth if fitted to data roughly up until 2010. However, stagnation ends, and from roughly 2014 onwards growth increases rapdily until 2017, when the second turning point arises and growth plumits. In very recent years, growth has seen slight re-acceleration again, but this is not captured by a turning point in our method because there are not enough datapoints for a model fit after 2020.

Figure 2 Turning points in onshore wind growth at which growth regimes change*. Data on capacity additions of onshore wind from IEA and IRENA. Take-off point is calculated based on a range of thresholds from the literature (see Methods). Turning points are assessed based on best-performing combination of growth regimes, ranked by AIC (see Methods).*



While these findings indicate that German onshore wind may have so far followed a logistic-linear growth curve, there are deviations from major growth regimes not captured by any single growth function.

Our next question is, what role may policies have played in the de- and re-acceleration of onshore wind growth in Germany?

Mapping policy interventions to wind deployment and turning points

First, we map the amount and types of policy interventions to growth regimes and turning points to visualize not only how many policies are added over time, but also which types of policies are added over time, and which policy priorities they indicate.

Figure 3 Number and types of active policies relevant for onshore wind over time. *Data on policies based on own data collection and classification (see Methods, Table 1). Data on capacity additions of onshore wind from IEA and IRENA. Take-off point is calculated based on a range of thresholds from the literature (see Methods). Turning points are assessed based on best-performing combination of growth regimes, ranked by AIC (see Methods).*

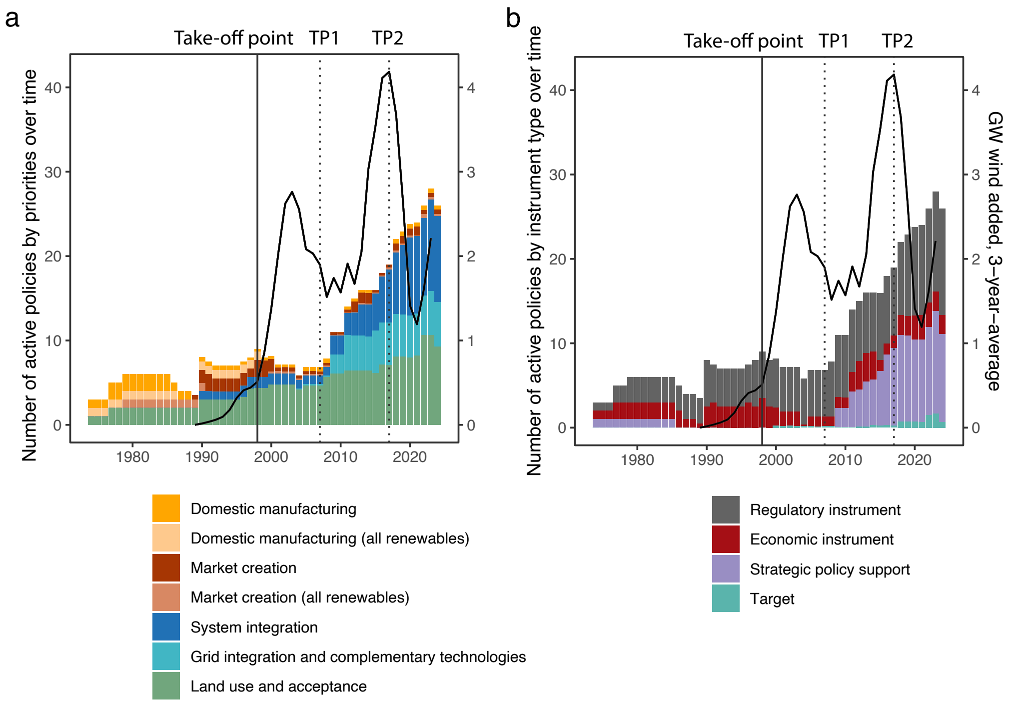


Figure 3 clearly shows that the amount of policies increases over time, with more policies being added than removed. It also shows that different types of policies are added over time.

In the formative phase, i.e. before the take-off point, policy priorities focus on Domestic manufacturing, indicating a focus on technology performance and supporting the domestic industry. This includes reearch funding, research projects, commissioning of studies around wind power, among other measures. There are also some early regulations of land use and noise imissions, as wind power becomes more widely delployed and thus more visible. In 1990, the first feed-in tariffs are introduced, coded here under market creation.

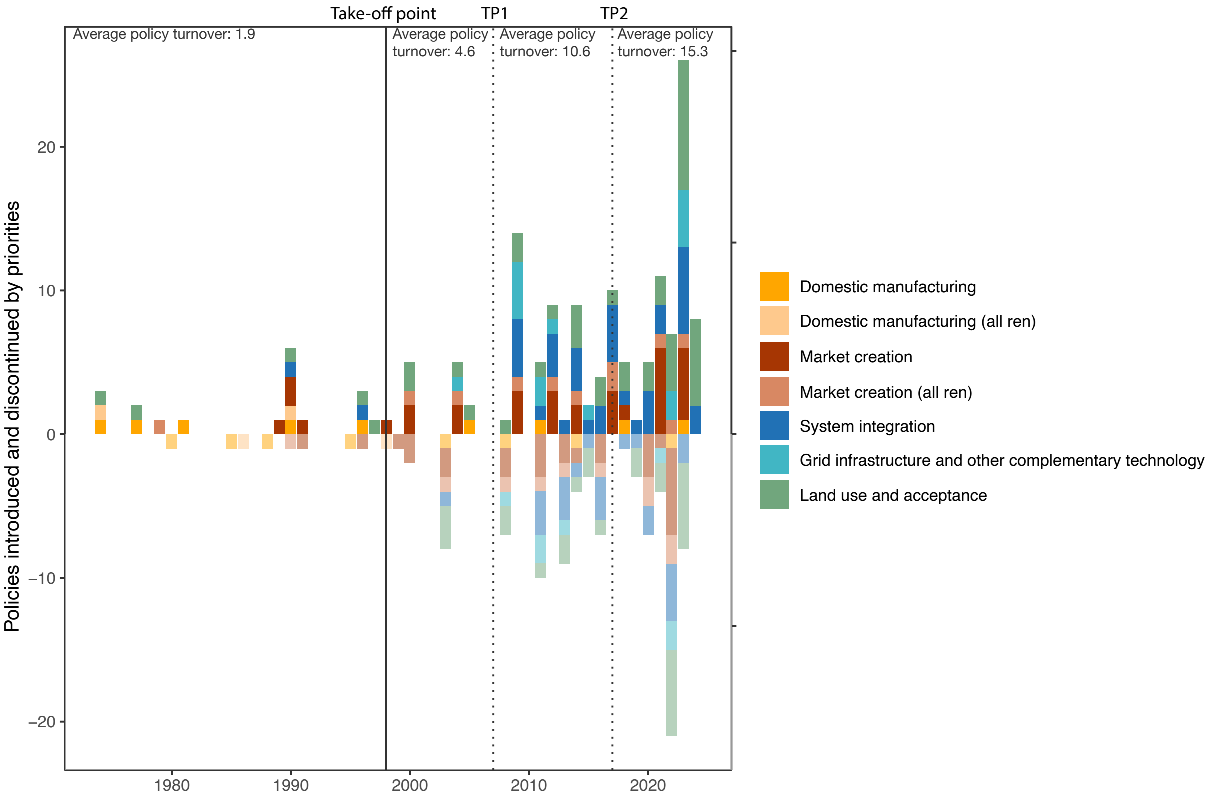
After the take-off point, there is a decline especially in market creation and domestic manufacturing policies. This may indicate a perception that technology performance and diffusion barriers have been surpassed; while land use and system integration regulations remain – this makes sense as bureaucratic rules around where wind power plants can be built, and what kind of permits are needed, remain relevant notwithstanding technological improvements.

After the first turning point, which indicates the beginning of the shift from declining to stable and then re-accelerating growth rates, more policies are added, and especially grid infrastructure and complementary seem to become prioritized. In terms of policy instruments, there are also several new instruments coded under "Strategic Policy Support" – this conincides with the start of the official "Energy Transtion (dt. "Energiewende") concept and with the Fukushima accident.

Policies continue to increase after the second turning point, with an uptick in system integration-related policies – this may indicate emerging barriers related to integrating renewables into the electricity market, a problem which may have become more urgent after the feed-in system was changed into a market premium in 2012. Additionally, the new system integration rules may reflect new rules and regulations in relation to the auction system for renewables, as well as additional regulations around permitting – some of which were aimed at accelerating permitting processes and limiting delays from lawsuits. After the second turning point, an increasing amount of targets is also being set, which may indicate the government's plans to re-accelerate onshore wind growth.

Despite the overall increase in policies, there were also several policy removals, and signfiicant policy amendments, that occurred over time. This figure shows that the amount of both policy additions and discontinuation increases over time, but especially after the first turning point, indicating that the policy mix overall becomes more "dynamic". The policy turnover index we show in this graph sums the amount of policy additions and removals each year - the higher the overall value, the more additions and removals. We have then averaged the annual values over the duration of each "phase", for example between take-off point and turning point 1. The index shows clearly that policy growth is not linear, but that there is an increasing amount of policy activity over time, possibly indicating the emergence of new barriers and mechanisms constraining technology growth. Recent years saw a large overhaul of the existing policy regime, coinciding with several major events: the recovery of the economy and uptick pf energy demand after Covid, and the start of the Russio-Ukrainian war, which also increased energy security concerns.

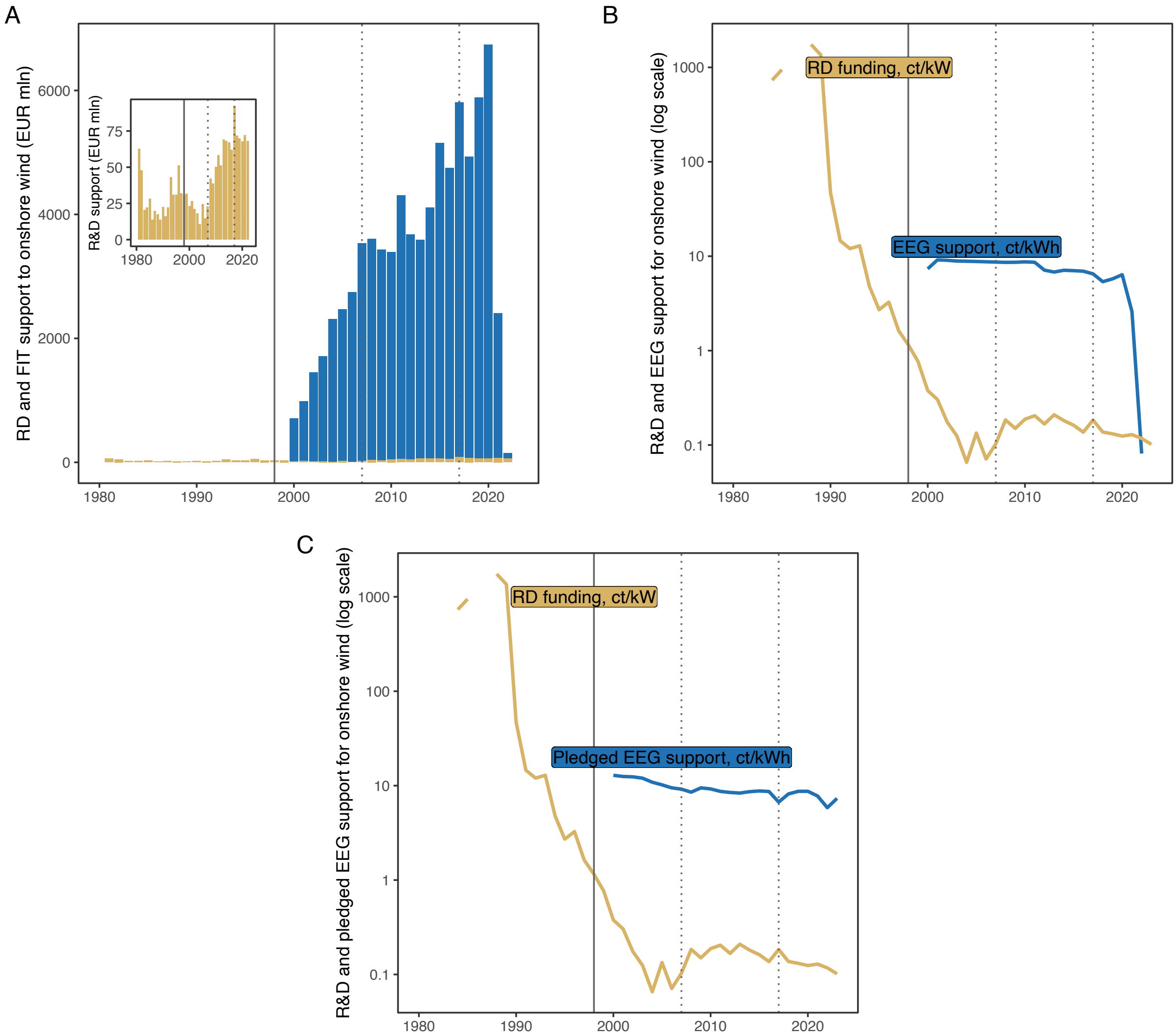
Figure 4 Policy additions and removals over time. *Data on policies based on own data collection (see Methods, Table 1). Major amendments of policies are also considered as "policy turnover" and thus captured as removals and additions respectively – for example, EEG2000 became EEG2004 in 2004, which is captured here as a removal in 2003 and an addition in 2004. Policy turnover index is calculated as the average annual sum of policy additions and removals over the respective time period.*



Mapping financial support to capacity additions and turning points

We then also map the amount of financial support for onshore wind power over time. We map two types of financial support: first, support paid under the EEG to operators of onshore wind plants (see Figure 5 in blue), and (2) public funding for research and development of onshore wind (see Figure 5 in yellow). While the feed-in tariff system has been active from 1990 onwards, there are no data on how much support has been paid per year to onshore wind producers, so we are not able to display this here.

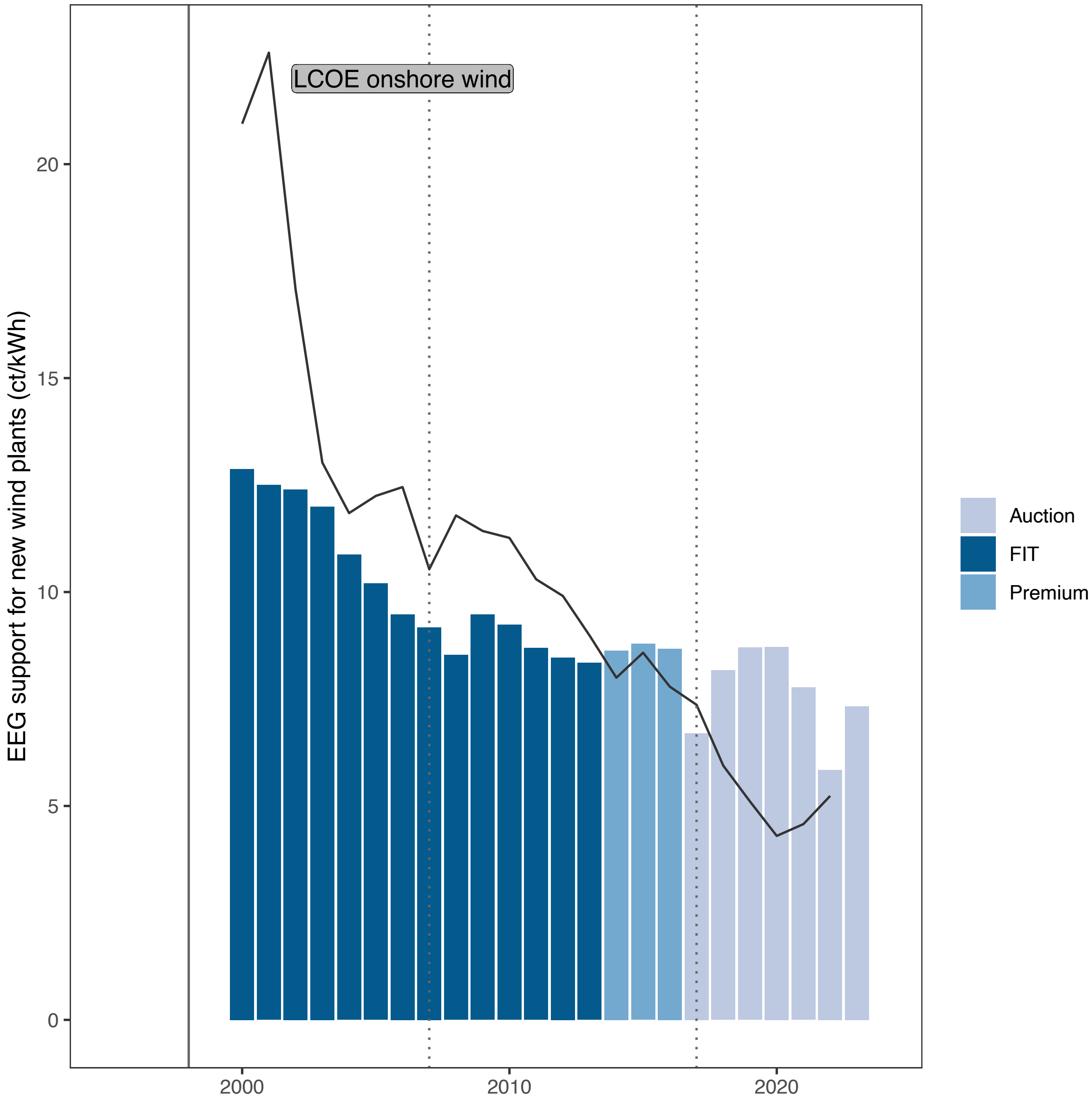
Figure 5 Public financial support for onshore wind over time. *Data for public research funding from the IEA. Data on EEG support from own data collection.*



Overall, total annual EEG-support is much higher than public R&D funding. Both funding streams have not significantly declined over time, but rather increased, which is intuitive especially for EEG-support, as more wind power is installed every year receiving such support (panel A). When mapping finanical support relative to installed capacity (panel B), amount of RD funding is very high initially and then declines as more capacity is added and technology deployment takes off. EEG-support, which has been normalized to electricity generated, has started to decline somewhat since 2010 – most likely as the first plants installed around 1990 reached the end of their 20-year lifetime over which support is guaranteed. The stark decline in EEG-support over the last two years (2021 and 2022) is a result of rising electricity prices, meaning that power plant operators receive less support on top of what is paid on the market.

Finally, panel C maps relative public R&D support to pledged EEG-support – i.e., levels of revenue guaranteed for each kWh produced by new wind power plants installed in a given year, for the next 20 years. The finding that pledged support has stayed relatively constant over time is curious, as one would expect it to decrease in line with decreasing technology cost. We thus take a closer look at the feed-in tariff, also in comparison to the development of the levelized cost of electricity production (LCOE) from onshore in Germany over time.

Figure 6 Support levels for electricity generated from onshore wind over time compared to LCOE. LCOE data from IRENA, converted to EURct2023/kWh using exchange rates from the OECD, and German producer price index from the Federal Statistics Agency. Support levels are converted to EURct2023/kWh using the German producer price index from the Federal Statistics Agency.



When mapped over time, and adjusted for inflation, it becomes clear that levels of EEG-support have decreased over time, but not at the same rate or in line with LCOE. While early EEG-support levels paid as a feed-in-tariff were below for onshore wind, they were roughly at the same level for several years (2013-2016), before the auciton system was introduced. Average EEG-support levels under the auction system have been relatively unstable, but have been consistently higher than LCOE. In recent years, LCOE has increased rather than decreased, which has reportedly led to an adjustment of maximum permissible bid values through the Federal Grid Agency (ref) to ensure that enough bids would be placed.

Discussion

Overall, we find that onshore wind growth in Germany has not followed a standard S-curve, or an exponential growth, but rather that onshore wind growth has experienced periods of acceleration and deceleration over time. To better understand the role that policies may have played for changing growth regimes, we test three hypothesis based on existing technology diffusion literature:

(1) **There are less policies over time as wind deployment increases**.
Our findings contradict the first hypothesis, as we find that more policies are added over time than are removed. While we find that there is a slight decrease of policies shortly after the take-off point, when increasing returns and declining cost may facilitate market uptake of the technology, our findings indicate that such increasing returns do not seem to be able to sustain exponential growth over an extended period of time – rather, there seem to be emerging barriers and constraining mechanisms that may hinder technology diffusion despite increasing learning and declining cost.

(2) **Policies other than financial support become more important over time, as cost of onshore wind increases, but other constraining mechanisms emerge.**
Our results confirm the second hypothesis, as we find that there is a higher share of economic policies in the formative phase before take-off, such as public research funding, subsidies to support domestic manufacturing, and feed-in tariffs to facilitate market access for renewables. Over time, other policy types are increasingly added, such as policies related to managing land use and social acceptance, as well as policies facilitating grid integration and integration into existing systems such as electricity markets, permitting and zoning processes, among others. Confirming this second hypotheses also provides interesting insights in relation to the debate around whether policy additions are a sign of increasing ambition, or whether they are a sign of malfunctioning bureaucracies – it seems that policies do not necessarily "add up" as a function of time, but also in response to developments in technological systems and the emergence of barriers. One indication for this is the uptick in policy changes especially after the first turning point, when the aim to re-accelerate onshore wind growth likely necessitated additional and new policies.

(3) **The amount of financial support decreases over time as wind deployment increases.**
Perhaps most surprisingly we find that while public R&D funding per MW installed capacity indeed declines over time, pledged EEG-support for electricity produced from wind power plants remains largely stable over time, and does not seem to show a clear relationship with LCOE development - while LCOE used to be much higher than EEG-support, it is now lower than LCOE.
One potential explanation for why a feed-in below LCOE was able to push wind power deployment in the 1990s and early 2000s may have been that at this time, there were also additional subsidies supporting installation of wind power, such as the 100/250 MW wind scheme (see e.g. Table 1). This may have removed (part of) the installation cost from project developers, and the feed-in-tariff may have been able to provide a stable revenue to ensure return on the remaining investment. What is also interesting

is that the feed-in-tariff seems to coincide with LCOE for the first time around 2013/2014, which is around the time when the guaranteed feed-in was switched to a market premium system, where power plant operators needed to participate in electricity markets for the first time. In earlier years, the removal of the “cost” and effort of participating in the market may have facilitated investment in wind power at feed-in rates below LCOE, while from 2014, these costs may have needed to be reflected in feed-in tariff levels as well.

Conclusion

Different strands in the technology diffusion literature disagree on how renewables deployment is expected to continue in the future, and what role policies can and need to play in facilitating renewables deployment at the levels required for climate change mitigation. Part of the disagreement arises from the fact that growth rates of renewables change over time, and that it is not clear how long certain growth rates can be sustained, and what a change in growth regimes means – some argue that a decline in growth rates indicates growth is likely to stagnate completely, while others argue one should expect overall exponential growth to be sustained over a long period of time. Neither side of the argument systematically assesses the role of policies in decelerating, accelerating, or maintaining growth regimes.

Here, we address these gaps by studying the case of onshore wind growth in Germany, which we find not to have stagnated yet, but also not to have followed either exponential or linear growth consistently – rather, we find several turning points at which growth regimes have changed. We develop a database of policies relevant to onshore wind in Germany since the 1970s, and map the amount or density of these policies over time to technology deployment. We find that more policies are introduced over time than removed, and we also find that turning points in onshore wind growth regimes coincide with changes in policy interventions – especially after the first turning point, there is an uptick in policy additions and amendments, and policies are shown to address new barriers including grid and system integration, as well as social acceptance, over time.

We also find that the total amount of financial support to onshore wind has increased rather than decreased over the time, and that levels of support per kWh of electricity produced have remained remarkably stable over time, despite policy adjustments from federally established feed-in-tariffs to market premiums and finally to an auction system where power producers bid on premium levels.

We have been able to show that even significant reductions in the LCOE of onshroe wind in Germany have not been able to single-handedly ensure its sustainaed exponential growth, but rather, that policies addressing non-monetary barriers constraining onshore wind growth are needed. Our results open avenues for further inquiry in the relationship between LCOE and feed-in tariff or market premium levels – what made investors able to invest in onshore wind at feed-in levels below LCOE in the early 2000s, but requires market-premium levels above LCOE in the 2020s?

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