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Reaccelerating wind power in Europe: growth pulses, turning points, cruising speed, and their policy drivers

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Abstract

Non-Technical Summary. European climate plans call for a doubling of onshore wind capacity by 2030, yet over the last 15 years growth has largely stagnated – contradicting technology diffusion theories that predict smooth acceleration until a substantial share of the market is reached. We show that early slowdowns in large countries were associated with the withdrawal or weakening of policy support, while reinstating support and higher electricity prices drove reaccelerations. Despite these pulses, the average deployment pace remained steady and below the first peak rate. Current targets aim for historical peak speeds, but forecasts revert to long-run rates, suggesting persistent limits that only sustained policy effort can overcome.

Technical Summary. Mainstream theories predict S-shaped technology growth with a single peak followed by slowdown, but recent literature has observed low-carbon technologies often departing from this pattern. We systematically show that over four decades, onshore wind trajectories in 16 of the 18 largest European Union countries have strongly deviated from S-curve expectations. Initial acceleration ended at just 2% of capacity potential (Interquartile range: 1–4%) or 4% of electricity (IQR: 1.5–6%), coinciding with the withdrawal or weakening of policy support. In 14 countries, the first slowdown was followed by secondary and sometimes tertiary reacceleration, forming distinct growth pulses, with peak growth rates at subsequent pulses statistically similar to the first. Pre-2021 reacceleration closely followed the reinstating or introduction of support schemes, while several post-2020 pulses were likely driven by better market conditions. Over the full period, the cruising speed – average additions after the first peak – was about one-quarter below the peak rate. National 2030 targets require growth close to historical peaks, yet the latest forecasts converge on the cruising speed. Germany is the sole outlier, consistent with unprecedented institutional reforms beyond financial incentives. Our multi-segment growth model, combined with growth metrics and policy mapping, can be extended to other policy-driven technologies.

Social Media Summary. Policy-driven technologies grow in pulses, not S-curves. Despite higher 2030 targets, EU wind expands at unchanged speed.

1. Introduction

Accelerating technological change is essential to the societal transformations needed for climate mitigation and sustainable development (Sharpe, 2023). Renewable electricity technologies such as wind and solar power have been expanding rapidly, yet not nearly fast enough to deliver the deep cuts in emissions required over the coming decade (IEA, 2021; IRENA, 2024b; Suzuki et al., 2023). The hope that the necessary acceleration will nevertheless materialize rests on two premises. The first is the common ‘S-curve’ model of technology diffusion and the related concept of positive tipping points in technological change: once a technology matures, self-reinforcing feedbacks are expected to propel continued acceleration until saturation is approached (Lenton et al., 2025; Mey et al., 2024; Nijssse et al., 2023). The second is that stronger policies – adopted in response to intensifying climate concerns and, more recently, to energy security pressures – will push growth beyond what market dynamics alone would deliver (Sovacool et al., 2025).

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However, empirically, slowing and even stagnating growth of renewable technologies are common (Cherp et al., 2021; Jewell et al., 2026). Nor do policies always deliver the expected boost: political setbacks – from shifting governing coalitions to organized opposition – frequently derail more ambitious measures (Markard, 2018; Stokes, 2020), while even well-designed schemes run up against limits in public finance, administrative capacity, and social acceptance (Boasson et al., 2025; Sovacool et al., 2025). Reflecting on these obstacles, recent transitions literature suggests that acceleration may be limited to only early phases of transition, after which near-linear growth at a high but stable speed can be expected (Jewell et al., 2026; Sovacool et al., 2025). Yet little systematic research has traced the actual shape and parameters of deployment trajectories of policy-driven technologies or linked turning points to specific policy interventions. We ask whether these trajectories differ from standard diffusion expectations and whether the differences are linked to policy shifts.

We address this question by analyzing the four decades of onshore wind power growth in European Union (EU) countries. Wind supplies a higher share of electricity in the EU than in any other major economy; its deployment accelerated strongly in the 1990s and 2000s, but has remained largely flat over the last 15 years. Many national and EU-level targets now call for reacceleration, including a doubling of installed capacity by 2030 (European Commission, 2022; Pavlenko & Cherp, 2026), which signals strong policy involvement. To conduct our analysis, we introduce a model for identifying turning points in growth trajectories as well as new metrics for measuring growth. We map growth peaks and turning points against policy shifts and also evaluate whether the 2030 policy targets and deployment forecasts fall within or exceed the growth rates that countries have historically achieved.

Our analysis shows that, contrary to positive tipping point theories, the initial acceleration of wind power has ended in most countries, and that this occurred much earlier than common S-curve theories expect: already when wind reached about 2% of its capacity potential (IQR 1–4%) or generated 4% of electricity (IQR 1.5–6%). In most countries, these first slowdowns closely followed the capping, withdrawal, or destabilization of financial supporting policies. Yet the first peaks were not the beginning of terminal stagnation: growth typically reaccelerated through secondary and sometimes tertiary growth pulses. Before 2020, this reacceleration was again led by policy changes, and starting from 2021, also by market dynamics: rising electricity prices and low technology costs. In both periods, the peak growth rates at subsequent pulses were statistically close to first-peak rates, pointing to persistent constraints such as fiscal capacity, permitting throughput, and social acceptance. The aggregate effect of these pulses has been a remarkably stable average rate of annual additions – ‘cruising speed’ (Jakhmola et al., 2026b; Jewell et al., 2026) – at roughly one-quarter below the first-pulse peak. Recent targets adopted in response to heightened climate and energy security pressures require growth close to historical peaks, but forecasted growth falls below these targets and reverts to the cruising speed. Policy-driven acceleration of mature technologies therefore appears to be bounded by persistent limits that may be difficult to surpass. Our data-driven approach – combining the identification of turning points, measuring growth rates, and policy analysis – can be applied to other technologies to generate ‘stylized facts’ essential for bridging mathematical modeling and mechanism-based explanations of technological change (Geels et al., 2016; Trutnevyte et al., 2019).

2. State of knowledge and theoretical framework

Technology diffusion literature commonly describes the growth of new technologies as an S-shaped trajectory: initially slow growth accelerates and then slows down (Griliches, 1957; Grubler et al., 1999). This pattern tracks the empirical reality of historical technologies and also captures two fundamental mechanisms governing diffusion. First, technology growth is driven by ‘increasing returns’ (Arthur, 1994) or positive feedback loops, the most prominent of them being cost decline through learning and economies of scale, whereby greater deployment reduces costs and thus stimulates further adoption (Lafond et al., 2018; Way et al., 2022; Wright, 1936). This mechanism underpins the early stage of the S-curve. Second, diffusion ultimately encounters finite market size or geographical constraints, which impose a negative feedback that slows growth at later stages (Cherp et al., 2021; Rao & Kishore, 2010). A key feature of both mechanisms is their monotonic dependence on deployment: costs progressively decline while untapped market potential is progressively depleted. Together, these dynamics yield a trajectory with a single inflection point – the moment at which positive and negative feedbacks balance, the growth rate peaks and then begins to decline (Cherp et al., 2021). The logistic function, which formalizes this process by placing the inflection point at the midpoint of the deployment ceiling, has been the canonical model in the technology diffusion literature (Grubb et al., 2021; Grubler & Nakicenovic, 1991; Marchetti & Nakicenovic, 1979; Wilson et al., 2013).

However, this framework struggles to explain and predict the growth of renewable power. The main explanatory variable in the S-curve model is the technology’s position with respect to the inflection point (Baumgärtner et al., 2024; Cherp et al., 2021; Jakhmola et al., 2026b; Way et al., 2022), yet this is difficult to determine for technologies that are still expanding (dotted curves on Figure 1). Interpreting an observed growth peak as the ‘true’ inflection point tends to under-predict future deployment (Baumgärtner et al., 2024; Madsen & Hansen, 2019; Rypdal, 2018), whereas inferring an inflection point based on assumed market potential or policy targets (Grubb et al., 2021; Way et al., 2022) tends to overestimate it (long-dash curve on Figure 1d). This problem reflects a deeper issue: the canonical diffusion model does not fully account for technologies whose expansion depends heavily on policy support, as is the case for renewable energy (Kulmer et al., 2022; Rao & Kishore, 2010; Schmidt & Sewerin, 2017). For such policy-driven technologies, growth is shaped not only by learning and market access, but also by the availability, design, and stability of policy instruments, including feed-in tariffs (FiTs), auctions, and planning regulations. These political drivers introduce their own feedback. Deployment can generate supportive constituencies that reinforce policy ambition (‘ratcheting up’) (Meckling et al., 2022; Pahle et al., 2018), but it can also provoke backlash through rising fiscal costs, distributional conflicts, local opposition, or shifting political priorities (Markard, 2018; Stokes, 2020). Moreover, policymakers may respond adaptively to emerging barriers or opportunities, introducing new interventions that reshape diffusion trajectories (Jewell et al., 2026). Crucially, these feedbacks do not necessarily evolve in sync with the technological dynamics underpinning the S-curve.

Whether and how political forces affect S-shaped trajectories depends on both the timing of policy interventions and their strength relative to non-policy diffusion mechanisms. With respect to timing, if policy dynamics broadly align with technological forces so that increasing political returns reinforce the positive

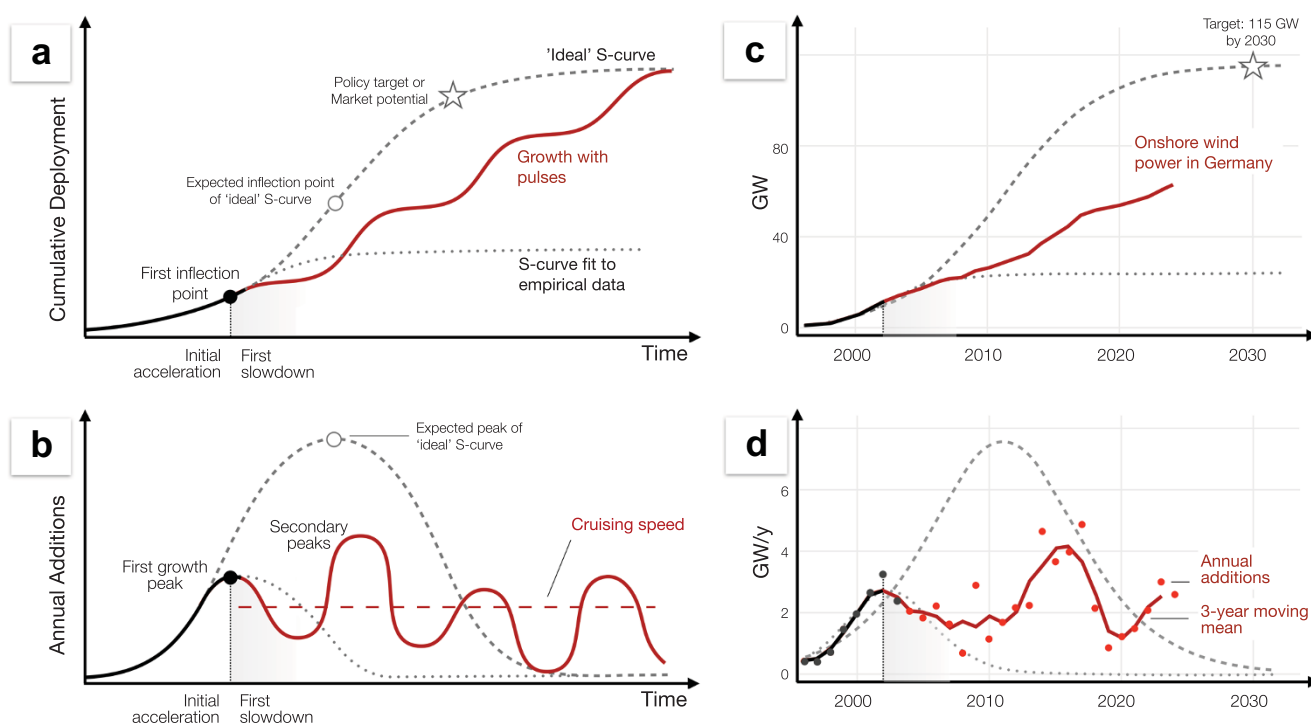


Figure 1. Growth of policy-driven technologies with multiple pulses and stable cruising speed deviates from standard S-curve models.

Notes: (a, b) – stylized illustration of cumulative capacity (a) and annual additions (b); (c, d) – empirical onshore wind power data for Germany: cumulative installed capacity (c) and annual additions with a 3-year moving mean (d). Policy-driven technologies experience multiple growth pulses (red lines) oscillating around a stable cruising speed (dashed red line). Dotted grey lines show single-inflection S-shaped logistic functions fitted to early empirical data, which typically under-predict growth. Dashed grey lines show projected growth based on an assumed ceiling using a logistic function, which typically over-predicts growth.

feedbacks from learning and scale, while political backlash coincides with tightening market constraints – single-inflection S-curves may still provide a reasonable approximation. Cherp et al. (2021) implicitly adopt this view, assuming that technological and political feedbacks balance contemporaneously, giving rise to a ‘stable growth phase’ around the inflection point. Jewell et al. (2026) further develop this mechanism, describing how a ‘steady growth phase’ can be sustained by policies that respond to emerging socio-technical barriers, thereby maintaining a balance between drivers and constraints and preventing premature slowdown before policy goals are reached. However, policy dynamics may also follow their own internal logic – shaped by electoral cycles, fiscal pressures, or geopolitical shocks – operating on timescales that are not synchronized with technological change. In such cases, political feedbacks are more likely to reshape standard diffusion trajectories. The magnitude of this effect also depends on the relative importance of policies vis-à-vis other factors: in contexts where renewables rely heavily on policy support, their trajectories are more strongly shaped by political change than in markets where they are already commercially competitive.

When policy interventions are both essential and not synchronized with technological evolution, they can interfere with the gradual, monotonic forces of cost decline and market saturation, producing qualitatively different growth paths (Figure 1). First, the slowdown following the first inflection point may occur not when a technology approaches half of its market potential, but when the policy support underpinning early growth is weakened, withdrawn, or destabilized. In such cases, the first inflection point reflects the limits of the initial policy regime rather than underlying market or geophysical constraints. Second, this initial growth

peak does not necessarily mark the onset of sustained deceleration. Because policy regimes can be reformed, strengthened, or reinstated, growth may reaccelerate, producing multiple growth pulses rather than a single transition from acceleration to slowdown. Kulmer et al. (2020, 2022) identified turning points in the deployment of electric vehicles, heat pumps, and solar PV in Austria and linked them to policy and technology changes. Cherp et al. (2021) detected surprisingly early inflection points in most countries and identified pulses in solar and wind deployment in several countries, but still used standard S-curve models for their analysis. Similarly, Baumgärtner et al. (2024) considered ‘periods of acceleration and deceleration’ as fluctuations of canonical S-curves. Vetier et al. (2024) discussed wind power growth pulses in European countries, arguing that they are caused by policy shifts and comparing growth rates at the initial and subsequent pulses. Jakhmola et al. (2026a) provided additional evidence for pulses of wind and solar power by demonstrating that the bi-logistic growth model (a combination of two logistic curves) can often capture deployment trajectories better than a standard logistic model. Jewell et al. (2026) argued that pulses are common and arise from the shifting balance of barriers and drivers. Despite these advances, the prevalence, drivers, and statistical properties of pulses and turning points remain largely unexplored. It is in particular not clear what typical pulses are, whether peak growth rate changes or stays the same across pulses, and whether pulses arise from socio-technical phenomena, autonomous policy shifts, or coupled policy-technology dynamics.

Systematically investigating the prevalence and characteristics of growth pulses requires tools and metrics that are different from standard S-curve models. These tools should be able to diagnose

distinct growth segments with different patterns of growth. Such patterns are most visible on charts of annual capacity additions where an S-curve appears as an inverted *U*-shape, with the inflection point at the peak where the growth is fastest; see [Figures 1 and 2](#). A growth trajectory with more than one inflection point would have more than one growth pulse separated by turning points, and a linear growth would be represented by a horizontal line. In addition to diagnostic tools, we use new growth metrics: peak growth rate, the maximum rate achieved at the inflection point of each pulse, and cruising speed ([Jakhmola et al., 2026b](#); [Jewell et al., 2026](#)), the average of annual additions after the first peak. Mapping the pulses onto policy shifts under different market conditions and comparing growth rates with policy targets advances the understanding of policy-driven acceleration of transition. Our approach and methods are discussed in more detail in the following section.

3. Methodology

3.1. Scope of analysis

We focus on onshore wind energy in the EU: a mature technology in a region with high deployment and pronounced national-level variation. Commercial onshore wind power in the EU originated in the 1980s ([Gipe & Möllerström, 2023](#)) and currently supplies around 15% of electricity generation ([Ember, 2026](#)), the highest share among major global economies. We analyze onshore wind in the 18 largest EU member states (those with total electricity generation >30 TWh in 2024), excluding smaller countries where individual projects can cause large fluctuations ([Cherp et al., 2021](#)) (see Supplementary Table S1 for the full list). We use historical data from 1992 onwards on installed capacity, generation, and total electricity supply from IEA ([2025a](#)), IRENA ([2025](#)), and Eurostat ([2025](#)).

Our analysis proceeds in four stages: diagnosing growth pulses from multi-segment model fitting, testing whether pulses are synchronized across countries, measuring and normalizing growth rates, and analyzing the role of policy shifts.

3.2. Diagnosing turning points and measuring growth

We build on the tradition of fitting growth models to empirical time series ([Cherp et al., 2021](#); [Griliches, 1957](#); [Grubler & Nakicenovic, 1991](#); [Wilson et al., 2013](#)), advancing the algorithm of [Kulmer et al. \(2022\)](#) for identifying significant changes in growth trajectories. We introduce the multi-segment growth model and inflection point algorithm because this method excels at detecting subtle shifts between growth regimes ([Jewell et al., 2026](#)). Our method involves three steps.

3.2.1. Filtering out early datapoints

We start the data series for each country 3 years before the technology ‘takeoff’, when wind power generation first exceeds 1% of the total electricity supply ([Cherp et al., 2021](#)), but not earlier than 1992 in order to exclude Denmark’s atypical pre-1992 deployment ([Meyer, 1995](#)).

3.2.2. Fitting multi-segment growth models

Following [Kulmer et al. \(2020, 2022\)](#) with modifications, we build compound growth models comprising multiple logistic and linear segments ([Figure S1](#) and [Equations 1–3](#) in [Supplementary Note S1](#)). To avoid overfitting, each segment must be at least 4 years

long – enough datapoints for meaningful parameter estimation while still capturing policy-relevant growth episodes ([Kulmer et al., 2022](#); [Wilson et al., 2013](#)). We fit all possible combinations of turning points and segment functions using the *nlsLM* function from the *minpack.lm* package in R. For example, for Germany (28 datapoints, 1997–2024), this yields 3,497 candidate models.

3.2.3. Selecting the best-performing model

We select the best model using a modified version (‘mAIC’) of the corrected Akaike information criterion ([Akaike, 1974](#); [Hurvich & Tsai, 1989](#)), which penalizes extra parameters and, additionally, extra curve segments to prevent overfitting ([Equation 4](#) in [Supplementary Note S1](#)). We tested a range of penalty strengths for the mAIC criterion and selected the $k = 3$ value that best matched the identified segments to the observed annual capacity additions across all countries. The best model for Germany, for instance, has three logistic segments separated by turning points in 2007 and 2017 ([Figure 2](#)).

3.3. Testing whether pulses are synchronized across countries

To test whether the timing of growth peaks was synchronized across countries, which would suggest shared European or global drivers rather than purely national-level mechanisms, we compared the observed distribution of peak years with an exposure-adjusted Monte Carlo null model. In the null model, the total number of observed peaks was held fixed, but peaks were randomly redistributed across years with probabilities proportional to the number of countries observed in each year. This accounts for variation in country-year coverage over time. We applied the same test separately to turning-point years.

3.4. Measuring and normalizing growth rates

For each segment, we calculate the maximum (peak) growth rate from the fitted model ([Figure S1](#)). For linear segments, this is constant; for logistic segments, the peak rate depends on whether the inflection point falls within the segment and on the growth duration of the fitted curve ([Equation 5](#) in [Supplementary Note S1](#)). When the inflection point lies within the segment and growth duration exceeds 3 years, we use the rate at the inflection point ([Cherp et al., 2021](#); [Wilson et al., 2013](#)); when growth duration is shorter, we use the maximum average 3-year rate ([Cherp et al., 2021](#); [Vinichenko et al., 2023](#); [Wilson et al., 2013](#)); when the inflection point lies outside the segment, we use the maximum rate achieved within it (see [Panel A of Figure S1](#)). We measure the cruising speed as the average annual capacity additions between the first inflection point and the end of the data series.

We measure target and forecast growth rates by taking the difference between the 2030 target or forecast and installed capacity at the end of 2024, divided by 6 years. Policy targets for onshore wind capacity in 2030 are derived from the most recent National Energy and Climate Plans (NECPs) ([European Commission, 2025](#)). Where NECPs specified targets in generation rather than capacity, we converted using the last 3 years’ average national capacity factor; where targets combined onshore and offshore wind, we consulted additional national and EU documents to isolate onshore values ([Supplementary Table S1](#)). Forecasts for 2030 are taken from [WindEurope \(WindEurope, 2026\)](#) and for sensitivity analysis also from IEA ([IEA, 2025b](#)). [WindEurope \(2026\)](#) provides consistent country-level estimates across all countries in our sample based on the project pipeline, permitting data, and auction volumes.

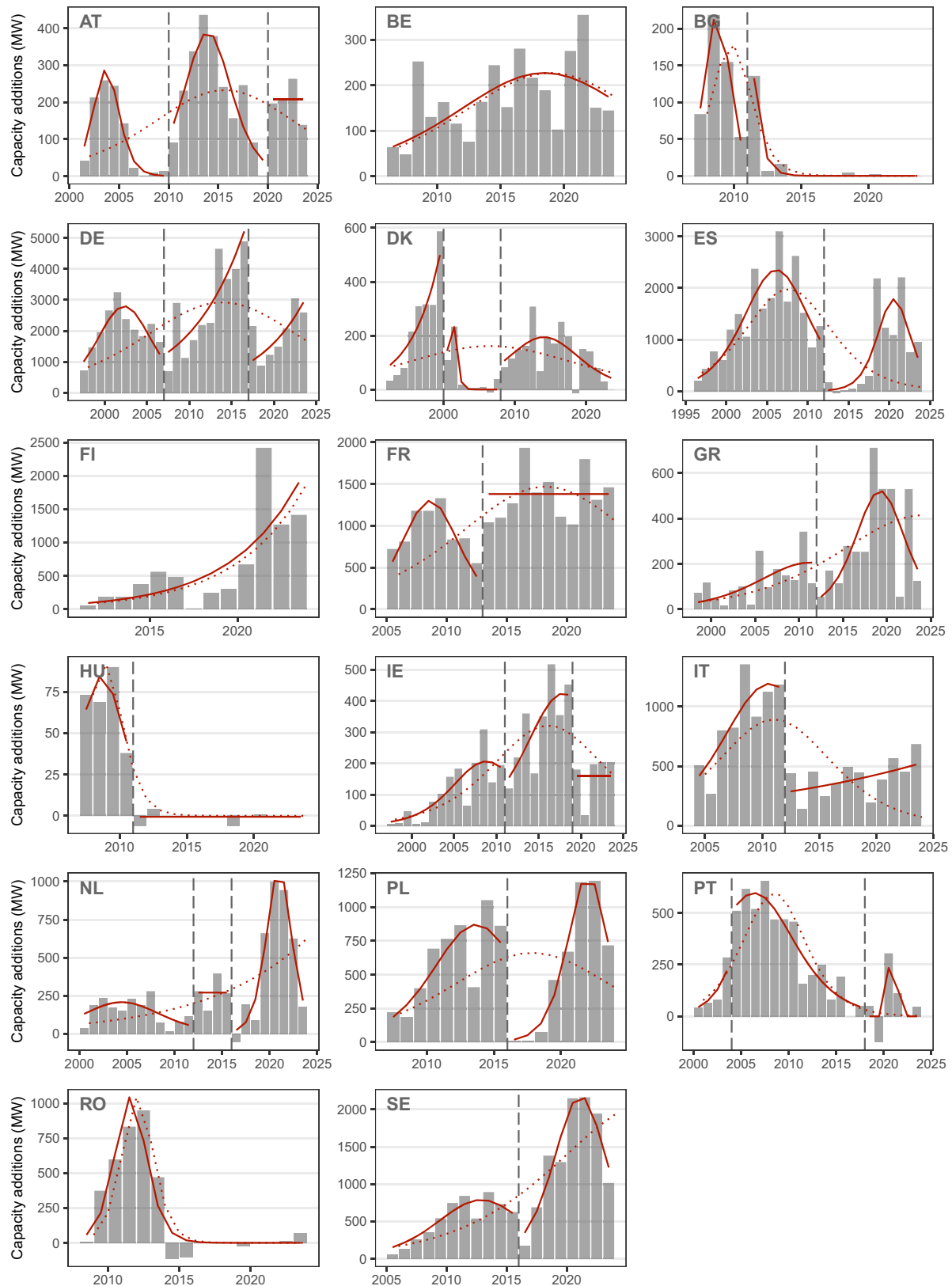


Figure 2. Annual additions of onshore wind capacity in 17 European countries with growth segments and turning points; Czechia is omitted because wind power has not yet taken off.

Notes: Grey bars – annual additions of onshore wind capacity; vertical dashed lines – turning points which separate growth segments including pulses; solid red lines – growth models of each growth segment; dotted red lines – logistic S-curves fitted to the entire data series. Countries are labeled with their ISO2 country codes; see Supplementary Table S5.

We normalize all growth rates for inter-country comparisons. Previous studies normalized by total electricity supply (Cherp et al., 2021; Vinichenko et al., 2023), but this does not capture spatial constraints such as land availability (Kohsaka & Kohyama, 2023) or changing electricity demand. We therefore additionally normalize by *capacity potential* – the estimated maximum installable wind capacity per country, using the median estimate from (Dupré la Tour, 2023).

3.5. Policy analysis

We analyzed the relationship between policy shifts and wind power growth at two levels. First, we identified the timing of each pulse's initial acceleration, its peak and subsequent reaccelerations (Table S2), distinguishing reaccelerations peaking before and after 2021 – when rapidly rising electricity prices (IEA, 2022) combined with the preceding decade of cost reductions (IRENA, 2024a) brought onshore wind close to grid parity (Batz Liñeiro & Müsgens, 2025; Enervis, 2022), potentially changing the role of state support. These events were mapped against policy shifts (introduction, expansion, cut, or switch of financial support instruments) documented in Council of European Energy Regulators (CEER) reports 2004–2025 (Supplementary Note S2, Section A). Second, we conducted detailed case studies of Austria, Denmark, Poland, and Spain – selected via a combination of extreme-case and diversity sampling (Patton, 2002) for their pronounced stalling episodes, geographic spread, and coverage of the main EU support-instrument types. For each, we traced the causal mechanism from policy change to deployment outcome, drawing on regulatory documents, industry reports, and country-specific literature (Supplementary Note S2, Section B).

4. Results

4.1. Wind power trajectories deviate from classic S-curves

Consistent with our hypotheses, the growth of wind power in nearly all European countries experienced peaks after initial acceleration (Figure 2). The only exception is Czechia, where wind power has not taken off. Our algorithm also classifies Finland as still in the initial acceleration, despite a visible slowdown in 2016–2020. The first peaks (inflection points) occurred at relatively low levels of deployment, at 2% (IQR: 1–4%) of capacity potential, when wind generated 4% (IQR: 1.5–6%) of electricity (Figure 3a, Supplementary Table S3). This is early compared to standard S-curve expectations based on an assumption that wind can supply 30–60% of European electricity (European Commission, 2018; Fraile et al., 2021), and therefore the inflection point of a standard logistic model should occur at around 15–30%.

In line with our expectations, the range of peak growth rates at the first pulse (median 0.49% of capacity potential per year, IQR: 0.26–0.74) was similar to subsequent pulses (0.46%, IQR: 0.28–0.97) (Figure 3b). The median rate for secondary and tertiary peaks also remained almost the same before and after 2020 despite an outlier, the Netherlands (Figure 4). Within countries, deployment after the first inflection point typically continued at a cruising speed about one-quarter below the initial peak under both normalizations, with median cruising-to-first-peak ratios of 0.78 for capacity potential and 0.77 for electricity share (IQR: 0.34–1.15 and 0.59–1.66, respectively). Across countries, the cruising speed had a median of 0.29% of capacity potential per year (IQR: 0.20–0.52)

and 0.72 percentage points (p.p.) of electricity share per year (IQR: 0.49–1.10) (Figure 3b).

4.2. Early slowdown and pre-2021 reacceleration are induced by policy shifts

What drives these turning points and growth pulses? Turning points show some concentration around 2011–2012 (Figure 4), coinciding with two EU-wide developments documented by Pavlenko et al. (2025): the implementation of the first Renewable Energy Directive (European Parliament and Council of the European Union, 2009), which set binding 2020 targets for all member states and prompted a wave of national support measures; and the prolonged eurozone debt crisis, which then forced austerity-driven rollbacks of renewable support across multiple member states. However, even this concentration is not statistically significant when accounting for the increasing number of countries in the sample (Monte Carlo $p = 0.186$, tested against a simulated null model accounting for the number of countries observed each year. The 37 peaks are even more evenly distributed over 25 years (Monte Carlo $p = 0.649$); thus, beyond this cluster, the timing of both peaks and turning points is asynchronous across countries. These observations, together with the ~10-year pulse duration – much shorter than typical technology diffusion timescales (Iyer et al., 2015) – point to national-level mechanisms, potentially political in nature, mediating these broader European drivers. A closer look at policy shifts confirms this connection.

The first deviation from the standard S-curve – a relatively early slowdown after initial acceleration – has in every case coincided with cuts, moratoriums, or weakening of support (unless otherwise noted, policy shifts are sourced from CEER reports 2004–2025, see Section 3). In Spain, the moratorium and the retroactive abolition and restructuring of feed-in support ended initial acceleration, stalling deployment for 5 years (2013–2017). In Austria, the 2004 halt of FiT subsidies and subsequent regulatory uncertainty produced a four-year standstill. Denmark experienced a deployment collapse from 2003 to 2008 after electricity market liberalization and the failed attempt to replace FiTs with tradable green certificates. In Poland, three concurrent policy shocks from 2015–2017 – a dysfunctional auction system, the '10 H rule' that excluded over 99% of land from wind development, and a tax increase on wind farms – stifled growth for several years (Supplementary Note S2, Section B). The same pattern extends to Italy (end of Green Certificate system in 2012), Greece (retroactive tariff cuts of ~25% in 2012–2014), Bulgaria (FiTs for onshore wind were phased out by 2014), Hungary (a regulatory freeze through multiple mechanisms [Antal, 2019; Szabo et al., 2021]), Sweden (certificate price collapse from 2018 [Windpower Monthly, 2019]), Romania (deferral of green-certificate revenue in 2013, effectively halving wind-farm income [Atănașoae et al., 2016]), Germany (the 2004 EEG revision that reduced tariffs while LCOE did not decline [Nacke et al., 2026]), and Finland, where the 2011 FiT was closed to new applicants in 2017 (Renewables Finland, 2024). In each case, the policy disruption precedes or coincides with the inflection point (Supplementary Note S2, Section A and Figure 5). Conversely, countries whose trajectories did not experience drastic deceleration – Belgium, France, and Ireland – did not experience comparable policy disruptions during their main deployment periods (Supplementary Note S2, Section A).

Secondary acceleration, which occurred in most countries, has led to pulses that can be divided into two approximately equal

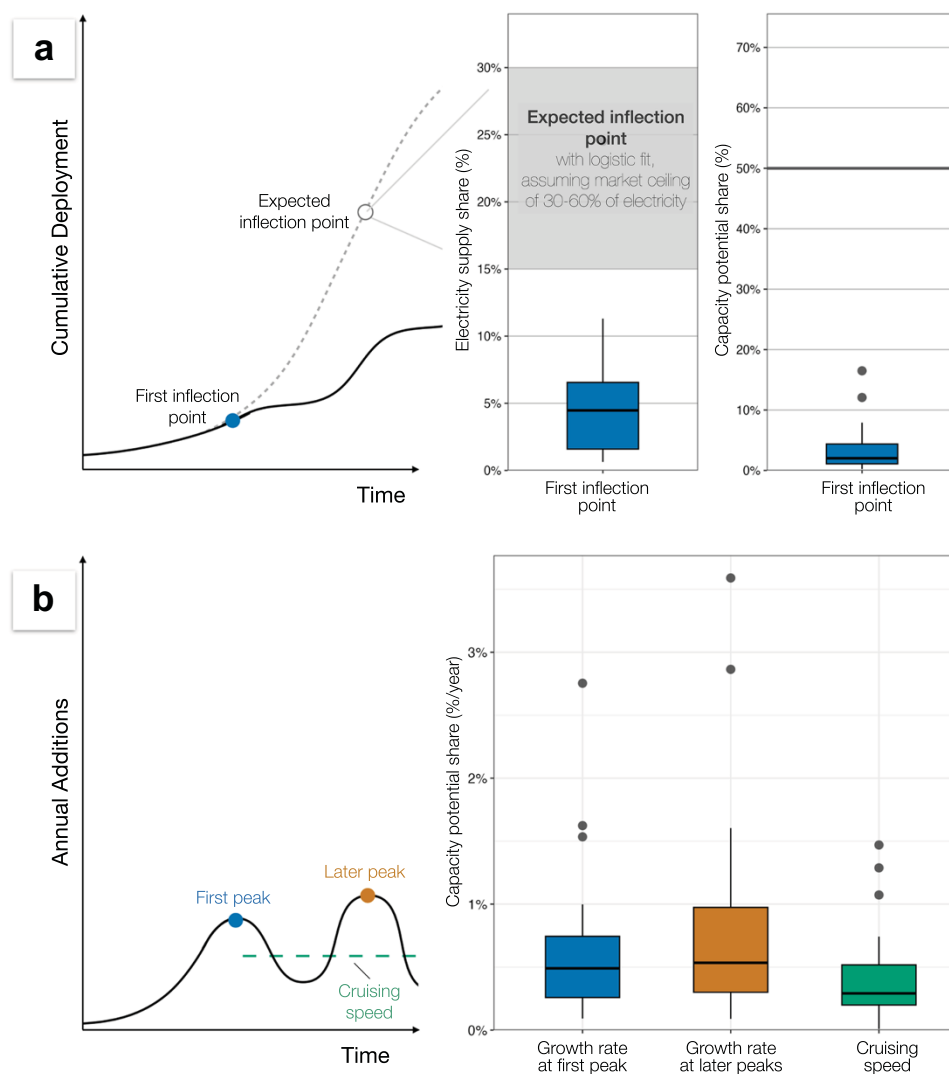


Figure 3. Deployment levels at first peak (inflection point), growth rates at first and subsequent peaks, and the cruising speed.

Notes: (a) Deployment levels at the first inflection point across countries, shown as a percentage of total electricity supply (left box plot) and as a percentage of capacity potential (right box plot). The grey area above the left box plot indicates the inflection-point range of 15–30% of electricity implied by a standard logistic model with a market ceiling of 30–60%. The horizontal grey line in the right box plot marks the corresponding standard logistic expectation: an inflection point at 50% of capacity potential. (b) Growth metrics as a percentage of technical capacity potential: (1) the peak of the first pulse, (2) peak growth at later pulses, and (3) the average growth rate after the first pulse (cruising speed). Box plots in both panels show the interquartile range (box), median (horizontal line), and outlier values (dots). The first inflection point occurs at lower levels than standard S-curve expectations (a), the rate of growth at subsequent peaks is similar, and the cruising speed is lower than the growth at the first peak (b).

groups: those with peaks before and after 2021. The year 2021 was a watershed year for renewable energy policies as it marked a drastic increase in electricity prices, followed in 2022 by the outbreak of the Russia–Ukraine war that resulted in even higher prices and triggered a flurry of political activity in the energy sector (Pavlenko, 2026). The pre-2021 pulses closely followed the introduction of new supportive policies. In Denmark, the 2008 Renewable Energy Act replaced the earlier premium-with-cap system with a 20-year feed-in premium, roughly doubling support and triggering a secondary pulse starting in 2008 and peaking in 2015 (IEA, 2008, 2013; Klima- Energi- og Forsyningsministeriet, 2008). In Austria, a pulse peaking in 2014 was driven by the 2009 ÖSG-Novelle, which reinstated financial support for onshore wind, and the 2012 Green Electricity Act, which tripled the funding envelope and earmarked support specifically for wind. Greece's reacceleration in the mid-2010s was triggered by the 2016 renewable energy law. Poland's reacceleration began after the June 2018 amendment unblocked

the auction system, and the real-estate-tax increase was revoked. In Spain, the first national wind auction in 2016, followed by substantially larger renewable-energy auctions in 2017 launched a second pulse, which was later reinforced by high electricity prices, peaking in 2021 (see next section and Supplementary Note S2, Section B).

4.3. Starting from 2021, trajectories are affected by price dynamics, feature higher policy ambitions, but retain similar growth rates

Post-2020 trajectories suggest somewhat different policy-technology dynamics. To begin with, in some countries, deployment surged even after direct support policies had been removed. In Finland, the largest annual additions came in 2022–2024 despite the end of FiT support in 2017, driven by Power Purchase Agreements and other market mechanisms (Renewables Finland, 2024). In Sweden, certificate prices collapsed toward

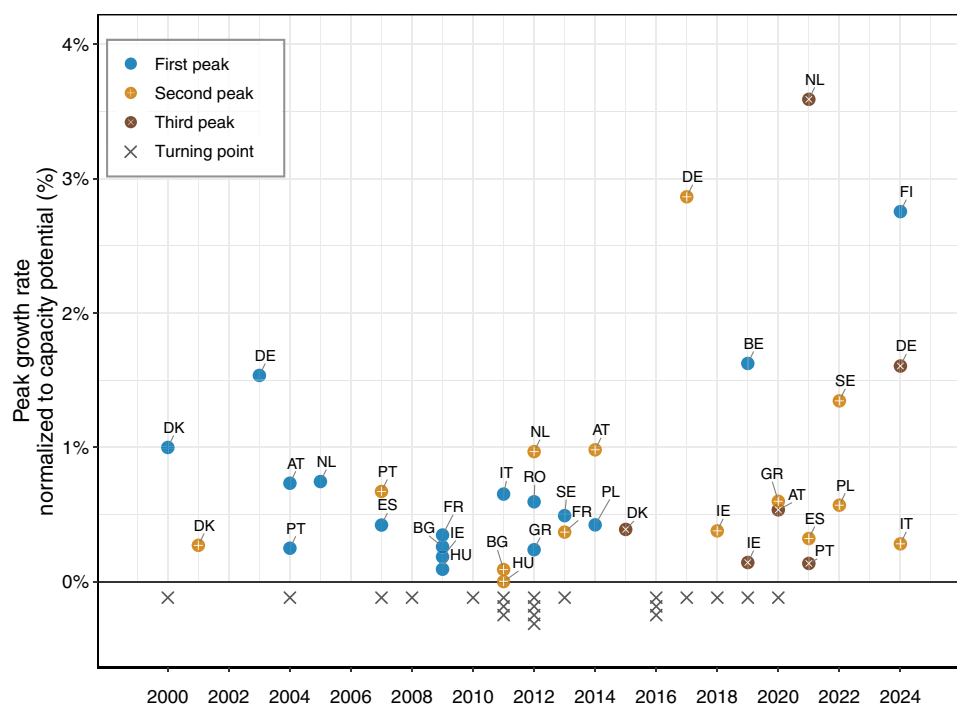


Figure 4. Timing of peaks and turning points in individual countries.

Notes: Dots show the year and normalized peak growth for each growth pulse. Crosses below the horizontal zero line indicate turning points in individual countries in a given year. Countries are labeled with their ISO2 country codes; see Supplementary Table S5. Pulses are distributed relatively equally across time, while turning points show a certain concentration around 2011–2012 that follows the adoption of the first Renewable Energy Directive and the eurozone crisis.

zero from 201 (Windpower Monthly, 2019), yet annual additions peaked in 2022 under de facto subsidy-free conditions. There has also been no obvious policy change leading to post-2020 surges in Austria, the Netherlands, Italy, and Portugal. In Spain and Poland, post-2020 pulses resulted from policy changes in 2017 and 2018, respectively (Supplementary Note S2, Section B). Only Germany's recent acceleration has an obvious link with its post-2020 legislation (German Federal Government, 2023).

The recently adopted NECPs (European Commission, 2025), which set growth targets to 2030, provide a unique window into the role of policies in a period when technologies require fewer subsidies due to higher electricity prices and lower costs. These national targets and the overall European targets were often portrayed as ambitious, as they aimed to double the installed capacity (Pavlenko & Cherp, 2026; Vinichenko et al., 2023). Yet, interestingly, the target rates are close to the historical peak speeds (Figure 6), even though they were set under grid parity and heightened energy security concerns. Strikingly, however, forecasts (IEA, 2025b; WindEurope, 2026) are much closer to the cruising speed than the set targets (Figure 6 and Supplementary Figure S2). Germany remains a clear outlier on both targets and forecasts, consistent with its recent unprecedented policy effort granting overriding public interest status to wind and dedicating 2% of land area for wind development (Federal Ministry for Economic Affairs and Energy, 2022). Overall, the post-2020 targets and the prospects for their implementation show how policy ambitions increase under favorable market conditions coupled with energy security pressures. Even the increased ambitions do not exceed historical peak rates. At the same time, these increasing ambitions do not seem to lead to acceleration beyond cruising speed, signaling fundamental constraints to the latter.

5. Discussion and conclusions

Our analysis shows that the growth trajectories of onshore wind power in Europe systematically deviate from the expectations of standard S-curve diffusion theory. The initial acceleration is typically interrupted much earlier than expected – already when wind reaches about 2% (IQR: 1–4%) of its capacity potential – and this first inflection point closely follows the withdrawal, weakening, or destabilization of supporting policies. Yet the first turning point is not the start of a permanent slowdown as implied by monotonic feedback mechanisms. Instead, growth is shaped by the alternating dynamics of policy support. In most countries, growth reaccelerates through secondary and sometimes tertiary growth pulses, before 2021 led by policy changes and afterward reinforced by market dynamics.

Strikingly, the peak growth rate at successive pulses closely matches the rate at the first peak. This suggests that deployment speed is bounded by persistent constraints – most likely the fiscal space available for support instruments, permitting throughput, and the limits of social acceptance – rather than by steadily declining technology costs. Each new policy reform can restart growth, but it encounters a similar set of constraints, resulting in similar peak rates. The average rate of additions after the first inflection point – the 'cruising speed' (Jakhmola et al., 2026b) – is about one-quarter below the first peak rate, reflecting not the weakening of individual pulses but the averaging of reacceleration phases with inter-pulse slowdowns when policy support falters.

From 2021, we observe a new dynamic. Lower technology costs and high electricity prices have enabled deployment to surge in some countries even after support instruments were withdrawn. In parallel, the recently adopted NECP targets, often portrayed as

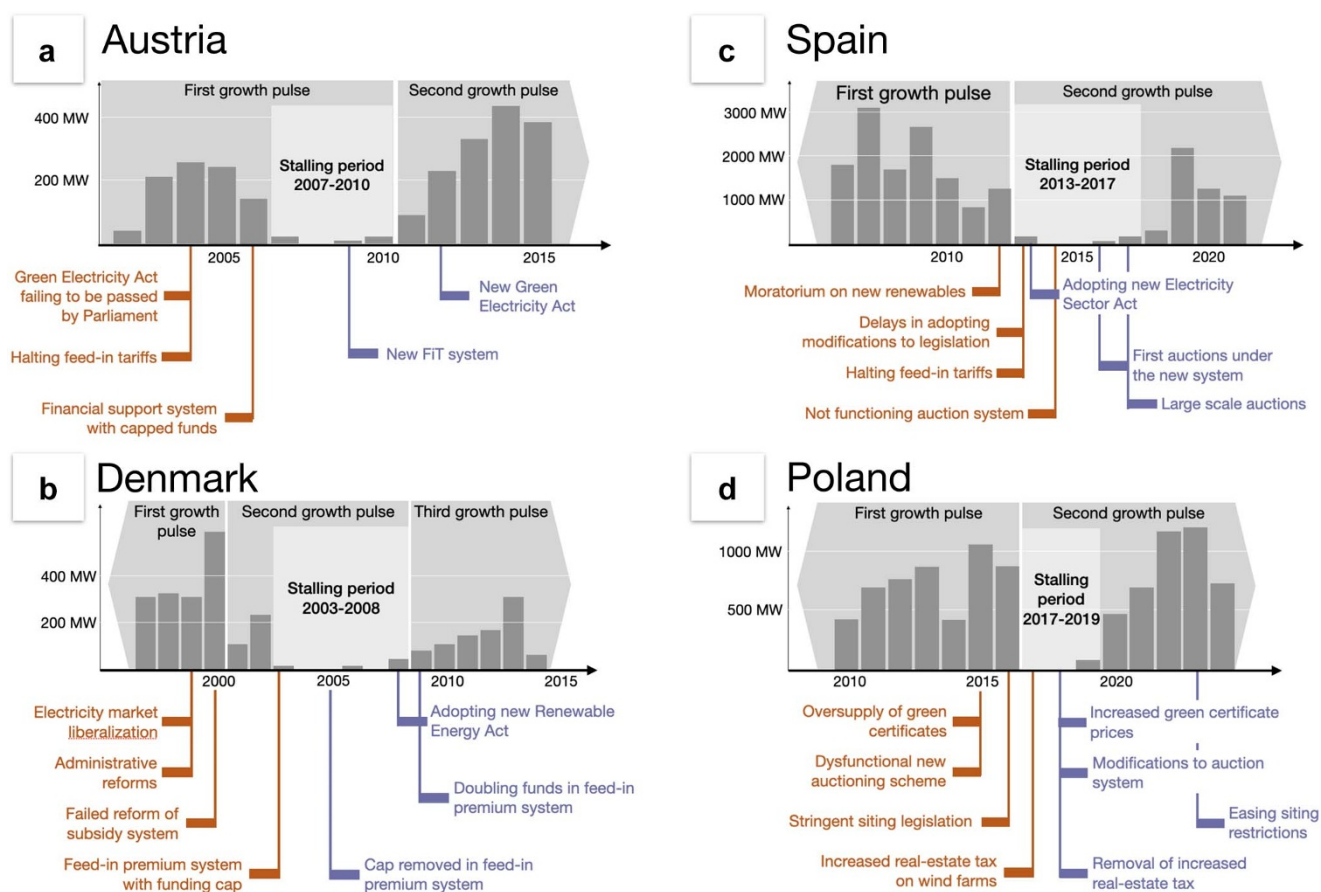


Figure 5. Policy changes, growth pulses, and slowdown episodes in selected countries.

Notes: Grey bars – annual capacity additions; colored lines and text – policy changes associated with slowdown (orange) and reacceleration (purple); grey shaded regions mark growth pulses and stalling periods.

ambitious, in fact call for growth rates close to historically achieved peaks. Yet, even these targets are not expected to be met, with forecasts converging on the historical cruising speeds rather than peak rates, which underscores the persistence of constraints not easily addressed by political rhetoric or even by improved markets. The failure to achieve targets may also be connected to the fact that, somewhat paradoxically, the overall level of financial support to renewables declined from 2021 even as targets increased (Pavlenko & Cherp, 2026). Germany stands out as the only country whose targets and forecasts substantially exceed its historical growth rates, consistent with its unprecedented policy effort to remove institutional barriers rather than merely increase financial incentives (Nacke et al., 2026).

Our study advances the methodology for analyzing and projecting growth trajectories. Mainstream modeling of technology growth based on one-inflection S-curves assumes acceleration can be expected on the rising portion while slowdown follows the inflection point. The methods used to investigate trajectories are structured accordingly, centered on locating the inflection point, predicting the ceiling, and anticipating the duration of the S-curve (Baumgärtner et al., 2024; Grubb et al., 2021; Way et al., 2022; Zielonka et al., 2023). We develop a different approach that identifies segments of growth trajectories with distinct patterns and measures growth at multiple peaks as well as the cruising speed. This reveals dynamics of policy-driven technologies that single-model fitting obscures: turning points, growth pulses, and

stagnation episodes. Our estimate of cruising speed at 0.72 p.p. of electricity supply per year (median; IQR: 0.49–1.10 p.p. per year) is broadly consistent with the maximum growth rate G estimated by Cherp et al. (2021), but our analysis additionally provides evidence that the average growth speed is generally neither increasing nor decreasing after the first inflection point. The multi-segment approach also enables systematic mapping of turning points against documented policy shifts, providing a more granular evidence base for causal analysis than aggregate cross-country regressions.

Our analysis advances understanding of phases of policy-driven technology transitions. Prior literature has shown that distinct growth phases are shaped by both technological and socio-political factors (Cherp et al., 2021; Jewell et al., 2026), but has not examined whether technology diffusion and policy change are synchronized in timing and aligned in direction. We find that, at least for onshore wind power in Europe, they are not: policy cycles often diverge from diffusion trends in both timing and direction, producing multiple turning points rather than a linear sequence of phases.

Our findings also inform how policy-driven acceleration is conceptualized. Jewell et al. (2026) define acceleration in the steady growth phase as either a higher linear growth rate or the avoidance of slowdown (see also Sovacool et al., 2025). We support this interpretation and propose a real-world benchmark for ‘faster’ growth: the speed observed at the first peak (inflection point). While later peaks in individual countries may occasionally exceed

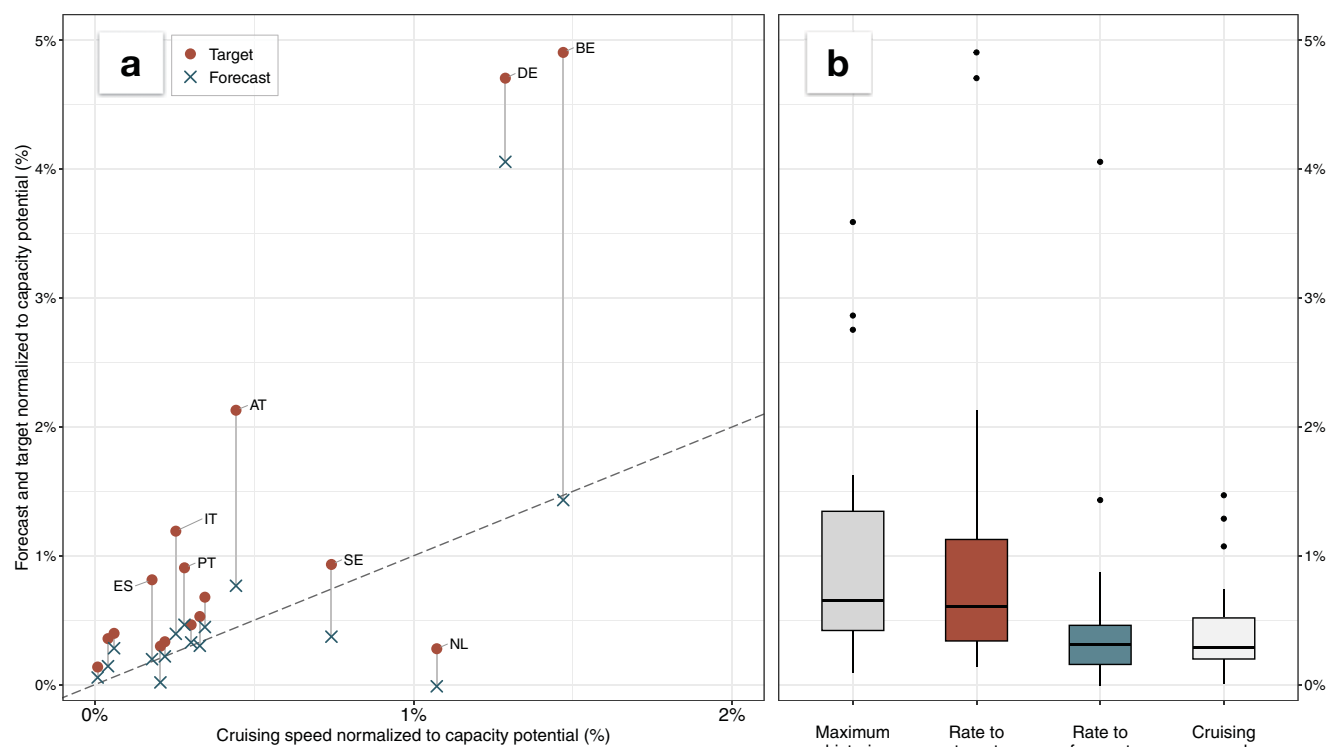


Figure 6. Onshore wind growth rates implied by NECP targets and latest forecasts compared to cruising speed and maximum historical growth rates.

Notes: (a) Growth rates required to meet NECP targets (dots) and forecasts (crosses) plotted against countries' cruising speed. Points above the dashed line indicate countries where the target or forecast growth rate exceeds their cruising speed. Countries are labeled with their ISO2 country codes; see Supplementary Table S5. (b) Box plots comparing four growth rate metrics: (1) maximum observed growth rate, (2) the growth rate required to meet NECP targets, (3) the growth rate implied by WindEurope forecasts (WindEurope, 2026), and (4) historical cruising speed (average annual additions following the first peak). Though many targets aim for growth close to historical maximum rates, forecasted growth converges to the cruising speed.

this level, the range of peak growth rates across countries remains stable. We further examine whether this benchmark holds once technologies become economically competitive and policies shift away from direct financial support. In this context, growth peaks remain similarly prevalent and average growth rates persist at comparable levels despite more ambitious targets. Exceeding historical benchmarks appears rare and typically requires dedicated policy interventions, as illustrated by Germany (Nacke et al., 2026).

Our analysis is specific to onshore wind in the EU: a capital-intensive, relatively decentralized but complex technology that requires local customization (Binz & Truffer, 2017) where deployment depends heavily on national support. Whether our findings about growth trajectories generalize to other types of technologies and contexts should be investigated in future research that could extend our framework to other policy-driven technologies – solar PV, offshore wind, heat pumps – and to regions where institutional contexts and policy capacities differ from Europe. Jakhmola et al. (2026b) provide a promising example of such a study. Onshore wind in Europe is also a technology which is both beyond its formative phase (i.e., a mature technology in this region) and still far away from saturation. For technologies that are still locally in the formative or slowdown phases, the effect of policy interventions may differ (Jewell et al., 2026; Markard et al., 2020). Further research should also investigate the relative contributions of non-policy factors, including macroeconomic cycles, supply-chain bottlenecks, and shifts in social acceptance, to the presence, timing, and magnitude of growth pulses. In part, this could be done by comparing the trajectories of policy-driven technologies and those historically driven by market forces and innovation (Jakhmola et al., 2026b).

Our policy analysis demonstrates a strong temporal association between policy shifts and growth turning points, but we do not claim that policy is the sole driver: macroeconomic conditions, supply-chain dynamics, and social acceptance also play a role. The 4-year minimum segment length may miss shorter policy effects, and the capacity-potential estimates used for normalization carry uncertainty about national conditions; these limitations could be addressed in future studies. In the future, it would be particularly valuable to investigate what specific policy designs and institutional reforms (permitting, grid planning, spatial allocation) can sustain deployment at peak rates rather than cruising speed, effectively raising the country-specific ceiling. Connecting the growth-pulse framework with the broader literature on socio-technical transitions and the political economy of energy policy could yield insights into the conditions under which reacceleration is possible – and what it would take to sustain the speeds required to meet 2030 climate targets.

Supplementary material. The supplementary material for this article can be found at <https://doi.org/10.1017/sus.2026.10086>.

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