Four phases of technology growth: implications for anticipating and guiding clean energy transitions

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Introduction

There is generally scientific consensus that accelerating the clean energy transition to meet climate goals is necessary (Cherp *et al.* 2021; IEA 2023; Markard *et al.* 2020b; Rogge & Goedeking 2024). But how *much* does the transition need to accelerate? How long should this acceleration last? And is it even possible?

Answering these questions requires resolving several scientific puzzles. For one, while it's clear that clean energy transitions are shaped by a number of mechanisms overtime (Cherp *et al.* 2021; Jakhmola *et al.* 2023; Kazlou *et al.* 2023; Markard 2018) there is no systematic approach to evaluate the timing and relative strength of transition mechanisms. When does experimentation and failure give way to declining costs and increasing returns? And how does the opposition and incumbent resistance interact with and balance of declining costs and falling costs and policy ratcheting up?

There is also a lack of consensus about where we are on the S-curve of clean energy technologies and as a result the most appropriate mathematical models for projecting plausible future developments. On the one hand are scholars who argue that the rapid technological progress has led to exponential growth of key technologies in the energy transition which can continue given the low cost of new technologies (Creutzig *et al.* 2023; Luderer *et al.* 2021; Rypdal 2018; Way *et al.* 2022). But on the other hand are those who have raised concerns about socio-political and wider challenges of acceleration (Markard *et al.* 2020b; Rogge & Goedeking 2024) and signs of slowdown of key technologies in several countries (Cherp *et al.* 2021; Hansen *et al.* 2017; Madsen & Hansen 2019; Vinichenko *et al.* 2023). The first group of scholars (implicitly) believes that we are very early on in the S-curve of the energy transition whereas the second suspects we are further along.

These debates are not a mere scientific curiosity but also have profound implications for creating realistic projections of clean energy transitions and designing policies for accelerating them. If the dominant technologies for the clean energy transition are very early on in the S-curve, then the mechanisms of learning and increasing returns will dominate and very optimistic assumptions about prolonged acceleration are reasonable perhaps even in the absence of strong policies. On the other hand, if the dominant technologies for the clean energy transition are further along in the S-curve, then mechanisms from opposition, incumbent resistance, and system-integration challenges

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are already active and prolonged acceleration is unlikely except under very strong policy action.

In this paper, we argue that there are four phases clean energy transitions, each characterised by distinct mechanisms and growth characteristics. The formative phase is characterised by experimentation, learning and volatile growth; the acceleration phase is characterised by increasing returns and positive feedback loops and, as the name suggests *acceleration*; the stable growth phase is characterised by a balance of driving and constraining forces which leads to approximately linear growth; and the stagnation phase is characterised by strong constraining forces such as opposition, integration challenges and/or market saturation which leads growth stagnation. We propose a diagnostic framework for the four phases based on assessing growth mechanisms for key technologies in the transition and analysing mathematical characteristics of their growth.

Our contribution departs from current literature which generally argues for two phases of transitions – the emergence phase and acceleration phase (Bergek & Jacobsson 2003; Jacobsson & Bergek 2004; Markard 2018; Markard *et al.* 2020b). We unpack what has been called the “acceleration” (Markard *et al.* 2020b; Rogge & Goedeking 2024) or the “second phase” (Markard 2018) of the transition into two distinct growth phase – the acceleration phase when increasing returns dominate and the growth of technologies, as the name suggests *accelerates*; and the stable growth phase when there is a balance of driving and constraining mechanisms and technologies enter a linear growth regime. We show that this distinction is crucial for creating realistic technology projections and informing policies to support the energy transition. We show how our framework can be used for creating more realistic technology projections and identifying the most important policies for the transition.

Intellectual history on the phases of energy and technology transitions

Technological change is at the heart of clean energy transitions. The non-linearity of technological change gives rise to the need to distinguish between different phases of transitions. In this section we trace the intellectual history which has wrestled with the non-linearity of such transitions – from the seminal work applying S-curve theories to technological change to more recent literature rooted in innovation and transitions scholarship identifying phases of energy transitions more broadly.

The application of S-curves to technological change dates back to the late 1950s with Griliches’ seminal work applying logistic growth curves to the diffusion of agricultural practices in the United States (Griliches 1957). In this early work, Griliches observed that the development of any technology needs to be analysed overtime and thus proposed to analyse technological development along three distinct points: the beginning of the movement, the rate, and the destination (the final saturation level). The bulk of literature in the intervening decades have focused on examining specific elements of technology change and measuring the growth rate of individual technologies. Recent work on S-curves has redefined what Griliches called “the beginning of the movement” as “takeoff” (Bento *et al.* 2018; Cherp *et al.* 2021; Golder & Tellis 1997; Markard 2018) or when a technology reaches 2.5% the final penetration level (Bento & Wilson 2016; Rogers 2003). And Dixon showed that the 'destination' is inherently unstable for still expanding technologies (Dixon 1980).

In the years since Griliches, scholarship has also worked on how to measure the speed of technological change. One approach has been to collapse the phases of the S-curve into what's known as the "duration of the transition" or Δt (Marchetti & Nakicenovic 1979), or the time it takes to grow between 10% and 90% (or 1% and 50% (Wilson *et al.* 2020)) of the penetration level. The trouble is Δt has also been shown to be unstable for expanding technologies (Cherp *et al.* 2021). Another approach has been to measure the initial acceleration speed (k) (Nemet *et al.* 2023; Odenweller *et al.* 2022), but this too, simply being the inverse of Δt, is also highly unstable. So far, the only stable metric of growth is known as "G" or the maximum growth rate, when growth peaks along the S-curve and stops accelerating (Cherp *et al.* 2021). When normalised to the size of the system, this has shown to be remarkably stable overtime (Cherp *et al.* 2021; Jakhmola *et al.* 2023). Formal (mathematical) application of these two phases depicts an initial exponential phase followed by a prolonged linear growth phase once the technology reaches 'materiality' (Kramer & Haigh 2009). The trouble is, it's unclear how long such a growth regime can last.

Another literature focuses not on measuring growth but distinguishing its phases. The bulk of literature rooted in innovation and transition studies identifies two phases of the transition: the formative or emergence phase versus the growth or acceleration phase (Bergek *et al.* 2008; Bergek & Jacobsson 2003; Jacobsson & Bergek 2004; Markard 2018; Rogge & Goedeking 2024). The first phase is characterised by learning, uncertainty and niche applications of a technology (Bento & Wilson 2016; Kemp *et al.* 1998) whereas the second phase is "characterized by an increasing scope and speed of change" (Markard 2018). The focus of this literature is on examining the shift in mechanisms and emphasis on the interaction of the technology with wider and wider systems. Finally, there is a proximate literature from political science which focuses not deployment over time but the changing politics at different parts of the experience curve (i.e. the relationship between costs and deployment) (Breetz *et al.* 2018). Here cost mechanisms are formally depicted and political mechanisms are conceptualised as a "third dimension". While useful for examining and grouping different policy options, this approach is agnostic about time and the potential to measure speed of acceleration.

All of these contributions aim to improve the understanding of clean energy and technological transitions based on a mathematical and/or mechanistic understanding of the empirical record. However, the mathematical understanding of development, pioneered with Griliches' S-curve work, has been largely independent from the mechanistic understanding rooted in transitions and innovation studies. Furthermore, the names that scholars use for the "second phase" bely the confusion of the key mathematical characteristics and how to diagnose post-formative phases. "Growth", used by earlier literature for the middle phase (Bergek *et al.* 2008; Jacobsson & Bergek 2004) simply means expansion whereas "acceleration", used by more recent literature (Markard *et al.* 2020b; Rogge & Goedeking 2024) means not only expansion but also an increasing *rate* of expansion. A final challenge of working with the existing literature is that different contributions emphasize different mechanisms – often arising from different systems implicated in the energy transition (Cherp *et al.* 2018). In the next two sections we present an integrated view of phases of transitions which bridges the different contributions and creates a systematic diagnostic tool for identifying the phase of a specific transition.

Diagnosing the phase of a technology transition

In this section we present a tool for diagnosing the phases of transitions: formative, acceleration, growth, and stagnation. This tool marries the mathematical understanding of technological transitions which has developed within the S-curve literature with the more mechanistic understanding from transitions and innovation scholarship. We recommend that in diagnosing the phase of growth the researcher combines both an assessment of the key mechanisms with a quantitative assessment examining the growth dynamics and overall penetration levels of a technology. In the assessment of mechanisms we propose to use the meta-theoretical framework designed to analyse the co-evolving systems implicated in energy transitions and bridge different disciplinary approaches to analysing energy transitions (Cherp *et al.* 2018). This section concludes with a word of caution noting that the phases and their sequence is an ideal type and many observations in the real world will pulse between different phases.

Table 1. Phases of technology growth and their key characteristics

Phase	Overarching state	Dominant mechanisms	Key indicators	Actors and institutions
Formative	uncertainty and volatility	**Socio-technical:** niche application with learning and experimentation **Political:** government R&D and commercionalisation support, little opposition **Techno-economic:** high technology costs	- very low deployment - volatile growth - high failure rate - no dominant design - few actors and markets	niche actors, government
Acceleration	increasing returns	**Socio-technical:** growing technological innovation **Political:** interest group creation with low incumbent resistance **Techno-economic:** declining costs and increased competitiveness	- more and more deployment each year - deployment >1% of the final market - competitiveness of technology - interest group emergence? - convergence of dominance design and unit upscaling - many countries/markets.	increasing returns of policies

Phase	Overarching state	Dominant mechanisms	Key indicators	Actors and institutions
Stable growth	balance between drivers and countervailing forces	**Socio-technical:** technology diffusion high **Political:** stronger interest groups with strong incumbent resistance and growing opposition **Techno-economic:** high economic profitability	- linear growth of a technology - evidence of clear struggle between new technology and old technology - emerging opposition to the new technology	Governments try to solve these barriers in different ways. Backlash.
Stagnation/ saturation	barriers stronger than driving forces and/or market saturation	**Socio-technical:** lack of new markets and/or consumers **Political:** strong opposition **Techno-economic:** reaching geophysical or other market constraints and declining profitability	- no increase in growth - lack of suitable markets for expansion - constraints and opposition lead to decline in profitability	

Formative phase

The hallmark of the formative phase is uncertainty and volatility. There is a high degree of experimentation and learning (Jacobsson & Lauber 2006), a small, often niche, market with only a small number of firms (Bergek *et al.* 2008). This is because the formative phase also typically precedes the emergence of a dominant design as firms focus on learning in order to identify a design that can survive market (Anderson & Tushman 1990; Murmann & Frenken 2006; Utterback & Abernathy 1975). For policy-driven strategic technologies, the formative phase can exhibit state-sponsored programs to support innovation, however the advocacy coalition within the technology is relatively weak (Bergek *et al.* 2008).

All of this leads to high uncertainty about the future of the technology (Bergek *et al.* 2008; Kemp *et al.* 1998; Ven 2017). Deployment during the formative phase is low – less than generally less than 0.2-2.5% of the final market penetration (Bento & Wilson 2016; Cherp *et al.* 2021; Grübler *et al.* 1999; Jakhmola *et al.* 2023; Kramer & Haigh 2009). In spite of low deployment levels, hopes for a technology during the formative phase can be very high. Consider for example the hopes expressed in 1954 that nuclear power would lead to electricity "too cheap to meter" of the current hype around hydrogen and CCS. Nevertheless this phase is inevitably plagued by a high degree of project failures as the industry goes through experimentation and learning (Kazlou *et al.* 2023) which translates to volatile growth (Jakhmola *et al.* 2023).

Today, carbon capture and storage and hydrogen are clean energy technologies that exhibit prototypical formative phase characteristics. Here we illustrate the characteristics of the formative phase with CCS. The technology currently accounts for under 0.2% of the estimated final market size and deployment is dominated by its application in natural gas processing facilities and within rich industrialised countries in Europe, the US and Australia. In spite of limited deployment today, near-term scenarios project up to an twenty-fold growth in CCS capacity by 2030 (IEA 2021, 2023; IPCC 2022; Kazlou *et al.* 2023) including in DACCS (Edwards *et al.* 2024) which is the least mature of all project applications. These hopes emerges not only from industry plans but also from strong government support policies and targets in industrialised countries (European Commission 2024; GCCSI 2023). Nevertheless, many suspect these hopes will not be realised – at least not in the nearterm (Kazlou *et al.* 2023) given the high failure rate of CCS projects (Abdulla *et al.* 2021; Kazlou *et al.* 2023; Wang *et al.* 2021).

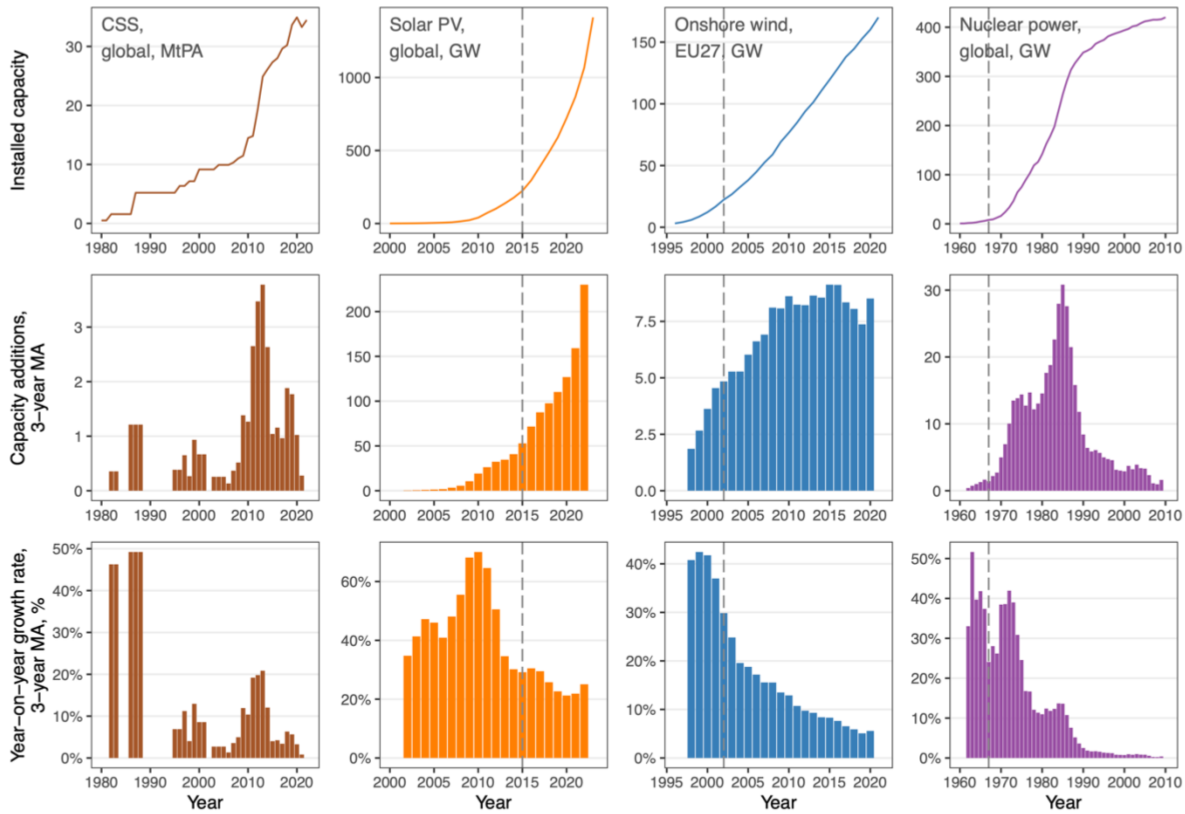
Acceleration phase

The hallmark of the acceleration phase is increasing returns and positive feedback loops. The technology shifts from being primarily characterised by experimentation and learning to rapidly moving down the experience curve (Moore 1998; Way *et al.* 2022; Wright 1936) and technology upscaling (Wilson 2012). As the costs of the technology fall and the overall scale increases, the technology quickly moves into new markets creating self-sustaining positive feedback loops. The start of this phase is often referred to as "take-off" (Bento *et al.* 2018; Cherp *et al.* 2021; Golder & Tellis 1997; Markard 2018). The positive feedback loops are not restricted to technological learning and cost decline but also penetrate the policy sphere with new entrants and strong coalitions who lobby for stronger and more supportive policies of the technology (Jacobsson & Bergek 2004; Jacobsson & Lauber 2006; Meckling *et al.* 2015).

During the acceleration phase, deployment has passed the formative phase threshold of 0.2-2.5% of the final market penetration though it is still quite low. Growth is accelerating meaning there are more and more additions every year. Similar to the formative phase, this growth regime is also accompanied by very high hopes and is commonly referred to as exponential which means the year-on-year growth rate is constant (though this characterisation is often incorrect). In fact during this phase, even though the additions increase each year, the year-on-year growth rate often steadily declines. This is observed both in common S-curve functions but also in empirical year-on-year growth rates (Figure 1).

Today, solar PV, offshore wind power, and electric vehicles are all in the acceleration phase globally. Here we illustrate the acceleration phase with solar PV. The capacity additions of solar PV have been growing while the cost of the technology has radically declined. This has led many to argue for more optimistic projections of solar PV (Creutzig *et al.* 2023; Victoria *et al.* 2021). Yet while many describe the solar PV's expansion as exponential (Rypdal 2018; Victoria *et al.* 2021; Way *et al.* 2022) (whose chief characteristic is constant year-on-year growth rates), upon closer examination one sees that the year-on-year growth rate is in fact steadily declining.

Figure 1. Phases of growth of different technologies. Top to bottom: deployment level; annual additions (3-year average); year-on-year growth rate (3-year average). Left to right: formative phase (global CCS); acceleration phase (global solar PV); stable growth phase (onshore wind, EU27); stagnation/saturation phase (global nuclear power). Dashed vertical line: take-off year.



Stable growth phase

The hallmark of the stable growth phase is a balance between driving and countervailing forces. The technology has moved from a niche to be material in the economy. As a result, the struggle from regime actors (Jacobsson & Lauber 2006) and public opposition begins to grow (Breetz *et al.* 2018; Stokes & Breetz 2018). Thus while in the acceleration phase, the technological innovation system is dominated by actors supporting the technology, in the stable growth phase actors opposing the technology also begin to play a role. The technological expansion also begins to face more general system integration and governance challenges (Markard *et al.* 2020b; Rogge & Goedeking 2024). At the same time, during this phase, policy-makers begin to deal with the barriers and challenges the technology faces (Edmondson *et al.* 2019; Rogge *et al.* 2020).

The barriers at the stable growth phase thus begin to significantly shape the pace of deployment and growth switches from more and more additions each year to constant additions and peak growth is reached. Thus a key indicator for the stable growth phase is that acceleration has stopped. While the technology still benefits from declining costs and increasing returns, achieving the same level of cost decline occurs slower due to the sheer size of the technology system (Cherp *et al.* 2021; Jakhmola *et al.* 2023). Consider Wrights's law which finds a consistent level of cost decline for each doubling of cumulative production (Wright 1936). Early on in deployment, doubling cumulative production may mean going from 100 units produced to 200 units produced. However, during the stable growth stage, doubling occurs at much higher orders of magnitude – say from 1000000 units produced to 2000000 units produced – and thus requires overcoming much higher barriers.

Today, onshore wind, particularly in Europe is an example of a technology in the stable growth phase. In Europe, onshore wind power deployment accelerated throughout the 1990s and 'aughts before stabilising at a nearly constant capacity expansion rate until about 2020 (Figure 1). The opposition to onshore wind expansion has been palpable in many countries (Donald *et al.* 2022; Hall *et al.* 2013; Jones & Eiser 2010), illustrated by the case of Sweden where 80% of onshore wind project applications rejected at the municipal level (SVT 2022) . Nevertheless, policy-action to deal with the barriers around competing land uses and public opposition is also evident in the case of onshore wind illustrated by the EU emergency regulation (Council of the European Union 2022) to treat renewable installations as a matter of overriding public interest, thus skirting standard environmental and planning processes (Pavlenko 2024).

Stagnation phase

The hallmark of the stagnation phase is that the barriers outweigh the driving forces of technological deployment. The key mechanisms which can lead to a technology entering this phase can include market saturation (Rogers 2003); public opposition; technological difficulties; and the age of existing infrastructure. Interests supporting the expansion of the technology are no longer stronger than the countervailing interests. This phase can be a temporary and end when there is re-acceleration and growth or it can be terminal in the case of full market saturation. While the mechanisms of the two are broadly similar, the longer this phase lasts the higher probability of being terminal as a longer stagnation period indicates stronger barriers and also a weakening of key components in the technological innovation system.

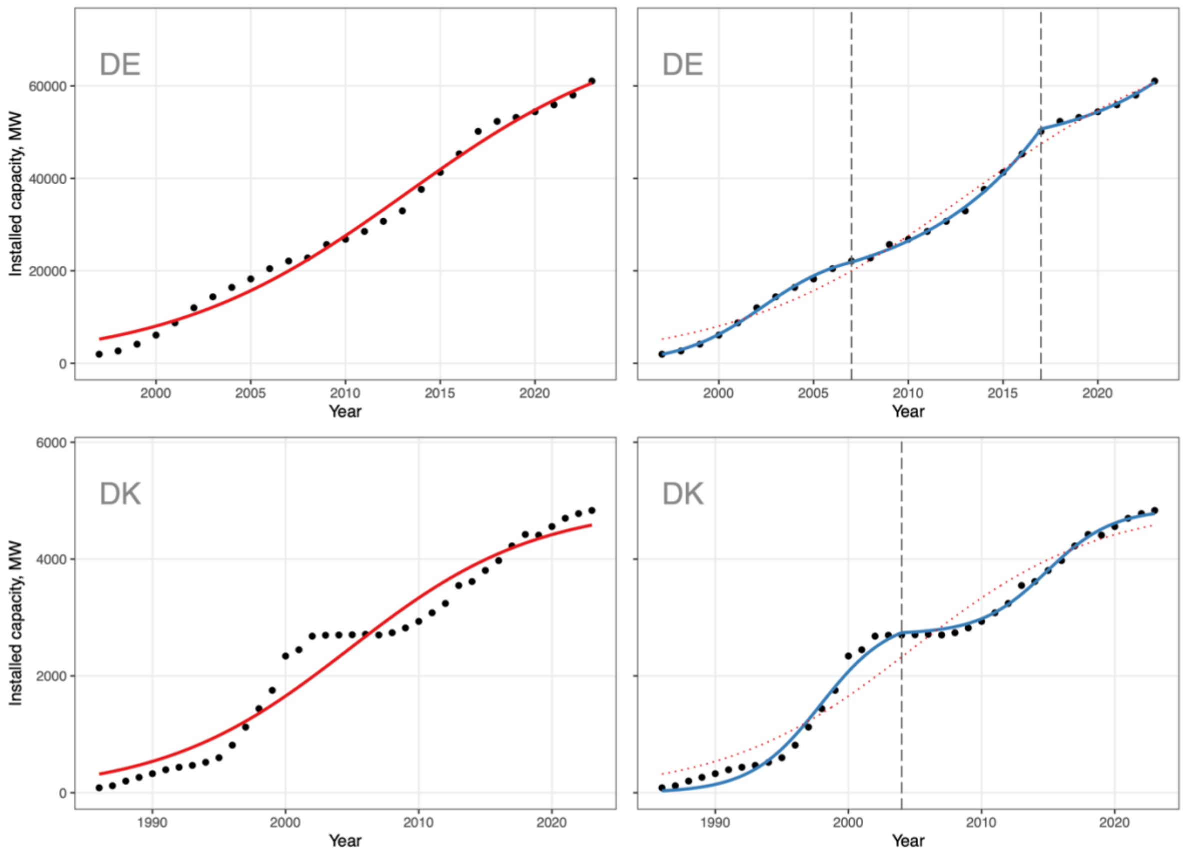
A key indicator of stagnation is the decline growth of technology deployment. While the technology may still be deployed, this deployment simply replaces retried infrastructure rather than leading to a larger technology ecosystem. Additionally, there may be a decline in actors within the technological innovation system as firms reorient their investments in the face of stagnating growth.

Nuclear power is a quintessential example of a technology in the stagnation phase. Emerging in the 1950s, after World War II, the technology grew in developed economies throughout the 1960s and 1970s. By the early 1980s, growth began to stagnate in Western countries with stagnating demand (Cherp *et al.* 2017) and nuclear manufacturers started to look for new markets (Poneman 1982). However, by the late 1970s, nuclear power had diffused to almost all countries with stable institutions and developed infrastructure (Brutschin *et al.* 2021). Combined with rising public opposition to nuclear power in the 1980s in the wake of nuclear accidents, the technology stagnated (Figure 1). In addition to the stagnation in growth, actors involved in the nuclear power industry declined (Markard *et al.* 2020a) such that by the mid 2010's, very few countries even had viable nuclear suppliers (Jewell *et al.* 2019). In the last two decades, there have been calls for nuclear power renaissance since the 'aughts, which have increased recently increased with the idea of SMRs, however to date a significant expansion has not started.

Non-ideal nature of phases in action

The description of growth phases above portrays ideal types, however it's important to note that in reality, technological growth often departs from this ideal. In particular, technological growth can experience pulses when the technology oscillates between growth, stagnation, (re-)acceleration, and growth (Figure 2). The example of onshore wind growth in Germany illustrates how what looks at first glance as one prolonged growth phase can actually be dissected into a number of different pulses. The example of wind growth in Denmark illustrates how a researcher standing in 2006 could have incorrectly diagnosed Danish wind as saturated.

Figure 2. Pulses in technology growth. Installed capacity of onshore wind in Germany (top) and Denmark (bottom). Left: single logistic curve fitted to empirical data. Right: several segments of logisitc curve fitted to empirical data and providing a better fit compared to a single curve. Dotted red line: fitted logistic curve (same as in the respective left panel); vertical dashed lines: boundaries between segments.



As a result, a diagnosis of the phase should examine the possibility of pulses and likelihood of shifting between phases. The presence of pulses and subsequent re-acceleration of stagnant growth is more likely with lower levels of deployment and also in smaller systems. With respect to the former, stagnation at lower levels of deployment likely don't indicate insurmountable barriers to deployment but rather hiccups of growth. With respect to the latter, smaller systems are more likely to experience shocks and the signal from stochastic events is weaker. In evaluating the possibility of re-acceleration and pulses, the researcher may also examine the presence of pulses in the past as this can indicate a higher likelihood of pulses occurring in the future.

Given the possibility of pulses, the reader may ask what role the phases of growth can play in formulating policy advice for technological growth or more realistic technology projections. The phase of a technological transition is the result of the balance of different mechanisms driving and constraining technological change. Thus even though mechanisms shift and the phase may oscillate along the S-curve, whatever the current phase is gives insights into the current balance of mechanisms. Thus, understanding the current phase is crucial for formulating policies to address the current barriers and balance of mechanisms and for assessing realistic deployment trajectories.

Discussion and conclusions

As technologies develop, they go through four phases, each of which is characterised by a distinct configuration of mechanisms. Learning, innovation and failure characterise the formative phase of technology development. Once the formative ends, technologies “take-off” and enter the acceleration phase when driving forces dominant from increasing returns and falling costs. Overtime, countervailing forces grow which leads to a balance of blocking and driving mechanisms when the technology enters the stable growth phase. Finally, countervailing forces become strong enough that technological growth stagnates. The evolution of these phases is reflected in the growth and deployment of new technologies. Formative phase growth is erratic and deployment is low. The acceleration phase displays accelerating growth but still relatively low levels of deployment. In the stable growth phase, the technology enters a linear growth regime as deployment levels become material in the system. Finally in the stagnation phase the technology ceases to grow.

Our contribution thus bridges two literatures relevant for understanding the technological development and clean energy transitions – the literature which focuses on the evolution of mechanisms shaping technology growth (Bergek *et al.* 2008; Breetz *et al.* 2018; Jacobsson & Bergek 2004; Markard *et al.* 2020b; Rogge & Goedeking 2024) with the the S-curve literature which formally analyses the growth of new technologies using mathematical models (Bento & Wilson 2016; Dixon 1980; Griliches 1957; Grubler *et al.* 2016; Wilson *et al.* 2020). By marrying these two approaches, we develop a method for diagnosing the phase of a given transition using a combination of quantitative and qualitative data.

One of our key innovations is identifying a growth regime which we call the “stable growth phase” which results from pulses of de-acceleration and re-acceleration. We also identify that this is distinct from the “acceleration” phase dominated by increasing returns. This also departs from previous literature which lumps everything into the “next phase” (Markard 2018) of the energy transition as the “acceleration phase”. Instead, we argue that the next phase of the energy transition includes both an “acceleration phase”, dominated by increasing returns, and a “stable growth phase” with a balance of driving and constraining mechanisms. Given that many of the key technologies needed for the clean energy transition have already entered the stable growth phase, this insight is particularly useful for formulating policy advice as well as for creating more realistic projections of technology growth.

The evolution of mechanisms and role politics plays in each phase informs policies for the clean energy transition. During the formative phase, the dominant challenges are to technological and enabling sufficient learning for the technology to take off thus policies should target R&D and technological innovation. During the acceleration phase, the dominant challenges are economic and making the technology cost competitive thus policies should target subsidising the technology in order to enable sufficient deployment levels and drive cost declines. At the stable growth phase, the technology has reached sufficient levels that it is noticeable to more and more actors, and the main challenges shift from being purely technological and economic to socio-political. During this phase, in addition to dealing with broader integration and systemic issues (Markard *et al.* 2020b), policies need to address the justice concerns which emerge (Rogge & Goedeking 2024) and the resistance from incumbents and the public. This policy priority also applies to growth stagnation as it signals barriers which outstrip the strength of driving mechanisms. The longer stagnation lasts, and the more stale the technological ecosystem becomes, the stronger the countervailing forces are, the more likely that re-accelerating growth would require policies appropriate for formative and acceleration phase development.

Our innovation regarding the dynamics of the stable growth phase – and in particular pulsing growth – also helps to design more realistic near-term projections for technological deployment. Predicting the most likely deployment of new technologies is challenging given the non-linearity of deployment and the fact that standard S-curve models are extremely inaccurate for predicting the ultimate deployment level when a technology is still expanding (Debecker & Modis 1994; Dixon 1980). However, while today scholars agree that technologies generally follow S-curves, they disagree about where we are on the S-curve. This has profound implications for the most-likely near-term deployment of new technologies because as a technology moves along the S-curve, growth shifts from exponential (or hyper-exponential) to near linear (Jakhmola *et al.* 2023; Kazlou *et al.* 2023). Thus if a technology is very early-on in the S-curve, near-term growth can be approximated by an exponential function and a constant year-on-year growth rate. If on the other hand, growth is further along the S-curve, near-term growth is best approximated to be linear.

The implications of this question are illustrated with the debate about the future potential of solar power. Many scholars believe that solar power can be approximated with an exponential function and see any decrease in the year-on-year growth rate as a mere fluctuation (Creutzig *et al.* 2023; Rypdal 2018; Victoria *et al.* 2022; Way *et al.* 2022). On the other hand are scholars who see any slow-down of renewable deployment as a sign of imminent stagnation (Hansen *et al.* 2017; Madsen & Hansen 2019). The introduction of the stable growth phase forges a middle-view between these two views – it shows that slow-down is a signal of strong barriers but doesn't necessarily imply imminent stagnation.

We find that it is the stable growth phase which ultimately determines the feasibility of technology growth fast enough for climate targets (e.g. see Kazlou et al. *under review*). Furthermore, we also see that many technologies central to the clean energy transition have already reached or are about to reach this phase. Thus understanding the mechanisms in the stable growth phase, including the role of policies will be central to effectively guiding clean energy transitions. In particular, let us conclude with three specific research avenues.

First, there's a need for the development new growth models which account for the stable growth phase and can identify and analyse pulses. Second, there's a need for greater understanding of the relative strength and evolution of specific mechanisms shaping the stable growth phase. In particular, there is a need to understand the role cost decline, socio-political opposition, and system integration plays in the stable growth in order to formulate the most effective policies. Third, there is a need for specific policy-mapping and evaluation of stable growth policies. Our analysis suggests that key clean energy technologies in many markets are already in the stable growth phase thus there is an opportunity to learn from policies in pioneering markets how to sustain stable growth as long as possible.

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