Current Research in Environmental Sustainability 11 (2026) 100342

Contents lists available at ScienceDirect

Current Research in Environmental Sustainability

journal homepage: www.sciencedirect.com/journal/current-research-in-environmental-sustainability

A simple yet holistic approach for assessing systemic change in sectoral zero-carbon transitions: The case of electricity in Europe

Germán Bersalli [a,*], David Gottheit [b], Johan Lilliestam [c]

[a] Research Institute for Sustainability (RIFS) at GFZ Helmholtz Centre for Geosciences, Berliner Strasse 130, D-14467 Potsdam, Germany
[b] Energy Transition & Utilities, Capgemini Invent, Potsdamer Platz 5, 10785 Berlin, Germany
[c] Sustainability Transition Policy, Friedrich Alexander University Erlangen-Nuremberg, Lange Gasse 20, 90403 Nürnberg, Germany

ARTICLE INFO

Keywords:
Climate policy
Net-zero
System change
Acceleration
Sustainability transitions
Europe

ABSTRACT

Many countries are seeking to accelerate their transitions to a zero-carbon energy system in line with their commitments under the Paris Agreement. In energy policy analysis, transition progress and policy success are often measured by trends in emissions and renewable energy deployment. While these outcome metrics are important, they provide limited insight into the broader systemic changes, as they overlook the underlying drivers and processes. Moreover, existing evaluation frameworks often lack theoretical grounding, leading to an incoherent set of indicators. Here, we assess transition progress from a system-change perspective by developing a theory-driven evaluation framework and applying it to the electricity sectors of four European transition "leaders": the UK, Germany, Denmark, and Norway. Unlike existing frameworks, our approach is rooted in sustainability transitions literature, improving interpretability while maintaining a focused set of systemic change indicators. Our analysis reveals significant progress in scaling up renewables and phasing out carbon-intensive technologies. However, persistent challenges—particularly in electricity grid infrastructure and regulatory adaptation—continue to hinder full decarbonization, especially in the UK and Germany, which are not on track towards zero-carbon power. The Norwegian and especially Danish electricity transitions are progressing well, not only in terms of emissions and technology deployment, but the underlying systemic measures make their transition policies credible. Our findings highlight the importance of including systemic metrics, going beyond emissions and renewables deployment metrics, and illustrate the feasibility of a "policy turn" in transition studies through forward-looking analytical tools.

1. Introduction

Under the Paris Agreement, countries have committed to climate goals that imply a profound transformation of fossil fuel-based energy systems towards zero- or near-zero-carbon configurations by mid-century. A sociotechnical transition on this scale entails more than merely replacing one technology with another; instead, it requires entire systems to change (Bauknecht et al., 2020; Victor et al., 2019). Unlike isolated changes to individual components in the energy system, energy transitions necessitate a complete overhaul of the system itself to support new zero-carbon technologies for a Paris-compliant energy future (Fouquet, 2016; Geels and Turnheim, 2022; Patt, 2015).

While many measures may reduce greenhouse gas (GHG) emissions, not all measures that reduce emissions are steps towards full decarbonization; replacing a coal power station with gas power or improving its efficiency, for example, reduces emissions but is not a step towards a zero-carbon system (Lilliestam et al., 2022; Meadowcroft and Rosenbloom, 2023; Vogt-Schilb et al., 2015). Many other systemic changes such as upgrading electricity grids, enhancing energy storage, or modifying market regulations to accommodate variable renewable power do not in themselves reduce emissions, but are nevertheless crucial for achieving full decarbonization. This means that evaluations of transition progress must take a systemic perspective, keeping the long-term goal of zero-carbon systems in mind Moreover, given the compressed timeframe of the current climate transitions compared to historical energy transitions (Fouquet, 2016), it is critical to periodically review the speed and direction of the transition and adapt policies accordingly.

In both public discourse and energy policy analysis, policy success and sectoral transition progress are often gauged by examining GHG

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* Corresponding author.
E-mail addresses: german.bersalli@rifs-potsdam.de (G. Bersalli), johan.lilliestam@fau.de (J. Lilliestam).

https://doi.org/10.1016/j.crsust.2026.100342
Received 3 July 2025; Received in revised form 6 March 2026; Accepted 6 March 2026

emissions trends. While short-term emissions reductions are undeniably an important metric for meeting specific carbon budget targets, the challenge of net-zero is more complex (Velten et al., 2021). Although various international organizations, think tanks, and governments have developed multi-indicator evaluation frameworks (Section 2.1), these generally focus on outcome variables (e.g., GHG emissions, technology deployment) rather than process variables (e.g., technological learning, infrastructure fit and adaptation). This limits their ability to evaluate progress in the *process* of transitioning to net-zero emissions (Hanna and Victor, 2021). These frameworks have important strengths: They are strongly empirical and often draw on deep, context-specific expert knowledge. At the same time, they also have notable weaknesses: They lack the theoretical grounding needed to guide the systematic selection and evaluation of indicators and their interactions, frequently resulting in a large set of loosely connected indicators, interpreted in a somewhat ad hoc manner.

Theoretical guidance can be found in the rich literature on sociotechnical sustainability transitions (Sections 2.2–2.4), which explains the dynamics and governance of energy transitions (Geels, 2019; Köhler et al., 2019). The Multi-Level Perspective on Sociotechnical Transitions (MLP) explains how multiple innovations and interactions across technological, economic, and governance dimensions drive transitions. Regarding the challenge of scaling up renewables and phasing out fossil fuels, the closely related and rapidly growing literature on accelerating net-zero transitions is particularly important because of its emphasis on system-wide change, looking beyond technology development and diffusion. However, transition studies papers are often theory-heavy, making them difficult to apply practically, and they rarely speak to policy audiences (Geels, 2019); thus, a turn towards empirically informed analysis of future transitions may increase their policy relevance (Rosenbloom, 2025).

This highlights the need for an evaluation framework that is both (i) theory-informed, guiding the selection and connection of indicators while helping evaluate what constitutes “sufficient progress” in climate transitions, and (ii) simple enough for relatively low-cost analysis without excessive data requirements, allowing for application across different countries and sectors. The key aim of this framework is to quickly identify areas of progress and areas where more effort is needed. Beyond being relevant in themselves, these insights offer a starting point for policy analysis and cross-country lesson-drawing.

In this paper, we develop a simple but holistic framework to assess sectoral transition progress from a system-change perspective and demonstrate its efficacy by applying it to four European countries to assess how they are progressing towards zero-emission electricity. Our primary contribution is methodological: the development of a comprehensive evaluation framework (Sections 3 and 4) for tracking sector-level zero-carbon transition progress. Unlike existing frameworks, which often have broad scope but lack theoretical grounding, our approach is theory-driven and anchored in the field of sustainability transitions research to improve the interpretability of results while maintaining a manageable number of indicators of systemic change. We seek to navigate the tension between simplicity, implying simple indicators that can be analyzed without deep context-knowledge, and holism, which requires deep system knowledge and multifaceted analysis. The result is a set of easily accessible indicators, that balance analytical simplicity with theoretical interpretability regarding the conditions required for systemic sectoral change. Our second contribution is empirical. To illustrate the applicability of this evaluation framework, we apply it to four national electricity system transitions—in Germany, Denmark, Norway, and the United Kingdom—each of which has been recognized as a zero-carbon electricity leader, while differing in energy mix, resources, size, and governance (Johnstone et al., 2021; Lipp, 2007; Molla et al., 2024; Rauter, 2022). The results of this analysis indicate progress in phasing out carbon-intensive technologies and integrating renewable electricity, but also reveal systemic challenges and risks, particularly regarding electricity grid infrastructure.

More generally, this paper takes steps towards making sustainability transition analysis more forward-looking and policy-relevant (Simoens et al., 2024). If transition studies are to influence real-world change, they must also be applicable to future transitions (Mey et al., 2024). This requires a shift—or *policy turn* (Rosenbloom, 2025)—in transition studies, where the focus is not only on understanding past transitions but also on assessing ongoing and future transformations and identifying actionable measures for near-term improvements. Indeed, a key shortcoming of sociotechnical transition research is the field's relative emphasis on theoretical advancement and conceptual fidelity over the development of actionable, policy-oriented knowledge. Much of the effort in transition studies is dedicated to extending theoretical frameworks, pursuing conceptual innovation, and refining approaches to fit new empirical phenomena. While theoretical refinement is an important enterprise, what is often needed from a policy perspective are pragmatic, implementable insights that can directly inform decision-making (Rosenbloom, 2025). Our study addresses this gap by developing an indicator-based framework to measure the acceleration of sectoral transitions. This approach enables a rapid yet holistic assessment of ongoing transitions, providing a theory-led method to evaluate what is going well and where progress is still low and additional or improved policies are needed.

2. Literature review and theoretical background

2.1. Existing evaluation frameworks to assess energy transition progress

Many studies assessing climate policy progress have been published. Often, they take the development of GHG emissions as the dependent variable (Bistline, 2021; Chateau et al., 2024; Lamb et al., 2022). Many studies base their analysis on the Kaya identity, disaggregating total emissions into key macro-factors—human population, GDP per capita, energy intensity of GDP, and carbon intensity (emissions per unit of energy consumed)—and identifying the proximate drivers of emissions (increases or reductions) (Bersalli et al., 2023; Karmellos et al., 2021; Kopidou and Diakoulaki, 2017; Robaina and Neves, 2021). However, these analyses offer limited insight into the progress achieved or future trajectory of transitions, as they only measure current outcomes, not underlying systemic developments.

Aggregated indicator approaches assess change from a broader perspective (Qi et al., 2024). For example, the Energy Transition Index (ETI) (World Economic Forum, 2024), focuses on economic development, environmental sustainability, and energy security in 120 countries. The ETI tracks national energy system *performance*, incorporating macroeconomic, institutional, social, and geopolitical factors. Similarly, the Energy Trilemma Index (World Energy Council, 2024) assesses energy transitions across equity, security, and environmental sustainability, ranking countries on their capacity to *deliver* sustainable energy transitions. Other influential indicator approaches include the Renewable Indicators for Sustainable Energy published by the World Bank (ESMAP, 2022), which evaluates policies on electricity access, clean cooking, renewable energy, and energy efficiency. Many of these frameworks draw on both hard data and expert assessments, providing rich annual updates on decarbonization efforts worldwide (Qi et al., 2024). However, these frameworks do not show if a country or a sector is transforming towards zero emissions.

Several governments, including France (MTEBFMP, 2024), the Netherlands (Rijksoverheid van Nederland, 2024), the UK (CCC, 2024), and Sweden (SCPC, 2024) have developed their own climate policy evaluation frameworks. A number of these operate with very large indicator arrays. For example, the Dutch framework includes 700 indicators, while the UK framework has 400. While such extensive arrays can offer a holistic view, they often become unwieldy. The lack of theoretical grounding and clear connections between indicators complicates result interpretation and hinders international comparisons.

Consequently, these frameworks struggle to explain how specific policies drive systemic transformation towards zero carbon.

2.2. Multi-level perspective: levels and phases of sociotechnical transitions

Sociotechnical transitions research offers a conceptual perspective to understand how systems—consisting of technologies, infrastructures, institutions, social practices, and economic factors—change (Geels, 2018; Köhler et al., 2019; Loorbach et al., 2017). The Multi-Level Perspective (MLP) has proven particularly useful in illustrating that transitions are not merely technological shifts but systemic reconfigurations involving interactions across multiple levels: niche innovations, regime structures, and landscape pressures (Geels, 2002, 2024).

Niches are protected spaces where radical innovations—technological, social, or business-related—can emerge and mature. The regime represents the dominant configuration of technologies, infrastructures, institutions, and practices that stabilize existing systems and often resist change. The landscape represents broader external pressures such as cultural shifts, economic trends, or geopolitical developments, which can destabilize regimes and open windows for change.

Transitions occur when landscape pressures or internal regime tensions allow niche innovations to break through and challenge the incumbent system. Over time, this can lead to regime reconfiguration, where elements of the old system are replaced, adapted, or integrated with the new. The trajectory of each transition depends on the timing and interaction of developments across levels, as well as the compatibility between emerging and existing system elements (Geels and Schot, 2007).

We draw on the MLP primarily because it emphasizes the multidimensional nature of transitions, which unfold across technical, institutional, and socio-cultural domains (Geels, 2002; Markard et al., 2020). This systemic view is essential for understanding complexity of change and to guide the search for the dimensions and variables to analyze – for identifying what must change in a transition.

The MLP conceptualizes transitions as happening in distinct phases—invention, market introduction, diffusion and reconfiguration—-with each phase presenting specific challenges to be overcome, related to changing aspects of technological development, diffusion and systemic change (Geels and Turnheim, 2022). This leads to sequential policy needs: A policy supporting R&D in the invention phase is not very useful to trigger rapid deployment in the diffusion phase or infrastructural change in the reconfiguration phase. Our analysis focuses on the latter two phases, where the new technologies already exist and are relatively mature, but the transition still needs to "happen"—the new technology must take over from the old, the old needs to be phased out, and all this requires the infrastructural and organizational systems to change. These phases are characterized by increasing contestation, resistance, and coordination challenges (Markard et al., 2020; Rogge and Goedeking, 2024). As innovations diffuse, they confront incumbent systems, triggering political, economic, and social frictions. Reconfiguration primarily involves scaling up the new to take over from the incumbent technologies, which are phased out in tandem with the transition to the new (Murphy et al., 2025).

2.3. Path dependence and carbon lock-in in sociotechnical systems

The concepts of path dependence and lock-in are used in sustainability transitions research to explain the persistence of unsustainable sociotechnical systems (such as fossil-based electricity) even in the face of available and often superior low-carbon alternatives (Geels, 2005). Path dependence refers to the self-reinforcing processes that shape system development over time, where early choices, increasing returns to scale, and institutional commitments progressively narrow the scope for alternative pathways (Arthur, 1989; Pierson, 2000). Within the MLP, lock-in occurs at the regime level, where the dominant configuration of technology, markets, institutions, user practices, and knowledge systems becomes stabilized and resistant to change. In the context of net-zero transitions, this is referred to as "carbon lock-in", a consequence of path dependency which inhibits the diffusion of zero-carbon alternatives to fossil fuel-based systems (Foxon, 2014; Seto et al., 2016). In this sense, path dependence is the cause, while lock-in is the symptom: Lock-in emerges as the observable outcome of path-dependent processes that constrain change.

For our purposes, path dependency manifests in two key ways: in the development of technologies and systems. Without path dependency, assessing transition progress would be a straightforward matter of tracking a linear decline in emissions alongside the replacement of coal-fired electricity with wind power, for example. Technology is path dependent, meaning that its present maturity and performance are shaped by its past development and use. Emerging technologies require cost reductions through R&D and market-based learning to become a viable alternative. Systems are also path dependent, having evolved in tandem with dominant technologies over decades, resulting in infrastructures and regulatory environments that are perfectly adapted to each other. New technologies lack these benefits and may face disadvantages due to systemic mismatches. Consequently, if the aim is to understand transition progress as it unfolds, it is necessary to assess technological development alongside market shares of both new and old technologies, and to assess infrastructural changes and regulatory reforms alongside emission trends. Path dependency complicates both transitions and their analyses.

These path dependencies lead to lock-in (Seto et al. (2016), which is a particularly relevant problem in sectors based on very long-lived assets, such as the electricity sector. Long-lived assets such as fossil fuel power plants and transmission grids create material and financial inertia that delays the adoption of renewable alternatives. These infrastructures are embedded in broader systems of standards, services, and workforce skills, making their replacement both costly and slow (Foxon, 2014; Geels, 2005). Institutional lock-in further reinforces this persistence, as electricity markets, policy frameworks, subsidies, and utility business models are often designed around the needs of centralized fossil-based generation (Pierson, 2000). Together, these forms of lock-in stabilize the existing sociotechnical regime, making ambitious climate targets harder to achieve even when clean technologies are mature and cost-competitive. Understanding the role of path dependence and lock-in is essential for assessing progress and designing effective interventions in net-zero transitions. They are not positive or negative per se: Transitions usually deal both with the unlocking and path-breaking of one regime, while creating new paths and profiting from the lock-in of new technologies, which profit from deployment, learning and improvement, and institutional and infrastructure adaptation (Geels, 2026). The transition away from carbon-intensive systems involves not simply replacing technologies but reversing the feedback loops that have sustained the dominant material and immaterial regime and directing them to support the new. Unlocking the system requires targeted interventions to shift incentives, remove institutional barriers, and decommission unsustainable infrastructure (Pierson, 2000; Unruh, 2000). In that sense, evaluating transition progress requires us to pay attention both to the expansion of new technologies but also to the persistence and dismantling of old ones—what some scholars describe as the dual process of "phase-in" and "phase-out" (Kivimaa and Kern, 2016).

2.4. The challenge of measuring acceleration of net-zero transitions

Much of the literature on sociotechnical transitions has concentrated on the *ex-post* analysis of past and completed (and sometimes failed) transitions, with most analytical tools designed for retrospective evaluation. More recently, scholars have turned to the study of *ongoing and future (incomplete)* transitions. A notable strand in this growing literature is the focus on the *acceleration* of net-zero transitions (Andersen et al., 2023; Rogge and Goedeking, 2024; Sovacool et al., 2025).

Acceleration is both a normative concept —highlighting the urgency of rapid sustainability transitions— and a systemic process. As a process, it involves the rapid accumulation of technological deployment, learning, and adoption that unfolds along aggregate transition curves, represented by several interlinked “S-curves”. As previously noted, accelerating deployment and maintaining a high deployment pace through to completion of sustainability transitions requires infrastructural adaptation and regulatory reforms to integrate new technologies, coupled with efforts to phase out the old emitting technologies. Acceleration is thus a multifaceted process, affecting all parts of the system, with the ultimate aim of letting the new technologies take over fully from the old.

This newer focus departs from earlier understandings in transition studies, which often relied on a simple S-shaped diffusion curve where acceleration was portrayed as the third phase in which radical innovations diffuse into mainstream domains. The more recent literature instead emphasizes system-wide change, looking beyond technology diffusion to include drivers, conditions, mechanisms, impediments, and dynamics across multiple dimensions—techno-economic, institutional, behavioural, and cultural (Sovacool et al., 2025).

Despite this progress, there remains no common understanding of which variables should be considered when assessing acceleration. Analytically, contributions on acceleration frequently conflate *depth of change* (the extent of systemic transformation) with *speed of change* (the rate of transformation), or treat them interchangeably (Sovacool et al., 2025). Yet, as Andersen et al. (2023) note, it is often easier to accelerate changes within components than across whole sociotechnical systems. This creates tensions between achieving rapid change and achieving deep, systemic change. Several studies blur this distinction, insufficiently addressing how to measure each dimension.

This raises a crucial question: How do we know whether ongoing acceleration (process dimension) is sufficient to meet future goals (normative dimension)? Relying solely on output variables—such as rates of renewable deployment or emissions reductions—may be necessary but is not sufficient for understanding the broader systemic shifts required. In the following session, we propose critical dimensions and associated variables of system change, going beyond a narrow focus on outputs.

3. Critical dimensions to assess system change in net-zero energy transitions

Drawing on the MLP, and the concepts of path dependence and lock-in as drivers out of one and into another system, we distinguish three interconnected dimensions of change for assessing energy transition progress. First, the technologies and artefacts that dominate the generation and/or use of energy. Second, the infrastructure environment that facilitates or hinders the use of the technological artefacts. Third, the institutional and regulatory environment, including markets and public policy (Mey et al., 2024).

3.1. Technologies: phase-in and phase-out

Technological artefacts are the most obvious factor that must change in a transition from high-carbon to zero-carbon systems: wind farms replacing coal power stations; electric vehicles replacing internal combustion engine vehicles. Replacing technologies alone is insufficient, but necessary for a transition. Therefore, the *performance* of new technologies is critical to overcoming carbon lock-in and making transitions feasible (Grubler et al., 2016; Sovacool, 2016). In purpose-driven transitions with significant time constraints—such as energy transitions—both the phase-in of zero-carbon technologies and the phase-out of carbon-intensive ones must be monitored.

We identify two phase-in variables, describing both the technology progress and the development of conditions for further growth: (1) the deployment rate of the New, and (2) the trend of costs of the New relative to the Old.

The deployment rate of new technologies is a key variable — not only because the New must grow, but also because deployment triggers increasing returns and is closely connected to the development and maturity of technologies, because costs often decrease as a function of deployment through economies of scale and technological learning (e.g., learning-by-doing and learning-by-using) (Arthur, 1994). In most countries, except very large ones like China, the national deployment does not directly or strongly affect technology cost: Technological learning is driven by global cumulated deployment, whereas the particular cost of a technology at a specific time is also affected by policy and market setting, geography, supply chain bottlenecks and a range of other economic factors. Nevertheless, global and national deployments are connected: Increasing global deployment can lead to decreasing global costs and better performance, which supports further national deployment, boosting global deployment, and so on: The sum of all national deployment and technological progress may form a virtuous cycle (Schmidt and Sewerin, 2017; Thonig and Lilliestam, 2024); it also triggers a growing expectation of further deployment leading to infrastructure development, and thus network effects further increasing the benefits of the New. Both deployment and market share are important metrics in transitions, because at some point, the New must overcome the incumbent technology and become dominant itself (Grubler et al., 2016). The ultimate sign of a complete transition is that the New has conquered the entire market and the Old has disappeared.

The cost relations between New and Old are a crucial part for transitions (Fouquet, 2016). While public procurement and support policies can initiate deployment of the New, a breakthrough in mass markets requires cost relations that make large-scale deployment of the low-carbon alternative financially viable and economically attractive for investors and consumers alike. Immature technologies are usually expensive, because learning processes have not yet taken effect, and costs will decrease as deployment starts. Cost not only captures performance (e.g., efficiency) but also scalability. High costs are not necessarily caused by inefficient or expensive processes but may also be explained by initial or transient issues like scarcity of materials, cost of capital, or other resources, for which there can again be different reasons endogenous or exogenous to the new technology. The fixed and variable costs of technologies hold valuable information, signalling what types of costs might be a barrier to diffusion. The cost and cost trend relative to the dominant incumbent technology is particularly relevant.

Given the short time available to achieve net-zero, existing carbon-intensive technologies are unlikely to be displaced solely through innovation (Meadowcroft and Rosenbloom, 2023). Instead, policy efforts must expedite the deliberate decline of carbon-intensive systems and their components, technologies and practices. In other words, policy must phase out the Old, not only phase in the New (Rosenbloom and Markard, 2020). For instance, if no policies are introduced to destabilize the fossil fuel regimes in the electricity sector, new renewable capacities might simply be added to the existing fossil fuel capacities instead of replacing them, particularly in countries with growing electricity demand. Kivimaa and Kern (2016) and Kivimaa et al. (2021) view destabilization of the Old and innovation for the New as mutually reinforcing processes, proposing that transition policy mixes should include policies that foster new technologies while simultaneously withdrawing support for old ones.

3.2. Infrastructure

The physical installations supporting a technology—its infrastructure—are an important part of the sociotechnical environment that facilitates adoption. While infrastructure itself consists of evolving technological systems (Unruh, 2002), its presence (or absence) strongly affects the performance of the main technological artefacts. A wind park, no matter how technologically sophisticated, is not useful without an electricity transmission grid and far less valuable without adequate storage capacity to manage fluctuations in generation. Infrastructure deployment must (at least) keep pace with the deployment of a new zero-carbon technology to support its continued adoption or the lack of infrastructure will become a barrier. Insufficient infrastructure may hinder the connection of new wind or solar parks or reduce the value of existing ones by increasing renewable energy curtailment. Infrastructure indicators should account for current and planned infrastructure and the extent to which such developments fit the zero-carbon technologies they must support.

Because it is very long-lived, infrastructure is a key reason for lock-in (Seto et al., 2016; Unruh, 2000): Once a highway, transmission line, or pipeline is in place, it will remain for many decades and operators have every incentive to keep using them. Simultaneously, infrastructure exists within institutions, with the development and operation of infrastructures often being subject to and the expression of public planning, regulation and policy. These institutions are often even slower to change, further impeding radical infrastructural change.

3.3. Institutions: policy targets and regulatory reforms

In sociotechnical systems, technologies and infrastructures interact with each other and society at large through institutions (Unruh, 2002). Institutions can take the form of written laws and regulations (e.g. rules for electricity metering, a ban on new coal power), but also of unwritten norms, practices and habits. They define the constraints and opportunities in sociotechnical systems—how the system is organized and operated (North, 1990; Pierson, 2000).

New technologies or infrastructures may be fully or partially compatible with the existing institutional setting. Often, new zero-carbon technologies and systems are however at odds with the exiting institutions as these have evolved over a long time to support and reinforce the incumbent, high-carbon technology and are perfectly adapted to it and maladapted to the new emerging needs (Unruh, 2002; Victor et al., 2019). The key questions are: Are institutions designed to support new technologies and infrastructure? If not, what changes are needed to make them fit for purpose?

The evolution of sociotechnical systems governance is very context-specific. For instance, many different styles of formal rules (e.g., market designs) can exist and work, depending on the context and history; informal institutions like cultural norms and consumption patterns, can differ significantly from country to country and are hard to measure and compare (Geels and Turnheim, 2022). Consequently, analyses should focus on (quantitively or qualitatively) measurable barriers to transition that must inevitably be overcome as well as sectoral specificities.

Within the broader concept of institutions some variables are particularly relevant to track transition progress. Climate and energy policy targets at the national and sectoral levels play an important role here. More than mere declarations of intent, such targets give investors and consumers a sense of direction of the technological path the country is pursuing (Brückmann and Stadelmann-Steffen, 2026; Geels et al., 2017). Targets are the outcome of political struggles and the consideration of different interests and goals (Cherp et al., 2017), and thus serve as a widely accepted (at a given time) benchmark against which the deployment of technologies and infrastructure can be measured.

Second, market regulations constitute the formal rules governing economic activities in a sector. Having developed as part of the incumbent regime—and thus designed to support incumbent technologies—regulations must change to now benefit the New, even if, and especially if, this disadvantages the Old. As Unruh (2000) points out, the ability of governmental institutions to guide and, if needed, override market forces makes them a key factor in shaping sociotechnical systems, particularly in purpose-driven transitions such as the energy transition. One example is the phase-out of fossil fuel subsidies for electricity generation and consumption. Another critical regulatory change is the introduction of dynamic electricity tariffs to improve consumer responsiveness to prices and unlock flexibility and efficiency potentials (this institutional reform is only possible by deploying the infrastructure smart metre).

Effective policy implementation and enforcement also depend on the capacity of the bureaucratic apparatus. For example, permitting delays are a major barrier to the deployment of zero-carbon technologies and infrastructure in many countries (McKenna et al., 2025; Victor et al., 2019). This has to do with the content of regulation—e.g., enforcement rules and opportunities to object etc. — but also with the efficiency of administrations and (in-)adequate staffing. Here too, institutional change and overhauls of locked-in practices and norms are needed.

Furthermore, regulatory adjustments must be legitimatized by public support (Hughes and Urpelainen, 2015). Public support is important for climate change policy, and for renewables policy specifically, as this affects both the likelihood of continued or increased policy ambition and the ease of getting on-the-ground projects permitted.

4. Evaluation framework: empirical approach and metrics

Building on the interconnected dimensions of change discussed above, we developed an evaluation framework for assessing transition progress, organized into five components, each further specified through a set of metrics. The selection of metrics—indicators used to capture changes in technologies, infrastructure and institutions within socio-technical systems (in this case, the electricity sector)—is a key foundation of this framework.

We selected the metrics through a multi-step process, beginning with a pre-selection based on three critical dimensions for assessing system change in net-zero energy transitions, as identified in the literature on sociotechnical transitions and detailed in Section 3. This selection focused on metrics that capture the most relevant aspects of systemic change, while keeping the total number of indicators manageable.

This was followed by an expert workshop in Berlin in September 2023, where we discussed the proposed metrics with eleven experts on energy transitions from Germany, the United Kingdom, and the Nordic countries. The participants were selected using purposive sampling based on predefined criteria, in particular their publication record on energy transition or climate policy topics relevant to this study, professional experience in academia or policy-oriented think tanks, and the direct relevance of their work to at least one of the four case studies. Potential participants were identified through a review of relevant academic and policy publications, and through the co-authors' professional networks. The final selection of experts and the invitations to the Berlin workshop were jointly agreed upon by the co-authors and the Bertelsmann Foundation, which funded the research project, with the aim of ensuring disciplinary (transition studies, economics, sociology and political science), gender and geographical diversity. One of the main recommendations from the workshop was to explicitly include indicators for the phase-out of carbon-intensive technologies alongside the phase-in indicators, which had been absent from our original selection. In March 2024, we held a second expert workshop online, with the same group of researchers and practitioners, to validate the final set of metrics and assess the evaluation method associated with each metric (see Supplementary Note 1). We then conducted a final workshop in Berlin in June 2024, inviting additional experts on climate and energy policy (following the same selection criteria than for the previous workshops) to review our preliminary results. The feedback received in this final workshop helped us refine and finalize the evaluation framework and confirm the selection of metrics described in the following subsections.

The first component of the evaluation framework (see Fig. 1) focuses on national decarbonization targets, including sectoral targets. To align with the Paris Agreement, sectoral decarbonization targets must establish a pathway to carbon neutrality by mid-century. Sectoral targets usually include specific targets for zero-carbon technologies, and sometimes also for infrastructure.

The second component focuses on progress in the decline of the Old, i.e., whether the phase-in of the New pushes out the old carbon-intensive

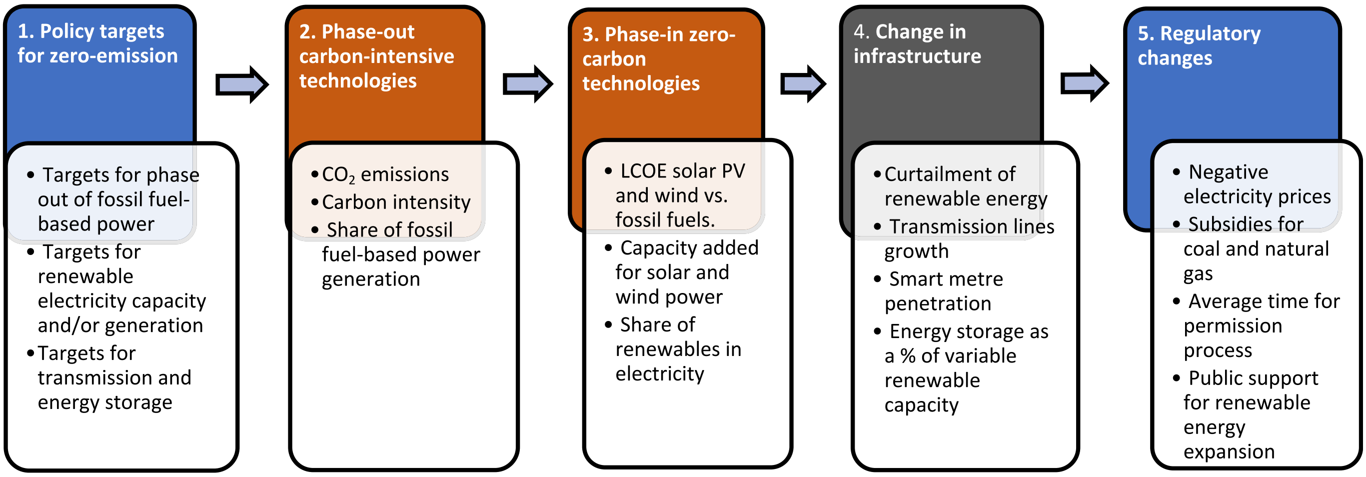


Fig. 1. Evaluation approach. Overview of the five components and the associated metrics to assess transition progress in the electricity sector. Steps 1 and 5 refer to the institutional dimension, Steps 2 and 3 to technology and Step 4 to infrastructure.

technologies, and whether this phase-out is on track. This can be observed in several metrics, including sectoral emissions, carbon intensity and share of fossil power in the system. Ultimately, a successful transition will see all three metrics decline to zero.

The third component is about the deployment and cost trends of zero-carbon technologies. We assess deployment in relation to the national targets and costs in relation to national trends of zero-carbon technologies versus fossil fuels-based technologies.

Fourth, we assess the state of infrastructure and its deployment and, fifth, the adequacy and development of the regulatory and institutional framework. Both components must change in sync with the (expected) deployment of zero-carbon technologies or the growing share of the New will cause increasing friction—economic losses, energy losses and inefficiencies, or even potentially system instability. Because of the diversity of institutions and ways to adapt them, it is challenging to measure progress, especially across countries. Our indicators here focus on the most important signs of regulatory misfit with the New.

This five-component framework is applicable to different sectors (e.g., transport, heating), although the specific indicators will differ. Fig. 1 provides an overview of the indicators for the electricity sector, which we describe in Sections 4.1–4.5. The evaluation method associated with each indicator and the respective data sources are presented in the Supplementary Note 1.

Overall, we evaluate the metrics in a forward-looking way: current and future progress is evaluated based on the current conditions and recent (last five years) trends. Our focus is on the transition process rather than solely on achieved outcomes, allowing us to capture recent policy and market dynamics. While we do include some outcome variables (e.g., emissions)—acknowledging their importance—we do not interpret them in isolation but rather in relation to their significance for the ongoing transition within the broader system. Depending on the metric, we compare five-year trends with the linear trajectory towards either (i) sectoral targets (e.g., renewable electricity capacity goals) or (ii) the benchmark of zero emissions.

There is disagreement regarding when exactly industrialized countries must reach zero emissions in different sectors to comply with the Paris Agreement. In recent years, many analyses have deviated from the previous consensus year 2050 towards 2045 as the latest year for achieving economy-wide net-zero in industrialized countries (IEA, 2021; Plötz et al., 2021). For electricity, an earlier decarbonization around 2035 is often viewed as both necessary and feasible in OECD countries, given the state of technological change in the power sector and its importance for the decarbonization of other sectors, such as road transport and heating (Boitier et al., 2023; IEA, 2021). For our analysis, we view full power sector decarbonization by 2035 as the benchmark for a Paris-consistent target.

All metrics assigned to the variables are evaluated for whether the value is "sufficient" (on track to meet target; costs lower than fossil, etc.), "insufficient" (trend in wrong direction, costs higher than fossil, etc), or "partially insufficient" for the sectoral transition to zero-emission by 2035. The evaluation "partially insufficient" holds results that point in the right direction, but not at the required speed. In Supplementary Note 1, we describe the boundary between the three evaluation categories for each metric and present the respective data sources.

4.1. Sectoral targets

The *technology targets for electricity* refer to the share of installed capacity and/or power generation/consumption from renewable electricity, including all renewable technologies; if a country has a target for nuclear power, we add this to the renewables targets as both are zero-emission technologies. To be deemed sufficient, the final target for renewables must meet two criteria. First, it must be sufficient to achieve a zero-emission system by 2035 (Table 1). Second, the timetable (i.e., intermediate targets) for the final target should envisage linear or stronger-than-linear growth of capacity, underscoring the ambition to accelerate a transition now, not delaying deployment to the future. Both criteria are useful for transitions in the diffusion or reconfiguration phase (such as the electricity transitions in Europe) but would be too strict for earlier phases. Similarly, with the metric "fossil fuel phase-out targets," we assess whether a country has Paris-aligned targets for phasing out coal and gas in electricity generation.

Infrastructure targets encompass multiple elements: transmission grids, distribution grids, and electricity storage. From a systemic perspective, grid planning must reflect expected future electricity generation and flows, aligning with national decarbonization targets and renewable electricity capacities. The task of ensuring this largely falls to the Transmission System Operators' (TSOs) and Distribution System Operators' (DSOs) through their respective grid plans. To evaluate how these plans support the energy transition, we compare these scenarios with the latest national energy targets. Due to data restrictions concerning distribution grid plans and actual deployment, we performed the analysis solely for transmission lines. Storage is usually not included in grid plans, so targets (if any) are typically set by governments. Here, we evaluate whether storage plans align with renewable deployment targets and the overall goal of full decarbonization.

Table 1

Evaluation approach for the 13 variables, 19 metrics of the framework. Further details and data sources are available in Supplementary Note 1.

Table 1 (*continued*)

Component	Variable	Metric	Evaluation
A: Policy targets	1 Phase out targets	1: Targets for phase out fossil fuel power generation (year)	Sufficient: Phase-out targets aligned with net-zero by 2035; Partially insufficient: Targets exist but not aligned with net-zero by 2035; Insufficient: No phase-out targets
	2 Technology targets	2: Targets for renewable electricity (RE) capacity and/or generation share (%, year)	Sufficient: 100% renewables by 2035; Partially insufficient: $<$100% renewables by 2035; Insufficient: No targets
	3 Infrastructure targets	3.1 Targets for transmission development national (km) – consistency with technology targets	Sufficient: Grid targets based on renewables; Partially insufficient: Grid targets not based on renewables; Insufficient: No grid targets
		3.2 Targets for energy storage (GW or GWh)	Sufficient: Storage targets (electricity & hydrogen) based on renewables; Partially insufficient: Partial or unrelated storage targets; Insufficient: No storage targets
B: Phase-out of carbon-intensive technologies	4 CO$_2$ emissions electricity	4.1: CO$_2$ emissions of electricity generation (Mt CO$_2$e), trend	Sufficient: Emissions falling at/above net-zero pace; Partially insufficient: Emissions falling below net-zero pace; Insufficient: Emissions rising or stagnating
		4.2: Carbon intensity of electricity (gCO$_2$e/kWh), trend	Sufficient: Below EU average and falling; Partially insufficient: Above EU average but falling faster; Insufficient: Not falling or slower than EU
	5 Phase-out progress	5: Share of fossil fuel-based power generation (%)	Sufficient: Decline matches/exceeds net-zero path; Partially insufficient: Decline slower than net-zero path; Insufficient: Share stagnates or rises
C: Phase-in of zero-carbon technologies	6 Technology cost	6.1: Levelized Cost of Electricity (LCOE) (EUR/kWh), national trend; solar PV	Sufficient: Cheaper than fossil fuels; Partially insufficient: More expensive but gap shrinking; Insufficient: More expensive, gap not shrinking
		6.2: LCOE (EUR/kWh), national trend; wind power	Sufficient: Cheaper than fossil fuels; Partially insufficient: More expensive but gap shrinking; Insufficient: More expensive, gap not shrinking
	7 Technology deployment	7.1: Capacity added (GW/year) for solar and wind power; trend	Sufficient: Growth meets/exceeds linear path to target; Partially insufficient: Growth below linear path; Insufficient: Stagnating or declining
		7.2: Share of renewables in electricity generation (%), trend; average for renewable energy technologies	Sufficient: Growth exceeds net-zero path; Partially insufficient: Growth below path, gap $<$20%; Insufficient: Growth below path, gap $>$20% or falling
D: Infrastructure	8 State of electricity infrastructure	8: Curtailment of RE (%), trend	Sufficient: Curtailment falling despite renewable growth; Partially insufficient: Curtailment stagnates despite growth; Insufficient: Curtailment rising
	9 Electricity infrastructure deployment	9.1: Transmission lines (km) trend	Sufficient: Grid growth exceeds path or $\geq$ 50% in 5 years; Partially insufficient: Grid growth $<$ path or 20–50% in 5 years; Insufficient: Grid growth $<$20% or declining
		9.2: Energy storage as a % of variable renewable capacity [%]	Sufficient: Above EU average and growing; Partially insufficient: Below EU average

(*continued on next page*)

Table 1 (*continued*)

Component	Variable	Metric	Evaluation
			but growing; Insufficient: Below EU average and not growing
		9.3: Share of households using smart tariffs/ having smart metres (%)	Sufficient: >70% buildings equipped; Partially insufficient: 30–70% equipped; Insufficient: <30% equipped
E: Market regulation	10 Negative prices	10: Negative (wholesale) electricity prices (% hours per year)	Sufficient: No negative prices; Partially insufficient: Negative prices falling, not tied to renewables; Insufficient: Negative prices persist or tied to falling renewables
	11 Fossil fuels subsidies	11: Subsidies for coal and natural gas (USD); trend	Sufficient: No coal/gas subsidies; Partially insufficient: Subsidies exist but falling; Insufficient: Subsidies persist or rising
	12 Administrative capacity	12: Average time for permission process, wind power (months)	Sufficient: Below EU limit; Partially insufficient: Above EU limit but below EU average; Insufficient: Above both EU limit and average
	13 Public support to the energy transition	13.1: Support to the expansion of renewable energy (%)	Sufficient: >50% support, not falling; Partially insufficient: >50% support, but falling; Insufficient: <50% support

4.2. Phase-out of carbon-intensive technologies

The ultimate objective of the electricity transition is to reach zero emissions by 2035. Consequently, the recent trend in *CO_2 emissions of electricity generation* is a central variable. However, *current* emissions are the result of *past* developments, which are directly related to efforts within the electricity sector but also to external factors like economic crises. Therefore, emissions metrics alone do not indicate whether the system is transforming, or whether observed reductions are steps towards zero emissions (Lilliestam et al., 2022).

We also measure progress in phase-out through the *share of fossil fuel-based power* and the extent to which these changes are aligned with 100% zero-carbon electricity by 2035. We do not take a position on whether to phase out coal before gas, or vice versa, as long as both are phased out by 2035.

Whereas CO_2 emissions and the share of fossil fuels trends indicate recent progress, the metric *carbon intensity of electricity* reflects the state of decarbonization, resulting from longer-term developments. For instance, a country may have recently slowed down its CO_2 emission reductions, but if its carbon intensity is comparatively low, it would be easier for this country to catch up with a zero-carbon trend in the future.

4.3. Phase-in of zero-carbon technologies

The cost relationship between old and new technologies and the speed of deployment of new technologies are critical elements of all sociotechnical transitions. The cost metric for electricity is the *Levelized Cost of Electricity (LCOE)*, which is used here to compare the main renewable technologies (PV, onshore and offshore wind power) with coal and gas power. It is easy to include further technologies, such as nuclear, if relevant for specific cases. LCOE is the most commonly used metric to compare the costs of different power technologies, including both investment and operational costs (IRENA, 2022). We consider the LCOE of renewables and fossil fuels *today*, as well as the five-year trends. To be deemed sufficient, the current LCOE for renewables must be lower than that of fossil competitors.

We measure deployment of renewable power by two metrics. First, by comparing the *solar and wind capacity added* with the linear path to the sectoral targets. This checks whether the speed of deployment is sufficient to meet the national goals. Second, deployment is measured by the five-year trend in the *share of renewable electricity* compared to the linear trajectory to zero-carbon electricity by 2035.

4.4. Adaptation of infrastructure

In a high-renewables power system, grid and storage infrastructures must be capable of dealing with the intermittency of wind and solar power. For the transmission grid, this means a longer and denser network, capable of handling fluctuating power flows over long distances. The distribution grid needs reinforcements to integrate a multitude of small-scale, decentralized generators and prosumers. Storage is vital to decouple generation from consumption over time.

For national *transmission*, the metrics are the *new lines,* measured in kilometres (corresponding to expansion plan targets), over the last five years. For distribution, we measure qualitative changes to increase flexibility (Guo, 2023) through the metric share of *households with smart metres*. As a benchmark, we apply fixed threshold values reflecting different stages of deployment, as smart metres constitute an enabling infrastructure for demand-side flexibility, for which higher penetration is associated with improved system functionality.

As the share of variable renewable electricity increases, so does the need for storage capacity to manage intermittency, including battery storage, pumped hydro, and hydrogen-based storage options (Agora Energiewende, Prognos, and Consentec, 2022). We therefore include a metric measuring *electricity storage capacity as a percentage of variable renewable generation.* Battery storage comprises both home storage systems and large-scale/industrial storage installations. Given the absence of a system-independent optimal storage level —and the strong dependence of storage needs on national system characteristics and alternative flexibility options— we use the EU average as a comparative benchmark for evaluating storage capacity. We acknowledge that storage is a complex dimension of zero-emission power systems that is difficult to capture in a single indicator; accordingly, this metric is not a strict benchmark for “certainly good enough”, but indicates that already in these early stages of the transition, a country above the EU average is at least doing better than the bulk of European countries.

Existing infrastructure must match the needs of the current technology mix, meaning that grid and storage must be able to transport or store the renewable electricity produced. We measure the (mis)fit of the infrastructure with the pace of new technology deployment as the trend for *renewable electricity curtailment.* Curtailment refers to an involuntary reduction in a generator's output due to the grid operator restricting electricity delivery from the generator to the grid (Gandhi et al., 2022).

If electricity is increasingly curtailed, it indicates that the infrastructure adapts too slowly to handle the growing renewables share.

4.5. Regulatory reforms

As renewables have very low, or zero, marginal costs, they are fundamentally different than fossil power, for which existing power market regulations were designed. High shares of renewables could lead to very low or negative prices, so a measurable symptom of misfit between renewables and the pricing mechanism is the occurrence of *negative prices* in the spot market. This is caused by low marginal-cost renewables and potentially exacerbated by infrastructure bottlenecks within a country and/or between neighbouring countries. The metric is evaluated based on whether the volume of electricity experiencing negative prices is increasing or decreasing.

Another vital aspect of market regulation is *fossil fuel subsidies*. Subsidies for fossil fuels for electricity must rapidly fall to zero; we see anything except zero as (partially) insufficient.

Administrative capacity is difficult to measure directly, as it is observable mainly when it is insufficient. We measure it via a proxy of the *duration of permission processes* for the most complex technology currently deployed: wind power. Specifically, we measure the average permission time; the 2018 Renewables Directive set a 24-month limit, which we use as benchmark too.

Finally, we track *public support for the energy transition* using Eurobarometer data on public perceptions of renewable electricity expansion. We assess whether a majority of national residents support the expansion of renewable energy and how this trend is evolving.

4.6. Case selection

The main criterion for case selection was that each country should be a frontrunner in the electricity transition, with clear zero-emission targets for the electricity sector and advanced renewable energy deployment, either in terms of the share of renewables in electricity generation or the pace of new capacity additions. This common basis enables us to compare how infrastructure, institutional adaptations, and other central elements of the energy system are evolving across these countries.

Germany and Denmark have long been regarded as pioneers in renewable electricity deployment, especially in onshore wind power. The United Kingdom is recognized for its complete phase-out of coal power generation and its strong support for offshore wind development. Norway, meanwhile, already has an electricity system approaching 100% renewable generation, primarily based on hydropower, but still faces the challenge of expanding wind and solar capacity (and the related system) to meet rising electricity demand driven by the electrification of other sectors. From a governance perspective, all four countries are highly developed with strong institutional capacities, but they differ in other relevant characteristics, such as EU membership.

Finally, the case selection aims to illustrate the applicability and flexibility of our evaluation framework across contexts that are broadly comparable yet distinct in key aspects—including electricity system size and energy mix. Other European countries, such as Spain and Sweden, could also be considered frontrunners in the electricity transition, and we encourage future applications of our framework to such additional cases.

5. Evaluating electricity transition progress in Europe

Denmark, Germany, the UK and Norway all have economy-wide targets for achieving net-zero emissions by 2050 or before and sufficient or partly sufficient targets for the electricity sector. While all have made progress in deploying renewables and phasing out coal, the paces of their electricity transitions differ. Norway and Denmark emerge as leaders, with most metrics sufficient and on track for achieving zero-emission electricity by 2035. In contrast, Germany and the United Kingdom lag behind, with most metrics assessed as insufficient or partially insufficient. While all countries perform (somewhat) well in all target and technology categories, progress on institutional and infrastructural change is uneven. This clearly shows that although emissions decrease and renewable increase, especially Germany and the UK are far from on track towards zero-carbon electricity: Much stronger policies for systemic change are needed (Fig. 2). Almost all "insufficient" scores concern infrastructure and regulation, demonstrating the importance of explicitly including these systemic indicators in an assessment: With these factors, the overall finding is much more critical than looking only at targets and outcome indicators.

Fig. 2 provides a synthesis of all evaluation metrics, while a detailed, metric-by-metric analysis for each country is presented in Tables S1–S4 in Supplementary Note 2 and a synthesis per country in Supplementary Note 3. In the following subsections, we summarize the most important transition dynamics, following the five-step evaluation method.

5.1. Sectoral policy targets

Both Norway and Denmark have sufficient fossil fuel phase-out targets: Norway has completely phased out coal, whereas Denmark plans to achieve this by 2028. Both countries use little gas power (Tables S2-S3). German and UK targets are partially sufficient: Both have coal phase-out targets (by 2038 in Germany) but not for gas, which still represents a substantial share of electricity production (Tables S1, S4). The UK closed its last coal power station in late 2024.

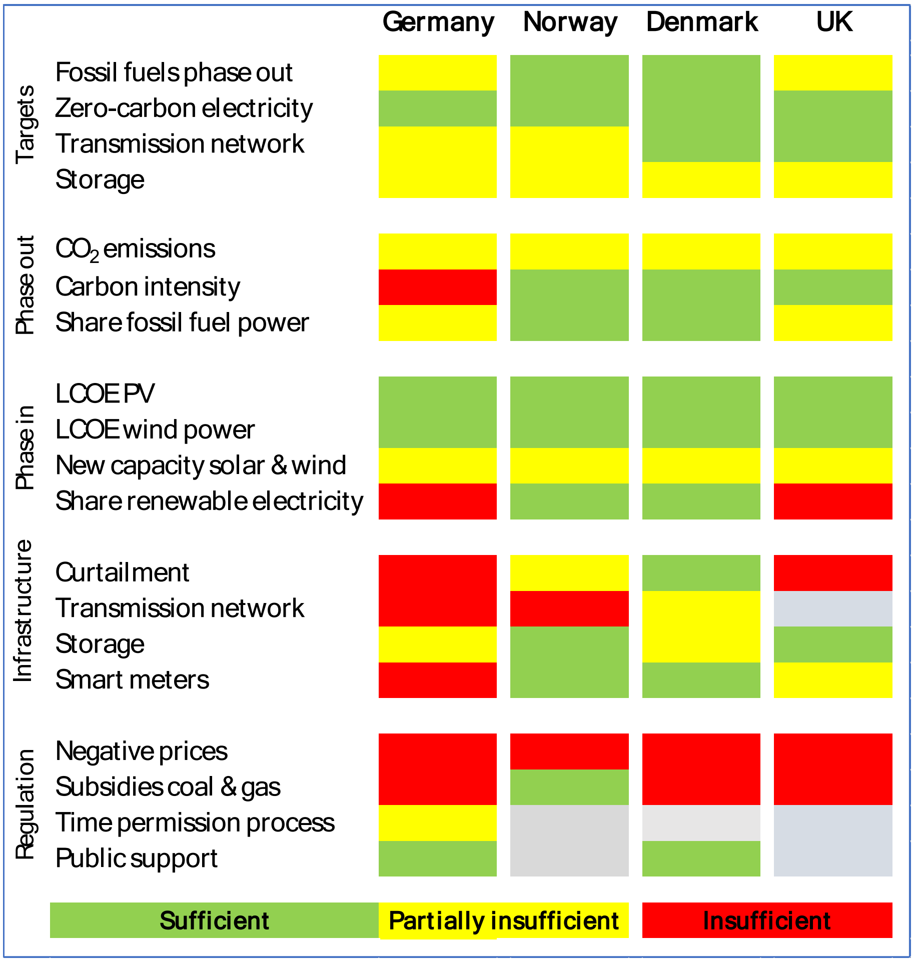
All four countries have increased their renewable power targets, which are aligned with achieving zero-carbon electricity by 2035—including 10% of nuclear power in the UK. Each country has capacity targets for specific renewable electricity technologies, aiming for a very substantial increase of solar and wind (Table 2). While the targets mostly refer to 2030, they can be used as an approximation for the development until 2035.

The targets and plans for transmission are rated as "partially insufficient". Denmark is a positive outlier: There, the TSO's transmission grid expansion plans are based on solar and wind capacities (44 GW) and exceed the national renewable electricity targets (Table 3), demonstrating a proactive approach to grid development. On the other hand, the German and Norwegian grid expansion plans are based on only two thirds to three fourths of the solar and wind targets, suggesting that even a future expanded grid may be insufficient to handle the planned amounts of renewables.

5.2. Phase-out of carbon-intensive technologies

Although CO_2 emissions are decreasing in all countries, the reduction over the past five years is partially insufficient compared to the benchmark for achieving zero emissions by 2035 (Fig. 3): Emissions decrease roughly, but not fully, aligned with target trajectories (in Norway, emissions are already near zero). However, as explained above, this is an incomplete metric that must be complemented by other indicators. When we examine the trend in the share of fossil fuels in electricity generation, we see that Norway and Denmark are on track, while the UK and especially Germany are not (Fig. 4). Norway no longer uses coal and relies on very little remaining gas for electricity generation. Denmark has completed its coal phase-out and is now rapidly phasing out gas-powered generation. In contrast, the UK has largely replaced coal with gas, which reduces emissions in the short term but does not put the country on a path towards zero emissions.

Denmark and Norway already have low and very low carbon intensities. In the case of Norway (30 gCO_2/kWh), this is mainly due to its longstanding reliance on hydropower, while Denmark (151 gCO_2/kWh)



		Germany	Norway	Denmark	UK
Targets	Fossil fuels phase out	🟨	🟩	🟩	🟨
	Zero-carbon electricity	🟩	🟩	🟩	🟩
	Transmission network	🟨	🟨	🟩	🟩
	Storage	🟨	🟨	🟨	🟨
Phase out	CO_2 emissions	🟨	🟨	🟨	🟨
	Carbon intensity	🟥	🟩	🟩	🟩
	Share fossil fuel power	🟨	🟩	🟩	🟨
Phase in	LCOE PV	🟩	🟩	🟩	🟩
	LCOE wind power	🟩	🟩	🟩	🟩
	New capacity solar & wind	🟨	🟨	🟨	🟨
	Share renewable electricity	🟥	🟩	🟩	🟥
Infrastructure	Curtailment	🟥	🟨	🟩	🟥
	Transmission network	🟥	🟥	🟨	⬜
	Storage	🟨	🟩	🟨	🟩
	Smart meters	🟥	🟩	🟩	🟨
Regulation	Negative prices	🟥	🟥	🟥	🟥
	Subsidies coal & gas	🟥	🟩	🟥	🟥
	Time permission process	🟨	⬜	⬜	⬜
	Public support	🟩	⬜	🟩	⬜

🟩 Sufficient 🟨 Partially insufficient 🟥 Insufficient

Fig. 2. Synthesis of the evaluation of transition progress of electricity systems in Germany, Norway, Denmark and the United Kingdom. Grey fields mean "no data available". Source: Tables S1-S4.

Table 2

Renewable electricity generation, targets for 2030 (see exceptions below). Sources: (IRENA, 2024). The values in brackets represent the renewable power share and installed capacity in 2023; *Germany's target of 80% of renewable energy in gross electricity *consumption* by 2030 and 100% in 2035. **Norway's offshore wind target is 30 GW by 2040.

	Denmark	Germany	Norway	United Kingdom
Share of generation (%)				
Renewable power	99.3 (87.6)	80 (52)*	98.7 (98.4)	85 (47)
Capacity targets (GW)				
Onshore wind	5.9	115	6.0	
Offshore wind	11.3	30.5	3.2**	50
Solar	11.7	215	5.4	
Bioenergy		8.2	0.2	
Hydro		5.2	34.7	
Total renewable capacity	**28.9 (13)**	**374 (167)**	**49.4 (39)**	**119 (55)**

has halved its carbon intensity over the past five years as a result of strong policies aimed at phasing out coal and gas while expanding wind and solar. In contrast, despite some improvements over the last decade, Germany's carbon intensity (381 gCO_2/kWh) remains high relative to the EU average (Fig. S1). This is partly because the growth in renewables has been used to complete the phase-out of nuclear before phasing out coal.

Table 3

Assumed solar and wind power capacities underlying the transmission grid plans (compared with wind and solar targets from Table 2). Sources: Cremona and Rosslowe (2024).

	Denmark	Germany	Norway	United Kingdom
Solar and wind capacity as basis for transmission plan (GW)	44	233–261	11.2	120
Transmission plan solar & wind capacity vs. actual 2030 targets (%)	150	65–72	78	100

5.3. Phase-in of zero-carbon technologies

The phase-in of renewables benefits significantly from the high cost-competitiveness of wind and solar power, which are now cheaper than fossil fuel power generation in all four countries (Tables S1-S4). For example, in 2022 in the UK, the LCOE for wind ranged from USD 52 per MWh for onshore to USD 91 per MWh for offshore (both decreasing by 30% in 2017–2022), while the LCOE for gas power was USD 113 and USD 94 per MWh for first- and second-generation plants, respectively.

Deployment of solar PV, onshore wind, and more recently offshore wind has increased across these four markets. In Denmark and Norway, this deployment is consistent with 100% renewables by 2035, whereas Germany and the UK are progressing, but too slowly (Fig. 5). To reach its 360 GW wind and solar target by 2030, Germany would need to add 29

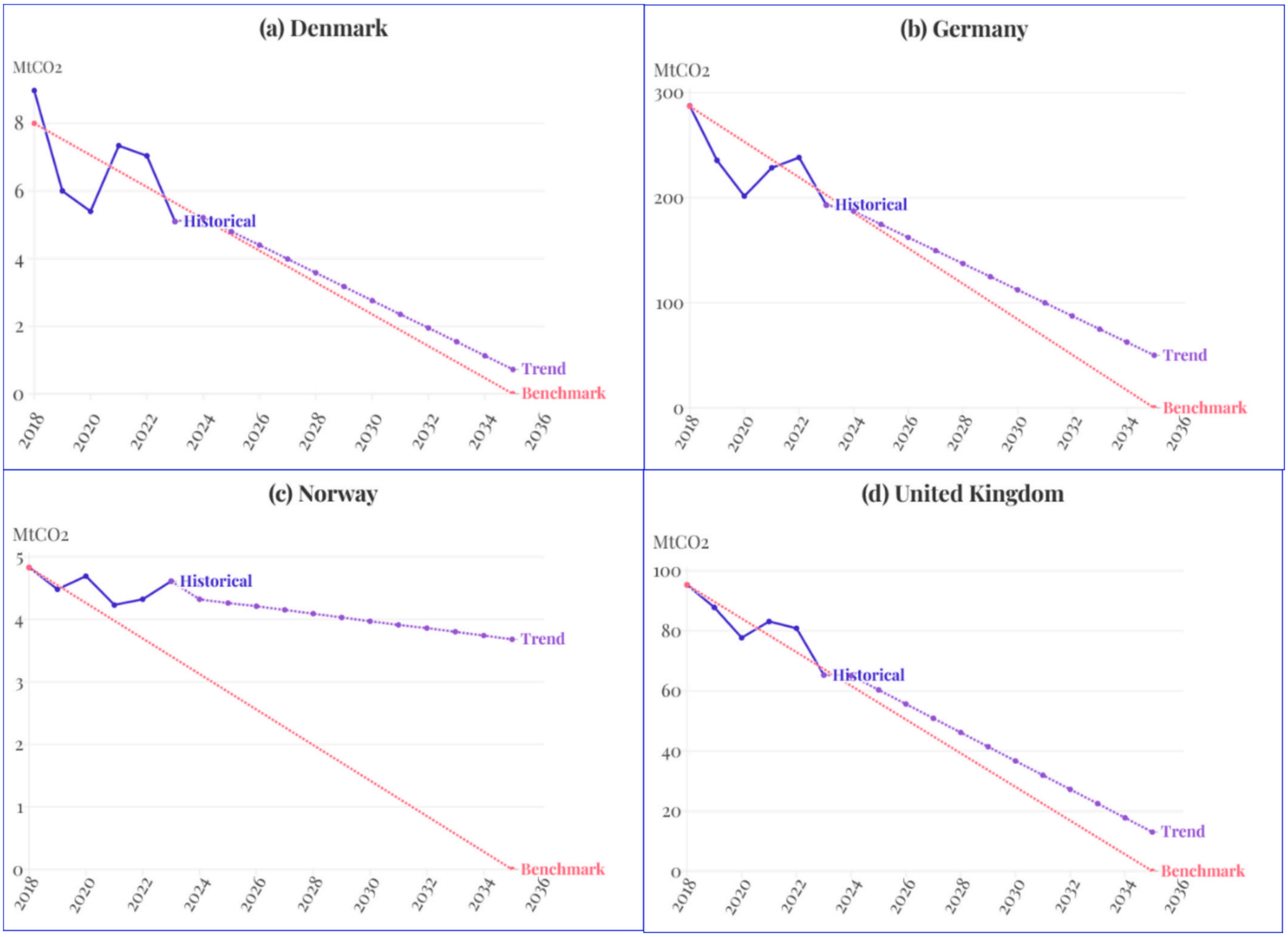


Fig. 3. Carbon dioxide emissions 2018–2023, trend to 2035. The historical/trend line is the five-year linear trend. Benchmark lines represent the linear trajectory from 2018 to zero emissions by 2035. Countries are on track where the historical and trend's gradient is below or equal to the benchmark line. Source: EMBER (2024). Generated using Flourish.

GW per year, but has added only 9 GW per year over 2018–2023; preliminary data from 2024 shows that deployment picked up strongly, reaching almost 20 GW thanks to the boom in solar PV (Bundesnetzagentur, 2025). In the UK, 9 GW per year would be needed, but the five-year average was only 2.2 GW per year. Denmark and Norway are on track overall, but risk missing their offshore wind targets (Fig. S1 in Supplementary Note 4).

5.4. Adaptation of infrastructure

Electricity grids must support renewable electricity generation both now and in the future, requiring capacity expansion that aligns with wind and solar development to maximize their full potential. The key question is whether countries are preparing their infrastructure for full decarbonization.

All countries face challenges in adapting their infrastructure to some extent. With the exception of Denmark, most grid expansion plans are insufficient to meet renewable power targets (Section 5.1), with on-the-ground progress remaining slow overall. Transmission expansion has been particularly sluggish in Germany, where it stagnated at around 37,500 km in 2018–2023, whereas Denmark has progressed more rapidly (Table 4).

Renewable energy curtailment has increased and has become a significant issue. In Germany, it accounted for 4% of total renewable electricity generation in 2023, with an increasing trend. In the UK, curtailment more than doubled over the past five years (Table 5). The situation differs in Norway, where curtailment remains rare, though some occurred in 2023, and in Denmark, where no curtailment was recorded in 2023.

Countries have made some progress on storage and smart metering. Both Norway and the UK have storage systems in place that correspond to significant portions of their installed variable renewable capacity, whereas Germany and Denmark are advancing more slowly (Fig. 6). Regarding demand flexibilization, Denmark and Norway have nearly completed their smart metre deployments, while Germany has yet to start (Fig. 6).

5.5. Regulatory reforms

Several challenges remain in adapting the regulatory environment to favour zero-emission technologies while disincentivizing carbon-intensive ones. Negative prices in all four countries' wholesale markets—and their increase in 2023—are indicative of regulatory challenges (Fig. 7). This situation may deter investment in new generation capacity. As the German and Danish, and the Danish and Norwegian, systems are closely interconnected, it is not certain that this reflects problems in all three markets: It is likely that negative prices in the much larger German market will “infect” the Nordic markets, although the extent of this effect is not yet known.

Except for Norway, fossil fuel subsidies have not decreased

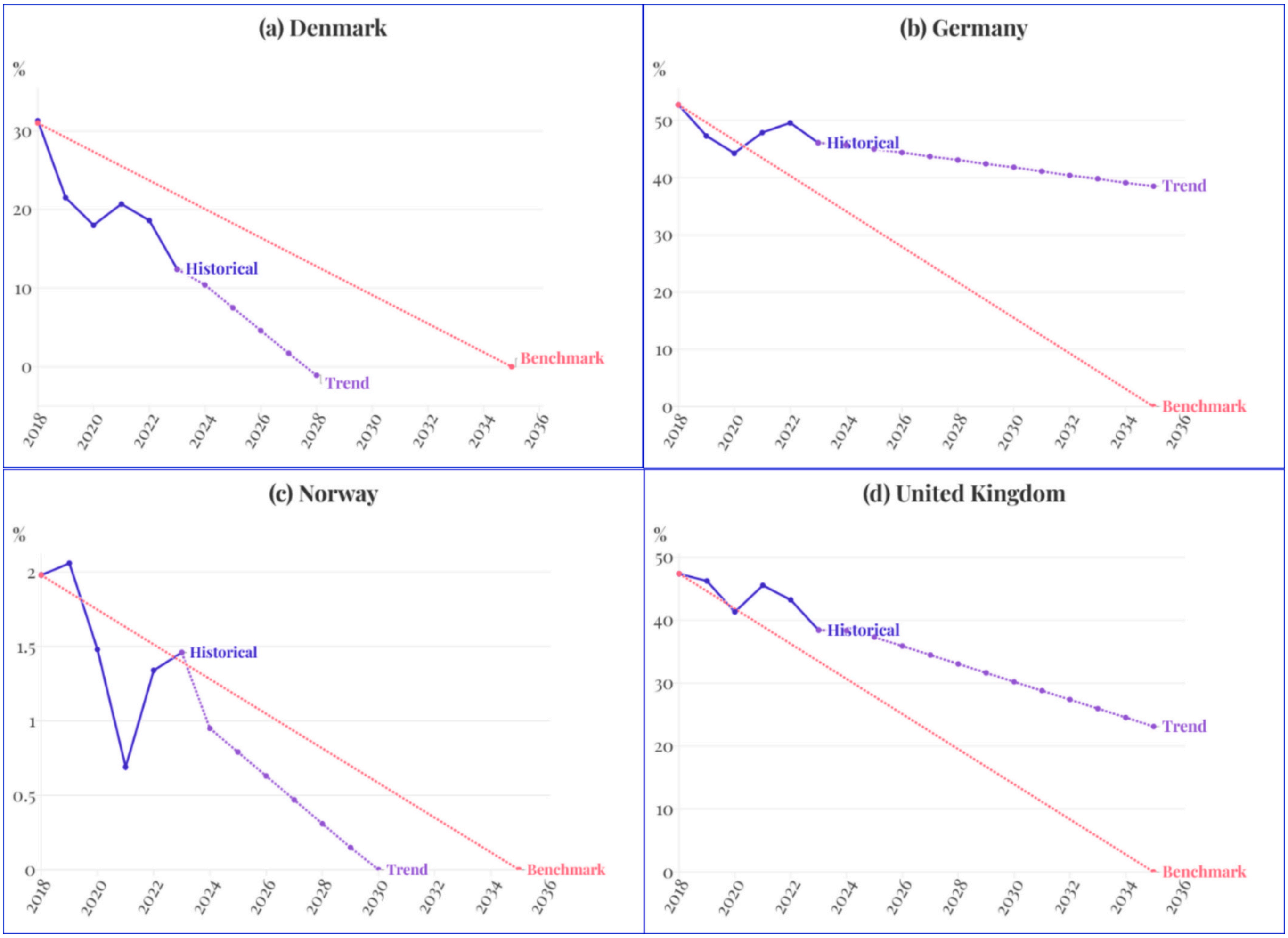


Fig. 4. Share of fossil fuels in electricity generation (%). The historical/trend line is the five-year linear trend. Benchmark lines represent the linear trajectory from 2018 to zero fossil fuel power by 2035. Countries are on track where the historical and trend's gradient is below or equal to the benchmark line. Source: EMBER (2024). Generated using Flourish.

significantly in the other three countries. Notably, there was a sharp spike in natural gas subsidies in 2022 due to price shocks triggered by the war in Ukraine; however, these specific subsidies have declined following the energy crisis. Even though not all gas and coal subsidies are directed towards electricity (an unknown portion supports heating), their continuation at least indirectly slows the transition in the electricity sector and remains a significant barrier to achieving a rapid net-zero transition (Table 6).

Data on permitting times for renewable electricity are not available for all countries. In Germany, the entire bureaucratic process—including environmental impact assessments, spatial planning, building permission, grid connection— took an average of 40 months in 2021. This exceeds the EU's 24-month limit but remains lower than in several other EU countries, such as France (65 months) and Croatia (120 months). The building permission process itself took on average 16 months, and has not changed noticeably in the last years (Jürgen, 2024). There is no data for the other three countries of our sample.

Regarding public support for the energy transition, data from the latest Eurobarometer (2023) indicate strong public backing for policies promoting the shift to renewable electricity in Germany (85%) and Denmark (93%), both above the EU average. For the non-EU countries, Norway and the UK, no Eurobarometer data are available. The UK government's DESNZ regularly publishes a public attitudes tracker; however, it mainly focusses on particular technologies rather than general transition support (DESNZ, 2025). Academic surveys exist for the UK and Norway (Kallbekken et al., 2025; Kaltenborn et al., 2023; Karlstrøm and Ryghaug, 2014; Roddis, 2020) but refer to specific years only.

6. Discussion and policy implications

In this paper, we show that it is possible to create and apply a theory-led, holistic, and yet simple array of indicators to assess transition progress. We do this by measuring the standard outcome indictors, such as emissions and technology deployment, and by adding several systemic process indicators that also measure infrastructural and regulatory adaptations as well as underlying technological progress. As demonstrated by our four empirical cases, the electricity transitions of Denmark, Norway, Germany and the UK, focusing solely on outcome indicators can be misleading. While renewables are growing and emissions are decreasing, there are large differences in transition progress not visible in these standard metrics. Adding the systemic indicators can lead to different and certainly deeper insight into transition progress and can point to more specific reform needs for finalizing a sectoral transition. As shown in Fig. 2, the countries perform relatively well in setting targets, phasing in zero-carbon technologies, and phasing out fossil fuels. However, their performance is considerably weaker in systemic dimensions, with the majority of "insufficient" scores relating to infrastructure and regulatory frameworks. This means that whereas technology deployment and decarbonization have progressed well so far,

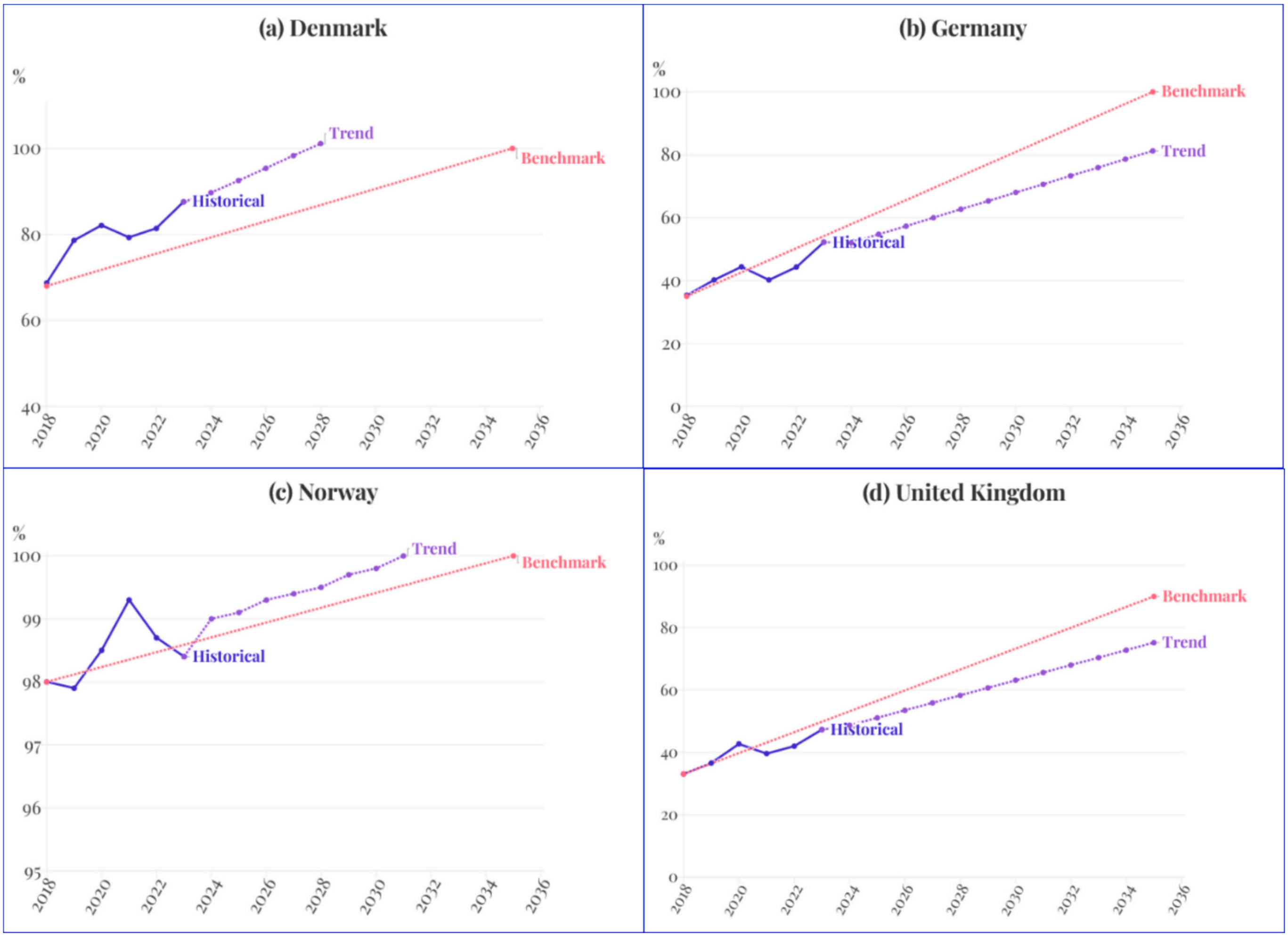


Fig. 5. Share of renewable electricity (RE) generation (%). The trend line is the five-year linear trend. Benchmark lines represent the linear trajectory from 2018 to 100% renewable power by 2035. Countries are on track where the historical and trend's gradient is above or equal to the benchmark line. In the UK, the renewables benchmark is 90%, as it encompasses a 10% nuclear share. Source: EMBER (2024). Generated using Flourish.

Table 4

Transmission network. Length of circuits. Sources: ENTSOE (2023). * There are inconsistencies in the reported data for Norway in 2018; the reported numbers correspond to 2023 and 2019.

	Denmark	Germany	Norway	United Kingdom
Transmission Network Length in 2023 (km)	7339	37,500	22554*	N/A
Growth 2018–2023 (km)	1848	1100	22999*	N/A
Growth 2018–2023 (%)	34	3	−2%	N/A

Table 5

Renewable energy curtailment. Sources: ACER (2024); Hawkes (2025).

	Denmark	Germany	Norway	United Kingdom
Curtailed electricity in 2023 (GWh)	0	10,479	894	3784
Curtailed electricity in 2018 (GWh)	n.a.	5403	N/A	1661
Growth 2018–2023 (%)	–	94	–	228

challenges in the continued transition are likely, as friction between the old system and rapidly growing new technologies will increase. This is especially pronounced in the transitions of the UK and Germany, as they have not adapted their systems at the same pace as the technological changes or as fast as would be needed to reach zero electricity emissions quickly.

Our empirical findings show that Norway and especially Denmark have progressed well towards 100% renewables and full decarbonization by 2035, but Germany and the UK have not. Technological progress has made wind power and solar PV cost-competitive with fossil technologies in all these countries; continued and accelerated deployment is thus economically feasible in the four countries and will not depend critically on additional economic support. In this perspective, the findings are positive: CO_2 emissions from electricity have decreased, as have the costs of renewables, and renewables deployment has increased. In Norway and Denmark, extrapolating these trends suggests that they could reach zero emissions and 100% renewables by 2035, but both Germany and the UK will miss this goal unless their recent trends shift quickly —although they are at least transforming in the right direction.

The main reason for our more pessimistic empirical conclusion, however, is not the extrapolation of trends, but the observation of underlying systemic change. Denmark and Norway have adapted both their infrastructures and their regulations to support the continued renewables deployment, whereas Germany and the UK are also lagging behind in this respect—and not only in terms of emissions and deployment. The Danish transition effort is particularly impressive, not only because of the shift from 91% coal power in 1990 to 8% in 2023, but also

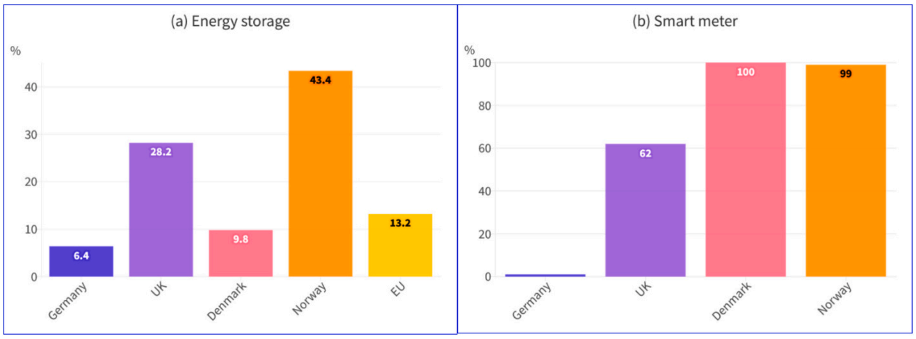


Fig. 6. Infrastructure for flexibility. (a) Electricity storage (operational and under construction in December 2024) as a percentage of variable renewable installed capacity; Source: ENERDATA (2024). (b) Percentage of households with smart metres by December 2022; Source: ACER and CEER (2024). Generated using Flourish.

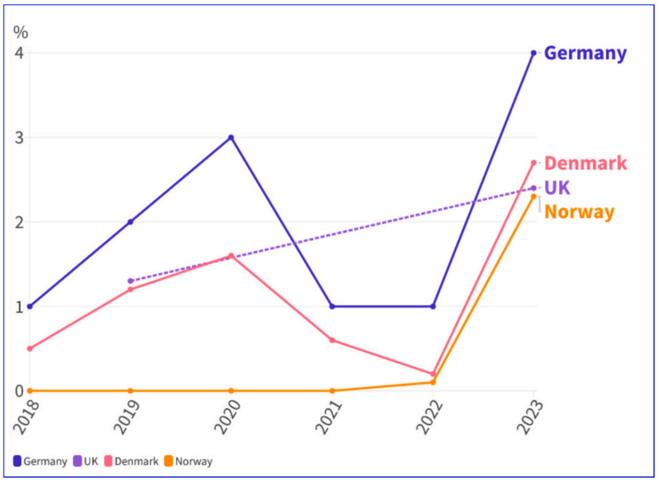


Fig. 7. Negative prices in wholesale electricity markets. Yearly percentage of hours with negative prices. For the UK, data is available only for 2019 and 2023. Data source: EMBER (2024).

Table 6
Fossil fuel subsidies. Sources: OECD and IISD (2024). Subsidies from natural gas and coal.

	Denmark	Germany	Norway	United Kingdom
Subsidies for gas in 2022 (billion USD)	293	9994	42	33,731
Growth 2017–2022 (%)	648	1085	- 45	526
Subsidies for coal in 2022 (billion USD)	0	2978	5	134
Growth 2017–2022 (%)	0	- 35	- 70	- 57

due to the underlying systemic changes, especially regarding infrastructure, that makes 100% renewable electricity by 2030 a credible target. This means that the extrapolated trends have greater explanatory value in Norway and Denmark: Much remains to be done, but if existing efforts are continued and reforms carried out as planned, the recent trend may very well continue. In Germany and the UK, even an extrapolation of recent trends appears optimistic. Deployment has not only progressed too slowly, but the systemic changes required to sustain—and especially to accelerate—future deployment have not yet materialized. This is particularly clear when looking at the cross-dimensional systemic indicators of curtailment and negative prices, which indicate a growing mismatch between infrastructural and regulatory reforms, and which have increased in both the UK and Germany, where even the relatively slow growth of renewables has led to problems in the power systems. This problem has impacts beyond national borders: At least part of the curtailment and negative prices in Norway and Denmark are likely due to spillover effects from the much larger German market.

The systemic view is essential to analyze not just decarbonization or renewables deployment to date but to understand how well a country is on track to meet more recent targets. For example, as electrification of transport and heating is planned and expected, the importance of electricity decarbonization rises accordingly. Consequently, a successful electricity transition, assessed in 2025, requires not only renewables deployment, grid expansion, and regulatory reform to replace fossil generation, but also a strong and rapid increase in electricity production to supply large parts of the transport and heating sectors. Measuring emissions or even the share of renewables risks missing this entirely. Indeed, our main empirical finding would have been different if we had focused only on outcome variables: in the systemic view, progress is (partially) insufficient, although emissions are decreasing roughly in line with mid-term targets.

The indicator approach allows for the rapid identification not only of barriers but also of solutions, especially in areas where some countries have made greater progress than others, enabling opportunities for lesson-drawing. Our framework does not in itself evaluate policies, but it identifies areas where policies have resulted in (in)sufficient progress, and is thus a comparatively simple tool for the first step of a policy analysis. For example, a central challenge in the electricity transition is the expansion of power grids, which must precede the deployment of zero-carbon technologies to avoid bottlenecks. Germany and the UK currently face substantial infrastructure adaptation challenges, whereas Denmark in particular has progressed much better. This identifies a promising field for deeper policy analysis: Which policies enabled anticipatory grid planning in Denmark, and to what extent can these experiences be transferred to the UK or Germany? A policy analysis would show that rather than basing their grid plans solely on current renewable electricity targets (as the UK does), Denmark plans for even higher future capacities, anticipating increased electricity demand from sector coupling. Our framework does not conduct that policy analysis, but it guides the search to the relevant transition processes, in this case helping identify the grid planning paradigm as a challenge that is closer to a solution in Denmark than in the other cases, and thus a potential field for lesson-drawing.

This example illustrates the value of our theory-led, holistic, and yet simple framework. Because transition processes are path dependent, assessing progress requires attention not only to outcomes but also to the processes that drive them. We recognize that sociotechnical transitions are complex processes, but not infinitely complex, as they follow certain regularities. In every transition, in every sector, the new technology must be developed to maturity—and then it must take over. In every transition, we must look at infrastructure and regulations: Is there a misfit between the existing regime factors and the needs of the new technology, and if yes, is the regime adapting to the new requirements? That is what we do here, seeking to capture the multiple processes that must change simultaneously, but without overburdening the analysis with too many details. Guided by a theoretical understanding of how transitions play out, interpretating a relatively small set of variables that nevertheless cover all central dimensions of the later phases of a sociotechnical transition becomes both manageable and meaningful. We recognize that there is tension between holism and simplicity, but we believe our case studies illustrate that a balance between the two is possible.

We contribute directly to the growing literature on the acceleration of net-zero transitions by addressing the fundamental question of *how to measure acceleration beyond simple indicators of speed*, such as technology deployment rates or CO_2 emissions reductions. Our framework should be understood as a step forward in this direction, offering a dynamic tool in which variables and metrics can be adapted to reflect the particular characteristics of different sectoral transitions. We demonstrate that systemic thinking from transition studies can be meaningfully applied to real-world, near-term analyses—without being overly complex. This paper focuses on the electricity sector but developing similar indicator sets for other sectors, adapted to their specific characteristics, is feasible. In fact, we demonstrated this in a 2024 project report (*reference not provided here to preserve anonymity*), where we applied the same systemic approach to the heating and transport sectors in the same four countries. The central argument in both this paper and that report is that while emissions reductions are necessary, they alone do not confirm whether a country or sector is on track to achieve net-zero. Only when emissions decrease as a result of underlying systemic changes, consistent with a zero-emission trajectory, can we confidently say that a country or sector is aligned with its Paris Agreement commitments.

Nevertheless, our evaluation framework has some limitations. First, there is an evident tension between *simplicity* and *holism*. Although our framework is holistic in the sense that it covers all three transition-relevant dimensions (technology, infrastructure, institutions), it is not complete; throughout, we have chosen what we—based on theory and on sectoral expert knowledge—see as the most important factors. Simplicity is important for usability but comes at the expense of completeness. Our framework seems well applicable to countries in the Global North, capturing the largely similar elements of the systems and system change as well as the locked-in constellations resisting change. These aspects are plausibly different in the Global South. In addition, the simplicity and usability of our framework cannot account for the particular context-specific stories, dynamics, and contradictions that each transition entails and that are usually highlighted by transitions literature. While our framework provides a good basis for inter-country comparison and overarching assessment, contextualization is key to deriving concrete country-specific policy recommendations. In this sense, we believe that this general framework is applicable to similar analysis in other sectors and countries; the specific indicators will be different, for example in a developing country context or for transport or heating transitions, but the overarching framework and dimensions should remain the same.

Evaluating each metric across three states (sufficient, partially insufficient, and insufficient) offers orientation for an expert-driven overall evaluation rather than representing fixed parameters; here too, case-sensitive contextualization of the framework may be needed. Finally, we operationalized many variables as five-year trends as we assess *current* progress rather than distant past progress. Despite this short time span, two dramatic "external shocks" occurred—the Covid-19 pandemic and Russia's invasion of Ukraine. Consequently, some variables may be distorted by these events or by singular policy responses to them. While these events caused strong landscape pressure and led governments to take strong policies, the lasting effects on the electricity transition, in terms of both unlocking and locking in, appears to have been limited (Geels, 2026). Nevertheless, further ex-post analyses are required to understand how such external shocks affected decarbonization trends.

Systemic change is essential for net-zero transitions —both in the electricity sector and beyond. In the case of electricity, past and ongoing technological developments have positioned most European countries well for a rapid transition: the costs of new renewable technologies are now generally lower than those of fossil fuels. Today, the main barriers to decarbonization are no longer technological, but systemic—namely, the institutional, infrastructural and regulatory changes needed to reliably integrate renewables and ensure a continuous power supply. Our framework provides a theory-led, holistic, yet straightforward approach to assess transition progress and identify remaining bottlenecks. While no country has completed the transition and setbacks remain possible, our analysis gives reason for optimism. Norway and especially Denmark demonstrate the feasibility of adapting infrastructure and regulations to support very high shares of renewables. Overall, our findings show that progress is good, although not fast enough and that the transitions are by no means complete—but there are real-world examples of how to solve each challenge ahead.

Funding sources

This work was supported by the Bertelsmann Stiftung (Germany).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

German Bersalli reports financial support was provided by Bertelsmann Stiftung. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2026.100342.

Data availability

Data will be made available on request.

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