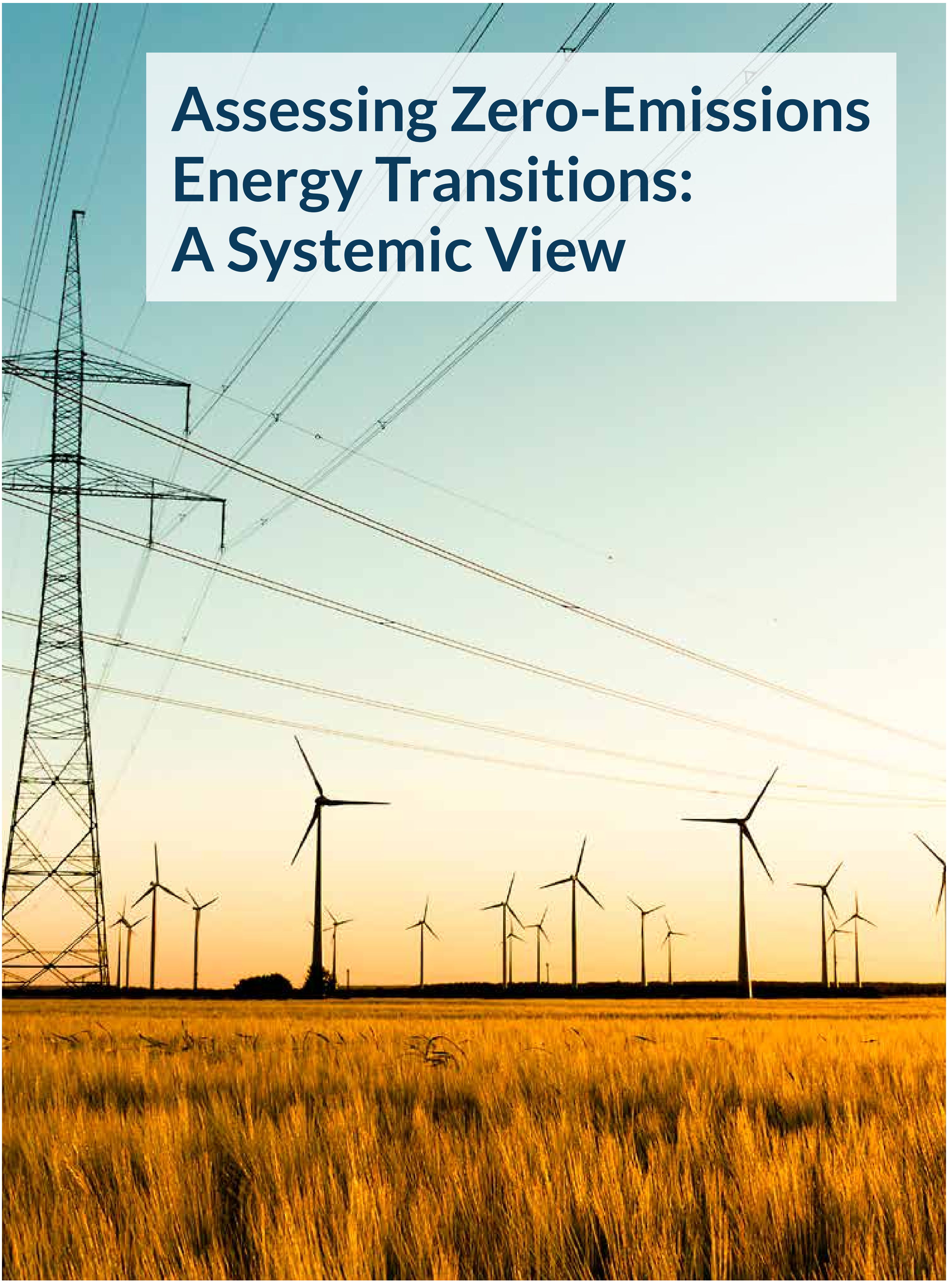
Assessing Zero-Emissions Energy Transitions: A Systemic View



RIFS POTSDAM

BertelsmannStiftung

Legal notice

October 2024

Publisher
Bertelsmann Stiftung
Carl-Bertelsmann-Straße 256
33311 Gütersloh
Telefon +49 5241 81-0
www.bertelsmann-stiftung.de

Responsible
Responsible on behalf of the Bertelsmann Stiftung:
Dr. Christof Schiller
Responsible on behalf of RIFS Helmholtz Centre
Potsdam: Dr. Germán Bersalli

Lead author
Dr. Germán Bersalli, RIFS Helmholtz Centre Potsdam

Contributors
Prof. Dr. Johan Lilliestam, Friedrich-Alexander-Universität Erlangen-Nürnberg
Lennart Brien, RIFS Helmholtz Centre Potsdam
David Gottheit, RIFS Helmholtz Centre Potsdam

Copy editing
Barbara Serfozo

Graphic design
Nicole Meyerholz, Bielefeld

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Suggested citation
Bersalli, G., Brien, L., Gottheit, D., Lilliestam, J. 2024.
Assessing Zero-Emissions Energy Transitions:
A Systemic View. Bertelsmann Stiftung (ed.)

DOI 10.11586/2024113

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Signatory countries to the Paris Agreement must fully decarbonize their economies by mid-century. This requires transitions in every sector, transforming systems reliant on fossil fuels into zero-carbon alternatives. Measuring CO2 emission trajectories is essential but insufficient; because they must transition to vastly different energy systems than those existing today, a climate policy assessment framework must evaluate the underlying systemic change. We introduce an analytical framework designed to track systemic change progress in climate transitions at the sectoral level. Unlike existing frameworks that are often broad in scope with limited theoretical foundations, we adopt a theory-driven and focused approach to enhance the interpretability and comparability of the results. Applying this analytical framework, we evaluate the progress of climate transition across three key sectors – electricity, road transport, and heating – in four countries: Germany, Denmark, Norway, and the United Kingdom. We show that although emission reduction progress is generally too slow, all cases show deficits – sometimes significant deficits – in systemic change. Focusing solely on emissions tends to overestimate progress by masking the sluggish pace of necessary infrastructural and institutional changes. Our findings illustrate the extent to which these systems are shifting toward zero emissions, enabling subsequent analysis of the policies that facilitated successful developments. We also pinpoint areas requiring additional efforts, prominently identifying electricity grids as the central bottleneck for continued transformation in all sectors.

Acknowledgements

A project of this scale would not have been possible without the advice, guidance and comments provided by many people. Our efforts to systematically measure progress in energy transition in the electricity, road transport and heating sector have been greatly enriched by the invaluable insights and rigorous feedback from a distinguished panel of experts. We would therefore like to express our sincere appreciation and gratitude to the following individuals: Claire Bergaentzlé, Duncan Edmondson, Philipp Heilmaier, Thorsten Hellmann, Lukas Hermwille, Katinka Johansen, Thorsten Lenck, Karsten Neuhoff, Peter Mock, Thieß Petersen, Felipe Rodríguez and Christof Schiller.

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EXECUTIVE SUMMARY

The problem: measuring systemic change

The Paris Agreement mandates full decarbonization, requiring a transition from existing carbon-based energy systems to zero-carbon alternatives. Unlike changes in individual elements, this energy transition necessitates a fundamental reconfiguration of the entire system, driven by the long-term goal of complete decarbonization. Even when system modifications lead to reductions in greenhouse gas (GHG) emissions, they may not align with the pathway to a fully decarbonized system (Lilliestam et al., 2022). For instance, switching to lower-carbon fossil fuels reduces emissions in the short term but does not contribute to zero emissions. Conversely, measures like electrifying transport, building passive houses, or developing offshore wind farms are necessary for zero emissions but may only reduce emissions in the longer term. To properly assess energy transition progress, we must evaluate trends and developments from a system-level perspective, keeping in mind that the Paris Agreement aims to eliminate, not just reduce, energy-related carbon emissions.

How can we assess progress in energy transitions? And how can we determine if a system or sector is actually undergoing the transformation needed to achieve zero emissions by mid-century? This study addresses these critical questions for climate mitigation and the effective implementation of the Paris Agreement.

In both public discourse and energy policy analysis, success is often gauged by examining the development of GHG emissions (Velten, Calipel, et al., 2023). While emission reductions are a key metric for decarbonization efforts, the challenge extends beyond reduction; it requires the complete elimination of emissions by establishing new systems for producing, consuming, and transporting goods and services (Lilliestam et al., 2022; Velten, Schöberlein, et al., 2023). Monitoring emissions alone offers limited value, as it does not provide insights into progress in areas where system transformations are most needed (Hanna & Victor, 2021).

Our primary objective is to formulate a comprehensive analytical framework for tracking sector-level zero-emission transition progress. Unlike existing frameworks that are often broad with little theoretical underpinning, we adopt a theory-led approach to ensure non-arbitrary indicator selection and enhance result interpretability. This holistic yet focused framework aims to cover various dimensions of transitions while concentrating on the most critical aspects of change. Our secondary objective is to apply this evaluation framework to a selected group of countries – Germany, Norway, Denmark and the United Kingdom (UK) – to demonstrate its usefulness and empirically assess progress in three interrelated sectoral transitions that represent the bulk of energy-related CO2 emissions: electricity, road transport, and heating.

Our approach: a holistic yet focused evaluation framework

The theoretical-conceptual field of sociotechnical transitions integrates various scientific perspectives and theorizes both stability and change in sociotechnical systems, providing useful insights into system evolution, critical dimensions of change, and conditions for transformation (Geels & Turnheim, 2022). Building on concepts like carbon lock-in, techno-institutional complexes, and deliberate decline (Rosenbloom & Rinscheid, 2020; Turnheim, 2022), we identify three interconnected dimensions central to energy transitions: technologies, infrastructure, and institutions. Each sector must see the emergence, maturation, and adoption of new technologies while old technologies decline. New infrastructures are necessary where existing ones are unsuitable for new technologies, and institutional reforms must support new technologies rather than the old ones.

We assess progress in sectoral energy transitions that have reached the third phase – diffusion and struggles against the existing system – and are now or soon entering the fourth phase (Reconfiguration) of the transition. This is the phase when the transition either happens or fails, as it involves material and immaterial regime changes leading to carbon-neutral systems, phasing out and locking out currently dominant technologies. The zero-carbon technologies needed for decarbonization already exist and are relatively mature. However, the key challenge lies in their widespread and rapid deployment, along with the necessary decline of carbon-intensive technologies. Infrastructure and institutional adaptation is crucial to facilitate these transitions.

For each of the three dimensions – technologies, infrastructure, and institutions – we identify the most critical variables and associate one or several metrics with them. Our evaluation method consists of five steps. First, we evaluate the sectoral decarbonization targets, including technology and infrastructure-related targets, that must be aligned with the national target of reaching carbon neutrality by mid-century as per the Paris Agreement. Second, we evaluate progress made in the phase-out of "old" carbon-intensive technologies and the related decrease in carbon intensity, which must eventually reach zero. Third, we assess the deployment, costs and cost trends of new zero-carbon technologies. Fourth, we evaluate the state of existing infrastructures and their deployment, which has to be aligned with the deployment of zero-carbon technologies. Finally, we assess the changes in key regulations.

Unlike previously published energy or climate policy evaluation frameworks, the transition policy progress framework we propose here emphasizes the importance of monitoring indicators that show systemic changes. These indicators connect: (i) "old" and "new" critical technologies, (ii) different dimensions of the system (e.g., technologies, infrastructure and institutions), and (iii) different sectors, such as electricity with road transport, or electricity with heating systems.

Cost relations between new and old technologies (e.g., renewable vs. fossil-fuel electricity, heat pumps vs. gas boilers) are crucial for transitions. While public procurement and support policies can initiate deployment, a breakthrough in mass markets requires cost relations that make large-scale deployment financially viable and profitable, attracting private investment, and making low-carbon alternatives economically attractive for investors and consumers. Cost not only captures performance (e.g., efficiency) but also scalability (Fouquet, 2016).

From a systemic perspective, infrastructure deployment and upgrading must keep pace with the deployment of zero-carbon technology to facilitate adoption and avoid becoming a barrier. Metrics like "energy curtailment" and "energy storage as a % of variable renewable capacity," and their link with market regulations such as "negative prices," are critical. The synchronization of grid expansion with renewable generation deployment and demand growth, driven by new demands in transport and heating, is essential for transition progress. Without adequate grids, renewable power deployment will halt, and new demands cannot be accommodated. This long-term vision must be reflected in transmission system operators' (TSOs) long-term plans, captured by the metric "Targets for transmission development."

Finally, some indicators connect several sectors. Electricity grids, for instance, are crucial for electricity decarbonization and play a critical role in transport and heating. Metrics like "Share of buildings using smart tariffs/smart meters" refer to these inter-sector elements, allowing consumers to adjust their practices (e.g., charging electric vehicles or using heat pumps) based on information and prices received.

Progress in European transitions: slow systemic change but potential for acceleration

1 | Emissions figures alone are inaccurate indicators

In most cases, emission reductions are too slow to be considered on track. This is, for example, the case in the heating sectors of Germany and the UK (insufficient) and Denmark (partially insufficient), whereas Norway is on track, or even exceeding its target trajectory. In some cases, emissions seem to be on track, but these observed emission reductions are not entirely associated with systemic change, meaning that they may not be continued in the future. Many of these reductions are incremental, meaning that they have an immediate effect on emissions but are not necessarily helpful in the long run. This is the case, for example, of the German and UK road transport sectors. Between 2016 and 2021, emissions decreased roughly along the path needed for zero emissions by 2045, partially due to the COVID-19 pandemic in 2020–21. However, all systemic and technological indicators are "insufficient" or "partially insufficient," showing that systemic change in technologies, infrastructure, and institutions is either not happening or is far too slow. Our indicators show only a slight decrease in the share of internal combustion engine (ICE) cars in the total fleet, due to sluggish electric car markets and the stagnation in the share of cars in passenger transport, which remains the dominant means of transportation. Norway is the counterexample for road transport: emissions are decreasing rapidly, the fleet of ICE cars is declining fast, and the share of zero-emission vehicles in total car sales approaches 100%. The necessary infrastructure of charging points accompanies such development, even if the path must be maintained in the coming years.

As shown, several countries and sectors show emission reduction trends that seem roughly compatible with long-term decarbonization goals. However, systemic assessments show that most systems are not changing significantly, making this progress temporary. This highlights the importance of adopting a systemic perspective when evaluating climate transition progress.

2 | Systemic change needed, but tech advances are facilitating rapid transition

Most systems studied have not, and are not, changing toward zero-carbon quickly enough, if at all. However, our analysis shows that in this four-country sample, at least one country in each sector is experiencing systemic change. These cases demonstrate that the necessary technologies exist and can be deployed rapidly if policy targets, regulations, and infrastructure changes are aligned.

For instance, in the German electricity sector, some indicators show a sufficient level of progress, while others are deemed to be insufficient or partially insufficient. Nevertheless, the necessary technologies to rapidly decarbonize this sector exist and are becoming cost-competitive with fossil-fuel ones, meaning the transition can accelerate if other critical elements of the system are aligned.

This means that whereas on-the-ground progress has been too slow to reach zero emissions, the underlying technological progress has been significant. Unlike a decade ago, countries are now well-positioned to carry out the transition: technologies are emerging, as is knowledge about institutional and systemic solutions to support new technologies. Experience with completing each sectoral transition is emerging in at least one country per sector.

3 | Key challenges: developing and monitoring electricity grids

Electricity infrastructure, including transmission, distribution, and storage, is vital not only for electricity decarbonization but also for linking the three examined sectors. They facilitate the integration of growing renewable power generation, particularly from intermittent solar and wind sources, and are essential for the decarbonization of heating and road transport through the adoption of heat pumps and the establishment of electric vehicle (EV) charging infrastructure. In all investigated countries, grid expansion is much too slow, and even the planning is lagging behind.

In our view, this is the single largest barrier to decarbonizing the three sectors, but it is masked by the achievements made in renewables deployment, which is progressing well in all investigated countries. Expanding and upgrading grids must precede the deployment of zero-carbon technologies to avoid becoming significant barriers to all three sectoral transitions. Monitoring key indicators, such as energy curtailment and the proportion of energy storage relative to variable renewables, and examining the relationship between infrastructure and regulation, such as occurrences of negative prices, is essential. Equally critical is planning future grids to align with the latest and most ambitious renewable power targets and the expected doubling or more of electricity demand to support other sectoral transitions, as shown by the example of system planning in Denmark. While strides have been made by the countries under scrutiny, sustained and, in some instances, intensified efforts are necessary to address these challenges effectively.

1

1 | BACKGROUND AND OBJECTIVES

The Paris Agreement, demanding full decarbonization, necessitates energy transitions that entail the transformation of existing carbon-based systems into zero-carbon counterparts. Such transformations span the realms of production, distribution, transportation, and consumption across various sectors (Victor et al., 2019). These transitions involve disentangling carbon-based energy technologies from their infrastructural, market, and societal contexts, replacing them with configurations suited for zero-carbon energy technologies and related systems. Energy transitions encompass both large-scale transformations across sectors and the specific systems of energy services within sectors, such as heating, transportation, and electricity (Fouquet, 2016).

Unlike changes in individual elements of a system, energy transitions necessitate a fundamental overhaul of the entire system itself, driven by the long-term goal of complete decarbonization. Even when modifications to the system result in reduced GHG emissions, such as switching to lower-carbon fossil fuels, it may not align with the pathway to a fully decarbonized system (Lilliestam et al., 2022). While this does not mean that transitions evolve in a linear way, it points to the necessity of evaluating change from a system-level perspective and keeping in mind the goal of zero-carbon systems.

The purpose-driven nature of today's transitions, aimed at eliminating GHG emissions, distinguishes them from past transitions (Geels et al., 2017). Governments, businesses, and societies must take deliberate and stringent actions to drive these transitions, mitigating the most dire consequences of global warming. While technological innovation remains central, its potential must be harnessed more systematically and on a larger scale. Given the compressed timeframe compared to historical transitions, the effectiveness and adequacy of government-implemented public policies are paramount (Fouquet, 2016).

In both public discourse and energy policy analysis, observers often gauge policy success and transition progress in various sectors by examining the development of GHG emissions (Velten, 2021). Emission reductions undeniably constitute a key outcome metric for decarbonization efforts. However, the challenge goes beyond emission reduction; it necessitates the complete elimination of emissions over the long term by establishing new systems for producing, consuming, and transporting goods and services (Lilliestam et al., 2022; Velten et al., 2021). In this context, measuring emissions alone offer limited value as they fail to provide insights into the progress made in the areas where system transformations are needed the most (Hanna & Victor, 2021).

This highlights the need for appropriate metrics and analytical frameworks to assess transition progress, evaluate policy effectiveness, identify drivers and barriers, and guide future actions. Several governments, including France, the Netherlands, the UK, Hungary, and Sweden, have developed evaluation frameworks. However, the breadth of scope, the diversity of indicators used, and the lack of clear connections between different indicators often complicate the interpretability of results and international comparisons.

The primary objective of this report is to formulate a comprehensive analytical framework for tracking sector-level net-zero transition progress. Unlike existing frameworks that often possess a broad scope with little theoretical underpinning, this report adopts a theory-led and focused approach to enhance result interpretability. By employing a holistic yet focused approach, this framework aims to encompass various areas and dimensions of transitions while concentrating on the most critical aspects of change. The framework is intended for application in OECD countries that share similar socioeconomic contexts, facilitating cross-country comparisons and promoting mutual learning based on best practices. It also seeks to identify systemic inconsistencies and risks within sectoral transitions.

2

2 | THEORETICAL FOUNDATIONS

Existing energy systems and related sectors, built over decades and centuries, now require transformation within a significantly shorter time frame. This challenge arises not only due to the numerous aspects affected but also because of mechanisms that render established systems resistant to change. The notion of "lock-in" and the literature addressing sociotechnical transitions provide the conceptual foundation for understanding how systems evolve and change.

2.1 | Systems dynamics and carbon lock-in

The concept of lock-in is a well-established way to describe and explain the inertia of systems (Arthur, 1989; Foxon, 2002; Unruh, 2000). It is based on the idea of increasing returns to scale, which generally denotes various forms of positive feedback loops within a system. These loops lead to the increasing adoption and entrenchment of key elements within the system, creating barriers to switching to alternatives. In the literature, this concept has been applied to describe inertia and path dependence across various dimensions and domains.

In the field of economics, Arthur (1989) first described how the initial adoption of a technology over competitors can trigger positive feedback loops within a system, incentivizing further adoption. Simultaneously, increasing concentration discourages the adoption of alternatives, even when superior technologies emerge (Foxon, 2002). Four classes of increasing returns are introduced: economies of scale, learning effects, adaptive expectations, and network economies (Arthur, 1994). Economies of scale describe cost reductions per unit of a technology, which become evident after overcoming the initial barrier of high fixed costs. Learning effects result from improvements in the production and use of a technology with increased deployment. Adaptive expectations refer to the growing confidence of consumers and markets in a technological system, which rises in tandem with the technology's adoption and system stabilization. Lastly, network economies describe the benefits for users from broader technology adoption, enabling interaction and collective utilization (Foxon, 2002).

North (1990) showed that the phenomenon of increasing returns to scale and the processes described by Arthur and others for technological systems also apply to institutions, broadly defined as social and behavioral constraints. These institutions are costly to initially establish but stabilize over time, benefiting from broader acceptance, influence, and learning. The interplay and mutual adaptation among institutions further entrench them (North, 1990).

While North's work on institutional lock-in relies on a broad definition of institutions, Pierson (2000) observes processes of increasing returns in politics, considering it particularly susceptible to lock-in, even more so than the economic sphere. Political vulnerability primarily arises from four key traits of political institutions: the pivotal role of collective action, the high density of institutions, the use of political authority to enhance power imbalances, and their inherent complexity and opacity (Pierson, 2000). The need to coordinate within and among a range of complex institutions and organizations slows down decision and change processes, as multiple actors must align their interests and positions, which can themselves be ambiguous. Consequently, there are strong barriers to moving away from established paths and overcoming existing power structures (Pierson, 2000).

Modern economies, where complex sets of technologies produce goods and services while adhering to specific rules, practices, and infrastructures, demonstrate that technological and institutional systems are interdependent and co-evolve over time, reproducing and mutually strengthening each other. Unruh (2000) theorized the interplay between technological and institutional systems in industrialized economies, where rapid economic development has relied on fossil fuels, leading to the concept of "carbon lock-in." The notion of a "techno-institutional complex," consisting of technologies, infrastructure, and the organizations and institutions that govern it, describes their synergetic and self-reinforcing relationship that shields and expands the system in place and blocks the growth of zero-carbon alternatives (Lehmann et al., 2012; Unruh, 2000).

The concept of carbon lock-in helps explain why governments and societies encounter great difficulty in transitioning away from fossil fuel-based systems, despite known and sometimes visible consequences, and even when suitable technological alternatives exist. Carbon-based technologies have remained dominant in many domains because they have benefited for an extended period from reduced costs, improved processes, network effects through industry coordination and adaptation, positive feedback loops with supportive infrastructure, as well as risk aversion and status quo bias from governmental institutions. This dominance prevents new technological alternatives from gaining rapid traction before establishing patterns of increasing returns.

2.2 | Transitions in sociotechnical systems

2.2.1 Taking a multilevel perspective approach to transitions

The insights on change-resistant and self-reinforcing high-carbon systems raise the question of how lock-in can be overcome and how transitions can occur despite existing systemic barriers. The theoretical-conceptual field of sociotechnical transitions integrates various scientific perspectives and theorizes both stability and change in sociotechnical systems, providing useful insights into the evolution of systems and the conditions under which they can be transformed.

The multilevel perspective (MLP) on sociotechnical system transitions is a theoretical framework that explains how societal changes occur through the interaction of technological, social, and economic factors (Geels, 2002). It provides a structured way to understand and analyze the dynamics of transitions from one dominant sociotechnical system to another, focusing on understanding why and how transitions occur and the role of different actors and institutions in these processes.

The MLP emphasizes that transitions are not isolated events but complex and long-term processes that unfold across multiple levels: niche, regime, and landscape. Each level represents a different scale of analysis and captures different aspects of the transition process. The niche level is where novel technologies and practices emerge. Innovations that challenge the existing regime (dominant sociotechnical system) are nurtured in niches, which are spaces of experimentation and development. The regime level represents the established system of technologies and infrastructure (material regime) and institutions (practices, rules, and norms that dominate a particular sector or field, sometimes called the immaterial regime). It is resistant to change and tends to maintain the status quo. The landscape level includes broader sociocultural, economic, and political trends, as well as external pressures like environmental concerns or geopolitical shifts. These factors influence the potential for transition by creating windows of opportunity or destabilizing the existing regime.

For transitions to occur, the regime needs to destabilize through landscape changes or internal disruption, creating a window of opportunity for radical innovations to break out of niches. These innovations, after maturing and stabilizing in the niche, now challenge the incumbent regime head-on and eventually provoke a reconfiguration of the regime, whose elements adapt to the innovation over time. Transitions involve struggles between old and new technologies, or specifically between the economic actors representing them, and, importantly, political and cultural struggles, given that established interests, practices, and norms are questioned (Geels et al., 2017).

How transitions play out exactly – regarding timing and sequence, and elements of continuity and discontinuity – depends on the shocks and developments in the landscape and the niches, as well as the characteristics of the system and the context of the case more generally (Geels & Schot, 2007). For instance, the compatibility and relation between old and new determines how far a transition requires disruption or if some elements of the incumbent system can be maintained.

A significant hurdle in sociotechnical transitions involves established players impeding change. When discussing profound technological changes, it is crucial to focus on both the winners of these changes and the losers who may hinder and slow down the transition process. For instance, in the shift from horse-drawn carriages to automobiles, those resisting the change implemented measures such as speed limits and flag laws to hinder cars from capitalizing on their primary advantage: speed (Hanna & Victor, 2021). Today's manifestation of this problem of strategic blocking can be seen in political opposition due to concerns of economic justice (e.g., presently coal-dependent communities "being left behind") or questions of how to provide baseload power after phasing out fossil fuel power (proponents of renewables, in turn, discarding the very concept of baseload) (Hanna & Victor, 2021). Because many regions and countries in Europe have made considerable progress in phasing in new zero-carbon activities and phasing out carbon-intensive ones, Europe has valuable insights to offer the world on how intelligent policy strategies can (and cannot) ensure continued prosperity in a zero-carbon future.

From a sociotechnical perspective, policy and politics are central variables in energy transition analysis. The environmental and hence political urgency of energy transitions, as well as the need for coordinated action to achieve them within the available timeframe, highlights the critical role of governments. Public policy is decisive in setting the regulatory framework and reshaping markets, which conditions the sociotechnical regime and enables the advent of zero-carbon technologies, paving the way for energy transitions (Geels et al., 2017; Unruh, 2002).

Sociotechnical transitions are non-linear processes occurring through interactions at niche, regime, and landscape levels, unfolding over time through four phases (Table 1). In the first phase, radical innovations emerge in small niches. They gradually build up internal momentum in the second phase but often face uphill struggles against entrenched systems. These two phases are sometimes grouped into the "emergence" phase (Victor et al., 2019). In the third phase, external landscape pressures and bottom-up niche pressures help destabilize the existing system, leading to visible struggles in business, sociocultural, and political dimensions. In the fourth phase, diffusing innovations replace the existing system, trigger wider system reconfigurations, and establish a new status quo (Geels & Turnheim, 2022).

Our analysis focuses on phases 3 and 4 of the transition process, rather than phases 1 and 2. Specifically, we aim to assess the progress made in sectoral energy transitions that have reached the third phase, where both material and immaterial regimes must undergo changes leading to the reconfiguration of systems into carbon-neutral ones. This implies that the zero-carbon technologies required for decarbonization are already in existence and relatively mature. However, the key challenge lies in their widespread and rapid deployment, alongside the necessary decline of carbon-intensive technologies. To facilitate these transitions, adapting infrastructure and institutions is paramount.

Table 1 | The four phases of sociotechnical transitions

Transition phases	Technologies and infrastructure	Institutions and policies
1: Experimentation in protected spaces	Technological, social, or business model innovations are just emerging, with significant uncertainties surrounding their characteristics, user preferences, policies, infrastructure needs, and cultural implications. Multiple design variations may coexist, exacerbating these uncertainties.	In the early phase, there are no stable design rules, guidelines, standards, policies, or governance structures, as radical innovations do not initially align with prevailing regulatory and selection environments. If there is policy support, it tends to be minimal and relatively non-committal, often in the form of seed money for demonstration projects or subsidies for R&D.
2: Stabilization in small market niches	Radical innovations break out of protected spaces, gaining a foothold in one or more market niches. This foothold provides a stable resource flow, stabilizing the innovation and making it more attractive to other actors. Learning processes focus on improving functionality and performance, with performance dominating cost in these initial niches.	Gradual learning processes lead to the stabilization of a dominant design, which becomes institutionalized in design guidelines, product specifications, best practice formulations, and standards. The innovation thus develops its trajectory through the stabilization of rules and social networks. Policy support often becomes more robust in this phase, taking the form of investment subsidies for firms, purchase subsidies for consumers, public procurement, or feed-in tariffs, which help create and expand market niches.
3: Diffusion and struggles against the existing system	As the innovation diffuses into mainstream markets, it competes directly with existing core technologies based on techno-economic performance and broader sociotechnical factors, such as "institutional fit." Diffusion typically follows a "niche-accumulation" pattern: starting in a technological niche, moving to a small market niche or application domain, and then expanding into larger mainstream markets. Adapting and expanding infrastructure and new supply chains are critical for the mass diffusion of these new technologies.	As innovations diffuse into mainstream markets, regulations and policies adjust to become more supportive of radical innovations. New product regulations (e.g., energy efficiency standards for cars, appliances, or houses) and performance regulations (such as renewable energy obligations for utilities or EV sales targets for automakers) drive company engagement. Capital grants or interest-free loans stimulate investment and uptake by firms, while purchase subsidies and information campaigns encourage user adoption. These policy instruments are often embedded in and supported by new policy goals, visions, and strategies.
4: Reconfiguration	In the fourth phase, new technologies replace existing ones, leading to the decline of the latter. This replacement involves further system reconfiguration, including the creation and expansion of new infrastructures and industrial supply chains, which generate forward and backward economic linkages. For example, the postwar establishment of the automobile system led to the expansion of the car industry and stronger linkages with the rubber, steel, and glass industries, as well as road building, oil, and servicing industries.	The new system becomes anchored in safety regulations, technological performance requirements, tax and subsidy rules, and professional standards. New government departments and regulatory agencies may be created to oversee and inspect the system, and new teaching curricula may be developed to train staff. Policies may also be needed to mitigate negative unintended consequences generated by the expanding system. For instance, the expansion of automobility led to more traffic accidents and air pollution, prompting new safety and environmental regulations.

Source: Adapted from Geels & Turnheim (2022).

2.2.2 Regime destabilization and deliberate decline

The sociotechnical transitions and innovation literature often attributes difficulties in initiating fundamental system transformations to various lock-in mechanisms. Thus, it primarily examines this issue from the perspective of the emergence and development of novelty, focusing on the systemic obstacles faced by such "emergent" processes. Promoting low-carbon innovation has long been central to both the practice and theory of mitigating climate change. However, the presence of deep-seated lock-ins and the short time windows available to achieve net-zero transitions suggest that existing carbon-intensive systems cannot be displaced or reconfigured solely through innovation. Increasingly, research and practical initiatives indicate that mitigation efforts must also encompass destabilization and the deliberate decline of carbon-intensive systems and their components, including technologies and practices (Rosenbloom & Rinscheid, 2020). Otherwise, old and new technology regimes could coexist for long periods, leading to trajectories incompatible with the rapid decarbonization of our societies. For example, without policies to destabilize the fossil fuel regimes in the electricity sector, new renewable capacities might simply be added to existing fossil fuel capacities instead of replacing them, especially in a context of growing electricity demand.

Overall, system decline can manifest as a quantifiable degradation of system performance (e.g., degrading economic performance of fossil-fuel systems), which can, though rarely, lead to total decline. The qualification of decline can vary, as it can be seen as a trend (e.g., declining performance), a process (e.g., a system in decline), or a potential outcome (e.g., decline resulting from destabilization) (Turnheim, 2022). In the context of decarbonization, deliberate decline can be understood as the systematic erosion of the lock-ins that perpetuate the production and consumption of fossil fuels (Rosenbloom & Rinscheid, 2020).

Deliberate decline relates to the broader concept of regime destabilization. According to Turnheim (2022), sociotechnical destabilization can be understood as a longitudinal process through which otherwise stable and coherent sociotechnical elements become exposed to challenges significant enough to threaten their continued existence and normal functioning. This triggers strategic responses from core actors within the framework of existing commitments, either to preserve the status quo or to pursue transformation. In the context of decarbonization, the concept of destabilization has gained prominence within the field of sustainability transitions (Rosenbloom & Rinscheid, 2020). It is seen as a crucial element of low-carbon transition processes, primarily related to forces disrupting a dynamically stable sociotechnical system, such as electricity or mobility. Transitions denote large-scale shifts within these systems as they transition from carbon-intensive to decarbonized configurations. These shifts entail profound and interconnected adjustments in social and technological innovations, infrastructures, institutions – especially markets – and sometimes lifestyles, collectively referred to as sociotechnical elements. Destabilization refers to the changes directly affecting the core structures of a regime, potentially breaking the existing lock-in (Arranz, 2017).

Sources of destabilizing change encompass technical dysfunctions, technological discontinuities, performance erosion, social and political mobilization, delegitimization, the emergence of new rules or the breakdown of existing rules, as well as challenges posed by new actor coalitions, the disbanding of existing coalitions, or the accumulation of poor strategic choices. Such sources of change are usually categorized according to their distance from the established system's boundaries (Turnheim, 2022). Exogenous sources of destabilizing change typically originate outside existing systems and extend beyond their immediate environment, including external threats or unforeseen discontinuities (e.g., surprises and shocks). Exogenous pressures are often less anticipated and lack dedicated monitoring compared to their endogenous counterparts. "Landscape changes," such as demographic shifts (e.g., urbanization), macroeconomic trends (e.g., transitioning to a service economy), geopolitical shifts, crises, and disruptive events (e.g., wars), are typical exogenous changes. However, exogenous changes are not necessarily macro-scale, as they can also result from competition from sociotechnical alternatives, social movement contestation, or shifts in practice and consumption, which may start as relatively isolated phenomena and gradually gain significance, exerting substantial pressure for change. Endogenous sources of change are more closely linked to established systems and activities or their immediate vicinity. These include deteriorating economic performance (e.g., at the product, firm, or industry level), declining income, resource slack (which reduces the ability to manage change), weakened connections between key sociotechnical components, changes in political support and coalitions, degraded infrastructures (e.g., material and knowledge), and internal divergence within organizational fields (Turnheim, 2022).

By encompassing both external and internal pressures that disrupt the dynamic equilibrium of a sociotechnical regime, destabilization processes create opportunities for alternative technologies to emerge and potentially replace the existing configuration. Kivimaa and Kern (2016) view destabilization and innovation as mutually reinforcing processes, emphasizing the role of policy in unlocking these complementarities. They propose that policy mixes aimed at sustainability transitions should include policies fostering the emergence of new technologies while simultaneously withdrawing support for old ones.

3

3 | ANALYTICAL FRAMEWORK

3.1 | Key metrics for assessing progress in energy transitions

Based on the literature on sociotechnical transitions, deliberate decline, and carbon lock-in, we identified three interconnected dimensions central to energy transitions: technologies, infrastructure, and institutions (Figure 1). Given the lock-in into a high-carbon configuration, each sector needs to see new technologies emerge, mature, and break in, while the old technologies decline. New infrastructures are needed where existing ones are unsuitable for the new technologies, and institutional reform is essential to support the new technologies rather than the old ones.

Technologies

Technological artifacts are the most obvious factor that must change in any transition from high-carbon to zero-carbon systems: wind farms, not coal power stations; electric, not gasoline-fueled cars. Although replacing technologies alone does not suffice to bring about a transition, technological stability and change are at the core of carbon lock-in and hence also of transitions (Grubler et al., 2016; Sovacool, 2016).

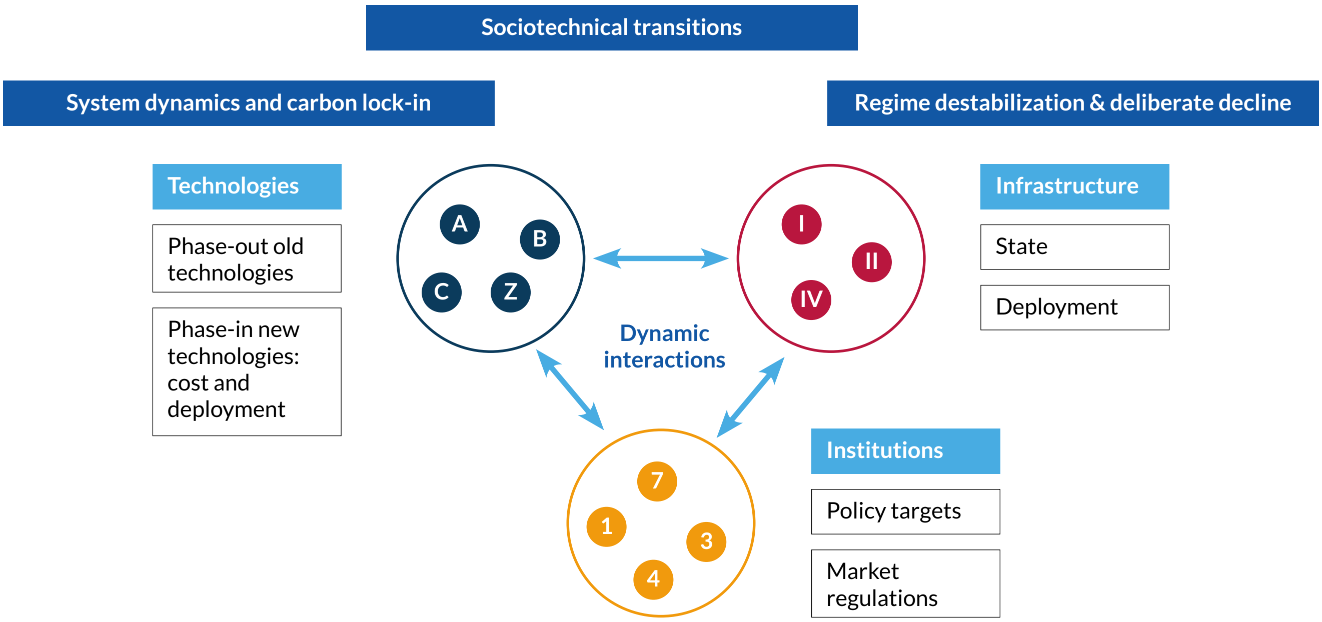
Drawing on the theoretical literature, we derive two key variables informing technology-related progress and the conditions for further growth and development: (1) deployment and (2) costs of new technologies. Additionally, in purpose-driven transitions that must be achieved in relatively short periods – such as climate policy transitions – we add (3) the rate of decline of carbon-intensive technologies – their market share, which should be equal to or close to zero.

In all phases of a transition, whether in niches or at a diffusion stage in competition with incumbents, deployment is a key variable. In the early phases, growing deployment initiates processes of increasing returns: more efficient use and higher performance of the technology, more confidence of users, expectations of further deployment leading to infrastructure development, and more benefits from collective use of the technology. Both deployment and its share of the total are important for transitions, as at some point, the new technology must overcome the incumbent technology and become the dominant way to provide certain goods (Grubler et al., 2016). In the long run, therefore, deployment and market share (the new technology versus the old technology) are the ultimate metrics of a successful transition.

Deployment is closely connected to the development and maturity of technologies, which strongly impacts costs through economies of scale (Arthur, 1994). Increasing deployment can lead to decreasing costs and better performance, which supports further deployment, creating a virtuous cycle (Schmidt & Sewerin, 2017).

The cost relations between new and old are crucial for transitions (Fouquet, 2016). While public procurement and support policies can initiate the deployment of the New, a breakthrough in mass markets requires cost relations that make large-scale deployment financially viable and profitable, attracting private investment and making the low-carbon alternative economically attractive for investors and consumers alike. Cost not only captures performance (e.g., efficiency) but also scalability. High costs are not necessarily due to inefficient or expensive processes but may be explained by

Figure 1 | Analytical framework for assessing progress in transitions



Note: One or more zero-carbon technologies (A, B, etc.) are essential for the transition within each sector, necessitating corresponding adaptations in infrastructure (I, II, etc.) and related institutions. These three dimensions are interdependent and evolve dynamically in a mutually reinforcing manner.
Source: Authors' elaboration.

initial or transient issues like the scarcity of materials, cost of capital, or other resources, which can stem from various endogenous or exogenous factors to the new technology. Thus, the various fixed and variable costs of technologies hold valuable information, signaling what types of costs might be barriers to diffusion. Moreover, their development provides evidence of whether cost-related barriers are being overcome or remain; the cost and cost trend relative to the dominant technology are particularly relevant.

Infrastructure

A crucial part of the techno-economic environment that facilitates the adoption of a technology is the related infrastructure – the physical installations supporting the use of the technology. While infrastructure itself consists of evolving technological systems (Unruh, 2002), its presence (or absence) significantly impacts the performance of the main technological artifacts and the development of the sociotechnical system overall. For example, a car, no matter how technologically sophisticated, is more useful on an asphalt road than on a cornfield; an electric car without access to a charger is entirely useless. From a system perspective, the key question is whether the infrastructure is keeping up with and enabling the continuous and rapid deployment of new technology. From a transition perspective, infrastructure deployment must at least go hand in hand with the deployment of zero-carbon technology to facilitate its adoption and avoid becoming a barrier. Metrics around this dimension should account for current and planned infrastructure and the extent to which such developments are sufficient to support zero-carbon technologies.

The way in which new technology overcomes old technology depends on various factors, including the extent to which they compete or are compatible (Geels & Schot, 2007). Regarding infrastructure, this is important to consider. Infrastructure for new technologies can be additive to the existing infrastructure, such as energy storage or charging infrastructure for EVs, which do not conflict with existing electricity and road transport systems. It can also replace existing infrastructure, thereby competing with infrastructure for old technologies, such as heating systems in buildings. The smoothest transition occurs when existing infrastructure can also be used by new technologies, such as roads for EVs.

Infrastructure is the structural link between technological artifacts and institutions. It is part of the physical environment and often consists of technological artifacts itself. Because it is often very long-lived, infrastructure is a key reason for lock-in: once a highway, hydropower dam, or pipeline is in place, it will remain for many decades, and operators have every incentive to keep operating them. Simultaneously, infrastructure also relies on and exists within institutions, with its development and operation often being subject to and an expression of public planning, regulation, and policy, which are even slower to change, often further impeding radical infrastructural change.

Institutions (market regulation and policies)

The essence of lock-in theory and the notion of sociotechnical systems is that technologies and infrastructures interact with societies through institutions. Institutions can take the form of written laws and regulations, but also unwritten norms, practices, and habits. They define the constraints and opportunities in sociotechnical systems and societies in general.

New technological or infrastructural systems may be fully or partially compatible with the existing institutional setting. Typically, however, new zero-carbon technologies and systems are at odds with existing institutions, as these have evolved over a long time to support and reinforce the incumbent high-carbon system and are perfectly adapted to this and maladapted to the new emerging needs (Unruh, 2002; Victor et al., 2019). The key questions are: are institutions designed in a way that supports the new technologies and infrastructure, or how would they need to change to become supportive of the new?

It is difficult to identify measurable aspects that capture the institutional change needed and that are applicable across sectors and countries. Even if industrialized countries show many similarities regarding the fossil fuels that have dominated energy use in different sectors, the evolution of institutions and how sociotechnical systems are governed is very context-specific. For instance, cultural norms and consumption patterns, which feature prominently in the MLP on sociotechnical transitions, can differ significantly from country to country and are hard to measure and compare. For this reason, we must focus on aspects that are observable across cases, that present barriers to a transition and inevitably need to change, and that are reasonably measurable, quantitatively or qualitatively.

Many measurable aspects of institutions can be found in public policy, which plays a crucial role in steering transitions by defining the course, shaping the rules of the game, and overriding market forces to enable transitions (Geels et al., 2017; Unruh, 2002). Sectoral decarbonization policy targets and institutional reforms are essential to shaping public support and guiding the direction of change in climate transitions. Since new technologies and infrastructures are generally significantly different from the old ones, adapting market regulations and norms to support new systems and disincentivize old ones is crucial. However, because institutions are often deeply entrenched, changing them is politically challenging and often requires increasing the administrative capacities of public bodies to ensure they can manage the necessary tasks at hand.

▶ **Policy targets:** National energy policies contain targets that define a country's climate goals. These targets typically address GHG emission reductions, which are explicitly formulated and quantitative, along with specific targets for the deployment of technologies. Targets can be relative (e.g., X% renewable power by 2030, 80% GHG emissions reduction by 2040 compared to 1990) or absolute (e.g., X GW wind power by 2030, X km new transmission lines by 2035), and they can be short- or long-term, referring to milestones or the final goal. These targets play a crucial role, not just in illustrating the government's plans and what they deem necessary to achieve the overall goals, but also as a signal to investors and consumers about the technological path the country is pursuing. They are the outcome of complex political struggles and consideration of different interests and goals (Cherp et al., 2017), and thus serve as a widely accepted benchmark against which the deployment of technologies and infrastructure can be measured.

- **Public support:** Public support plays a crucial and multifaceted role in the energy transition. On the one hand, public support is crucial for the development and implementation of climate mitigation policy. Governments are more likely to pass ambitious environmental legislation and commit to international agreements when there is a clear mandate from the electorate. On the other hand, the success of new energy technologies often depends on the willingness of people and communities to adopt or accept them. For example, the siting of wind turbines or new transmission lines often requires local approval.

- **Market regulation:** Regulations constitute the formal rules for economic activities in a sector. Having developed as part of the incumbent regime to support existing technologies, regulation must generally be adapted to the needs of new technologies and ideally to disadvantage the old.

In the market economies of OECD countries, regulation of markets is crucial to enable the flow of transition-related goods and services, from the components and materials for technological artifacts and infrastructure to the services sold to end-consumers. Markets and sectors are regulated to generate specific economic and political goals and outcomes. As Unruh (2000) points out, the ability of governmental institutions to guide and, if needed, override market forces is a key aspect that makes them so important and powerful regarding the evolution of sociotechnical systems, especially in purposive, target-driven transitions like the energy transition. Market regulation for energy transitions needs to facilitate the growth of technological innovations throughout their evolution, from their emergence in niches to diffusion in mass markets, in competition with incumbents.

In general, market regulation is complex and addresses technicalities specific to each case and technology. However, some regulatory aspects apply broadly and need to change for a transition to occur. One fundamental issue subject to regulation is financial incentives and subsidies, including direct payments or tax exemptions, or disincentives like additional taxes.

- **Administrative capacity:** Another key institutional aspect is the capacity of the administration and bureaucratic apparatus to implement and enforce policies and regulations. Permitting procedures present a significant barrier to the deployment of technology and infrastructure in many sectors (Victor et al., 2019). This involves the formulation of regulation – such as enforcement rules and powers, clarity of processes, wording of laws – and the productivity and efficiency of the workforce of the competent authorities. Here too, institutional change and the overhaul of locked-in practices and norms are needed.

3.2 | The reconfiguration of electricity, heating and road transport sociotechnical systems

Sectoral transitions follow successive stages, with each phase requiring different policy approaches and evaluation logics. For instance, the transition to zero-carbon aviation relies on synthetic fuels derived from atmospheric carbon. These technologies are speculative at the scale needed and currently very immature, requiring R&D support rather than significant infrastructural reform. In contrast, renewable power technologies are often mature, challenging incumbent technologies and requiring institutional reforms and infrastructural refurbishment instead of strong R&D support. Thus, transitions necessitate both sector-specific policy mixes addressing various barriers at a given time and adaptive policy sequences that respond to evolving needs as the transition progresses.

The evaluation framework developed in this paper is intended for application in sociotechnical transitions within developed (OECD) countries, which have similar political and institutional systems. It is important to note, however, that the necessary data for the different metrics proposed in this framework may not be publicly accessible for all countries. Data is more accessible for European countries, where data harmonization and free access are more common. Furthermore, the evaluation framework presented in this study focuses on three closely related sectors: electricity, heating, and road transport. Across these sectors, alternative technologies to fossil fuels have emerged and spread in most OECD countries, albeit at varying rates. According to the characterization outlined in Table 1, sectoral transitions in most countries are presently positioned at phase 3 – “Diffusion and struggles against the existing system.” In a few pioneering nations, electricity transitions may even be progressing into phase 4, characterized by “reconfiguration.” In the heating sector, the transition is at an early diffusion stage in most countries. In all three sectors, it is imperative to expedite the pace of transitions beyond “natural” diffusion rates to align with the targets established in the Paris Agreement. Public policy, including policy targets and incentives, must be adjusted to reflect and support these accelerated objectives. Sectoral transition targets, the speed of diffusion of key technologies, and reconfiguration elements are critical components of this evaluation framework.

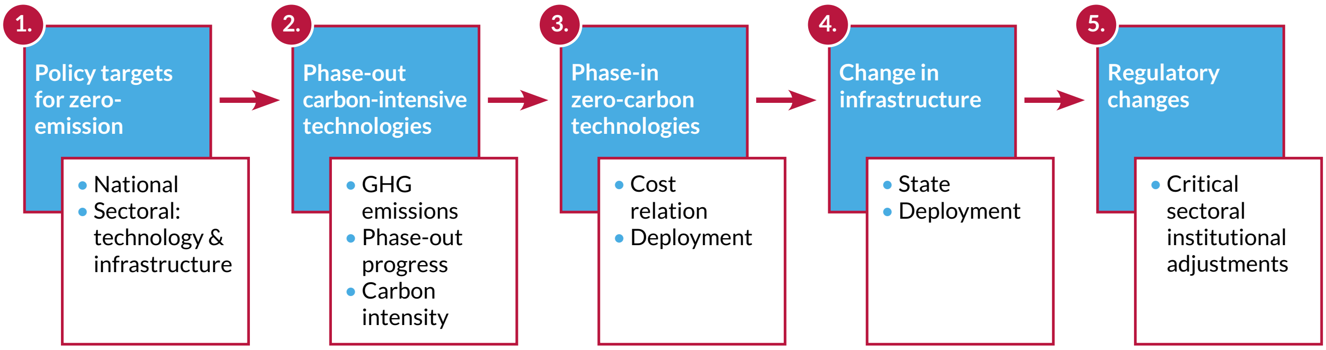
The electricity production system is divided into two subsystems: generation and grid. These subsystems are distinct in terms of technologies, actors, and institutions but are closely integrated because electricity generation and consumption need to be exactly matched to avoid blackouts. This means that the transport and distribution grids – including storage technologies – are crucial. Electricity fulfills multiple societal functions such as lighting, heating/cooling, hygiene/washing, cooking, and entertainment, but also enables the functioning of essentially every societal system from banking and food production to the military. In this sense, electricity differs from the other two systems, which are linked to specific societal functions such as heating/cooling and mobility. The heating system involves two closely related subsystems: heat supply and building systems, which shape heat demand. The mobility system can be divided into land, water, and air systems, and for passengers and freight. Here, we focus on land-based passenger mobility by cars, which accounts for the largest part of transport-related GHG emissions. Once this transition progresses, we expect strong spillovers to trucks and the freight sector, but these are not considered here.

3.3 | Evaluation method

Our evaluation method consists of five steps (Figure 2). We start by assessing the national policy targets for carbon neutrality and the respective sectoral targets. Every sectoral decarbonization target must align with the national goal of reaching carbon neutrality by mid-century, as stipulated by the Paris Agreement. Next, we assess the decline of carbon-intensive technologies and the related decrease in carbon intensity. This decline must eventually reach zero, signifying a complete phase-out of old, high-carbon technologies. We then evaluate the deployment, costs, and cost trends of zero-carbon technologies. Deployment is assessed in relation to national targets, while costs are compared to national and international trends of zero-carbon versus fossil fuel-based technologies. In a fourth step, we examine the state of infrastructure and its deployment, ensuring it aligns with the targeted deployment of zero-carbon technologies. Finally, we evaluate the adequacy of institutions using a few key indicators. Due to the diversity and complexity of institutional settings, measuring this dimension across countries is challenging. Therefore, institutional metrics are not exhaustive but aim to provide an overview of the degree to which institutions are being adapted to new zero-carbon systems.

Overall, we take a forward-looking approach to evaluating the metrics: current progress (over the last five years) is assessed based on present conditions and recent trends. This approach involves examining whether the critical variables for a zero-carbon transition are changing quickly enough, rather than the progress achieved so far, as is the case in most existing frameworks. Given the urgent need for rapid decarbonization within short timeframes, we believe it is essential for the framework to reflect recent policy and market dynamics. Therefore, we focus on a brief five-year period, despite the availability of historical data for longer spans, such as 10 years, for some variables. Depending on the metric, 5-year trends are compared with the linear trend to either (i) the national target (e.g., renewable energy target) or (ii) the benchmark of zero emissions by 2035 (electricity) and 2045 (road transport and heating). There is uncertainty regarding the exact year different sectors should reach zero emissions to be compatible with the Paris Agreement. The year 2045 should be considered the upper limit, particularly because an increasing number of advanced economies have established 2045 as the year to reach net-zero emissions (IEA, 2021a; Plötz et al., 2021). For electricity, earlier decarbonization around 2035 is generally considered feasible, given the state of technological change in the power sector (Boitier et al., 2023; IEA, 2021a).

Figure 2 | Evaluation method



Note: Overview of the five fundamental steps and principal analytical dimensions in evaluating sectoral transition progress.
Source: Authors' elaboration.

Some metrics refer to a specific year (the last year with available data), while others refer to a trend. For the latter, based on historical data, we calculate the trend over a specified period. All data points refer to annual values. The trendline is calculated using a least squares method, as proposed by Velten, Schöberlein, et al., (Velten, Schöberlein, et al., 2023):

$$m = \Sigma(x-\bar{x}) \times (y-\bar{y}) \,/\, \Sigma(x-\bar{x})2$$

$$\bar{y} = m\bar{x}+b$$

With: m = slope of the trendline; b = y-axis intercept; x = given value on the x-axis (here: years); $\bar{x}$ = mean value of the covered x-axis values; y = given value on the y-axis (here: indicator value for the given year); $\bar{y}$ = mean value of the covered y-axis values.

By doing so, the trendline smooths out outliers and variations between years, avoiding emphasis on specific years. We compared the slope of the trend with the slope of the benchmark (national target or zero emissions). In the absence of further indications for specific metrics, trends are presented for the five most recent years. Finally, the evaluation focuses on the national level; values for OECD or EU averages are used as references.

All metrics assigned to the variables are evaluated using a three-tier logic, indicating whether the value is **sufficient, partially sufficient or insufficient** for the sectoral transition to zero emissions. The "partially insufficient" category includes results that show momentum and change in the right direction without being fully on track or fully insufficient. In the next sections, we explain the boundaries between the three evaluation categories for each metric. This three-tier evaluation logic is designed to guide expert assessments rather than represent strictly fixed parameters. If adjustments are needed for specific cases, they will be explained in the respective tables in the "results" section.

3.4 | Electricity sector

Policy targets

Eliminating GHG emissions in line with the Paris Agreement requires an appropriate policy strategy, particularly targets for phasing out carbon-intensive assets. Therefore, we first include an indicator referring to a target for the phase-out of fossil fuels for electricity generation.

The technology targets for electricity refer to the share of installed capacity and/or power generation from renewable energy, including solar power, onshore and offshore wind power, and other renewable technologies. Infrastructure targets are divided into different elements: transmission lines, distribution lines, and electricity storage.

To be deemed sufficient, the final target for renewables must meet two criteria. First, it must plausibly be sufficient for a net-zero system by/before 2050. We evaluate this by considering studies that have modeled decarbonization pathways at the national level. While there is some uncertainty regarding the exact year by which 100% renewable power (or a combination of renewable and nuclear power) is necessary, this approach provides orientation. 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 initiate and accelerate a transition now, not delaying deployment to the distant future, and to contribute to the Paris goals.

Grid targets formulated by the grid operators of transmission and distribution networks in their respective development plans should be based on calculations regarding the expected installed electricity generation and energy flows in the future. Notably, such grid targets should consider the renewable electricity capacities needed to meet the national decarbonization targets. Synchronizing grids with renewable generation and clean demand-side technologies is essential to ensure that the benefits of the energy transition reach consumers. TSOs grid plans offer valuable insights into future alignment. These plans are grounded in energy supply and demand scenarios, dictating the necessity for infrastructure expansion or upgrades based on various forecasts. To evaluate how these plans correspond to the current trajectory of Europe's energy transition, our analysis compares these scenarios with the latest national energy targets and recent market projections for wind and solar energy (Cremona, 2024). This comparison serves as a high-level assessment of the readiness of national transmission grids to accommodate the envisioned changes in the energy system required to achieve policy objectives and facilitate the integration of rapidly increasing renewable energy deployment (Cremona, 2024).

Storage is usually not part of the grid; therefore, targets typically come from the government or government agencies. To evaluate planning for the grid and storage, the criterion is whether the targets are based on the deployment targets for renewables and the overall goal of full decarbonization, that is, infrastructure targets must align with technology targets. If this is the case, and the technology targets are sufficient, then the infrastructure targets are deemed sufficient.

Variable 1: Phase-out targets

Metric 1: Targets for phase-out of fossil-fuel power generation (year)

Evaluation:
Sufficient: The country has clear phase-out targets aligned with achieving a zero-emission electricity system by 2035.
Partially sufficient: The country has phase-out targets, but they are not aligned with achieving a zero-emission electricity system by 2035 (e.g., coal phase-out by 2040).
Insufficient: The country has no phase-out targets for coal, oil or gas.

Variable 2: Technology targets

Metric 2: Targets for renewable electricity capacity and/or generation share (%, year)

Evaluation:
Sufficient: Renewable energy targets of 100% of generation/capacity by 2035 or before.
Partially sufficient: Renewable energy targets that represent less than 100% of electricity generation by 2035.
Insufficient: No targets.

Note: if a country has a renewable energy target and a target for nuclear power, both are added as they allow for a zero-emission electricity mix.

Variable 3: Infrastructure targets

Metric 3.1: Targets for transmission development national (km) – consistency with technology targets

Evaluation:
Sufficient: Targets for the transmission grid exist and are based on renewable energy targets.
Partially sufficient: Targets for transmission grid exist but are not based on renewable energy targets.
Insufficient: There are no targets for transmission grids.

Metric 3.2: Targets for distribution network (km)

Evaluation:
Sufficient: There are targets for distribution grids based on renewable energy targets.
Partially sufficient: The targets for distribution grids are not based on renewable energy targets.
Insufficient: There are no targets.

Metric 3.3: Targets for energy storage (GW or GWh)

Evaluation:
Sufficient: There are targets for energy storage (electricity and hydrogen) based on renewable energy targets.
Partially sufficient: There are targets for electricity storage but not for hydrogen or vice versa, or the energy storage targets are not based on technology targets.
Insufficient: There are no targets for energy storage.

Phase-out of carbon-intensive technologies

The ultimate objective of the energy transition in electricity is to reach zero GHG emissions as soon as possible and no later than 2050. Consequently, the recent trend in GHG emissions is a central variable that should be included in all evaluation frameworks. However, it is important to remember that current emissions are the result of past developments, which are directly related to the energy sector but also influenced by external factors like economic crises. Therefore, such metrics do not necessarily indicate whether the system is transforming and to what extent that change will enable future emission reductions. Another closely related aspect is the carbon intensity of electricity generation, which must eventually be reduced to zero.

We also measure progress in the phase-out of fossil fuel-based electricity and the extent to which these changes are aligned with the respective target.

Variable 4: CO2 emissions electricity

Metric 4.1: CO2 emissions of electricity generation (Mt CO2), trend

Evaluation:
Sufficient: Emissions are decreasing at an equal (+/– 10%) or higher rate than the linear trend to zero-emission by 2035.
Partially sufficient: Emissions are decreasing at a lower rate than the benchmark for zero-emissions by 2035.
Insufficient: Emissions are increasing or stagnating (+/– 10%).

Metric 4.2: Carbon intensity of electricity (gCO2e/kWh), trend

Evaluation:
Sufficient: National carbon intensity is lower than the OECD average and is on the decline.
Partially sufficient: National carbon intensity is higher than the OECD average, but the national decreasing rate is higher than that of the OECD.
Insufficient: National carbon intensity is not decreasing or decreasing at a lower rate than the OECD average.

Variable 5: Phase-out progress

Metric 5: Share of fossil fuel-based power generation (%)

Evaluation:
Sufficient: The decrease rate of the share of fossil fuels is equal to (+/- 10%) or higher than the linear path to zero emissions by 2035.
Partially sufficient: The share of fossil fuels is decreasing but at a rate below the linear path to zero emissions by 2035.
Insufficient: The share of fossil fuels is stagnating (+/- 10%) or increasing.

Phase-in of zero-carbon technologies

The cost relationship between old and new technologies and the speed of deployment of the new technologies are critical elements of all sociotechnical transitions. The cost metric for electricity is the Levelised Cost of Electricity (LCOE) in EUR per kWh, comparing solar PV, onshore, and offshore wind power with electricity from coal and gas. Currently, these are the most relevant renewable power technologies, and it will be easy to include further technologies in future work as they gain significant market shares. LCOE is the most transparent and commonly used metric to compare the overall costs and profitability of different modes of electricity production, including upfront costs and operational costs (IRENA, 2022). We consider the national LCOE of renewables and fossil fuels today, as well as the five-year trends. To be deemed sufficient, the current cost relations between new renewable generation capacities and the cheapest fossil fuels must be favorable for renewables.

Deployment of renewable energy is measured by two metrics. First, by comparing the capacity installed (%/year) with the linear path to the national targets for solar power, onshore wind, and offshore wind, respectively. This checks whether the speed of deployment is sufficient to meet the goals. Second, renewables deployment is measured by its share of total electricity consumption in percentage over the last five years. The five-year trend of the share is evaluated by comparing the trend to the linear path to the next target.

Variable 6: Technology cost

Metric 6.1: LCOE (EUR/kWh), national trend; solar PV

Evaluation:
Sufficient: Solar PV is cheaper than the cheapest fossil fuels for electricity generation nationally.
Partially sufficient: Solar PV is more expensive than the cheapest fossil fuels nationally, but the gap is narrowing (by at least 5% per year).
Insufficient: Solar PV is more expensive nationally and the gap is not narrowing.

Metric 6.2: LCOE (EUR/kWh), national trend; wind power

Evaluation:
Sufficient: Wind is cheaper than the cheapest fossil fuels for electricity generation nationally.
Partially sufficient: Wind is more expensive than the cheapest fossil fuels nationally, but the gap is narrowing (by at least 5% per year).
Insufficient: Wind is more expensive nationally and the gap is not narrowing.

Variable 7: Technology deployment

Metric 7.1: Capacity added (GW/year) for solar and wind power; trend

Evaluation:
Sufficient: Capacity is growing at (+/- 20%) or above the linear trajectory toward the 2030/2035 national target.
Partially sufficient: Capacity is growing below the linear trajectory toward the 2030/2035 target.
Insufficient: Deployment is stagnating (+/- 20%) or decreasing.

Metric 7.2: Share of renewables in electricity generation (%), trend; average for renewable energy technologies

Evaluation:
Sufficient: Renewable energy share growth is higher than the linear trajectory toward the benchmark of 100% clean electricity by 2035.
Partially sufficient: Renewable energy share is growing below the linear trajectory, but the difference between the historical trend and the benchmark is less than 20%.
Insufficient: Renewable energy share is stagnating, falling, or growing, but the difference between the trend and the benchmark is greater than 20%.

Infrastructure

Infrastructure development for a zero-carbon transition in the electricity sector largely concerns the transmission and distribution grid and storage. In a system with a high share of renewable electricity, the grid and storage must be capable of dealing with the intermittency of wind and solar power. The transmission network must grow significantly to support the balance of supply and demand. Improvements in the quality of grids, such as using superconducting cables are also crucial. Additionally, the distribution grid needs enhancements in both size and quality to integrate decentralized production sites. Storage is vital to enable the decoupling of generation from consumption over time.

State of infrastructure

Existing infrastructure must match the needs of the current technology mix, meaning the grid and storage must be able to transport or store the renewable electricity produced. We measure this by checking whether renewable electricity is curtailed for grid balancing reasons and, if so, whether the amount is decreasing or increasing over time. If electricity is curtailed in large amounts, it indicates that renewables deployment has outpaced infrastructure.

Deployment trend

Regarding the grid deployment trend, transmission, distribution, and storage are considered separately and compared to the linear path to the respective target. For national transmission and distribution, the metric is the capacity built in kilometers over the last five years. Especially for distribution, extending the grid length must be complemented by increasing its quality, notably by enabling smart grids and flexibility, such as through two-way transformers and smart meters. While data on these elements is currently scarce, it should become more available in the future and can be included in future work. Regardless, grid size matters and allows for clear measurement and evaluation.

Storage capacity is measured in GW and GWh. Various technologies serve as storage, including pumped storage, battery storage, and "power-to-x"' applications like hydrogen. Although near-future hydrogen demand will mostly come from industries, it can also replace natural gas in the long run for flexible electricity production and district heating. Modeling indicates that these applications will eventually account for the largest portion of hydrogen demand (Energiewende & Prognos, 2023). Hydrogen should therefore be considered when analyzing storage and flexibility capacity. Battery storage includes home storage systems, large and industrial storage systems, and vehicle-to-grid applications (Figgener et al., 2022).

Given that distribution grids and storage are used and planned mostly at the national level, we do not consider the transnational level here.

Variable 8: State of electricity infrastructure

Metric 8: Curtailment of RE (%); trend

Evaluation:
Sufficient: Curtailed renewable energy decreases despite renewable electricity growth.
Partially sufficient: Curtailed renewable energy stagnates, despite renewable electricity growth.
Insufficient: Curtailed renewable energy increases.

Variable 9: Electricity infrastructure deployment

Metric 9.1: Transmission lines (km); trend

Evaluation:
Sufficient: The growth rate of the transmission grid is exceeding the linear path to target. In the absence of an official target, a five-year growth of at least 50% is recommended.
Partially sufficient: Growth rate of the transmission grid is below the linear path to target. In the absence of an official target, a five-year growth of anywhere between 20% and 50% is recommended.
Insufficient: Decreasing or stagnating transmission grid (5-year growth less than 20%).

Metric 9.2: Distribution lines (km), trend

Evaluation:
Sufficient: The growth rate of the distribution grid is exceeding the linear path to target. In the absence of an official target, a five-year growth of at least 50% is recommended.
Partially sufficient: Growth rate of the distribution grid is below the linear path to target. In the absence of an official target, a five-year growth of anywhere between 20% and 50% is recommended
Insufficient: Decreasing or stagnating transmission grid (5-year growth less than 20%).

Metric 9.3: Energy storage as a % of variable renewable capacity (%)

Evaluation:
Sufficient: The energy storage rate is higher than the EU average and growing (new storage facilities are under construction).
Partially sufficient: The energy storage rate is lower than the EU average but growing.
Insufficient: The energy storage rate is lower than the EU average and not growing.

Market regulation

Market regulation is particularly relevant for electricity, given the complexity of the electricity market and the changing parameters with the advent of renewables. One measurable symptom of problems with the pricing mechanism is the presence of temporarily negative prices for renewables on short-term markets, caused by market oversupply with low-cost renewables and potentially exacerbated by infrastructure bottlenecks. We calculate the volume of these negative prices by summing up the negative, volume-weighted hourly prices by year for the last five years. The metric is evaluated based on whether the volume of negative prices is increasing or decreasing; we also consider the share of renewables in the electricity mix in the same year to see if a higher share of renewable energy correlates with more negative prices.

Another vital aspect of market regulation is energy subsidies. Subsidies for electricity from fossil fuels are measured, distinguishing “pro-fossil fuels” from “undifferentiated” subsidies. To be deemed sufficient, subsidies for fossil fuels must fall to zero, whether they directly target fossil fuels or come from undifferentiated electricity subsidies that benefit fossil fuel-based generation.

Administrative capacity is difficult to measure directly, as it can be a central bottleneck in the value chain of technology and infrastructure but is often noted mainly when it is “insufficient.” We measure it via a proxy of the permission processes for the most complex technology currently deployed, wind power. Specifically, we measure the average time for the permission process based on EU guidelines; the 2018 Renewables Directive set a 24-month limit, and there is currently a discussion to shorten it further. Onshore wind power, which prominently faces permission delays and has available data, serves as the benchmark.

Finally, public support for the energy transition is relevant for two main reasons. First, without public support legitimizing government actions, policy measures supporting the transition could be weakened or discontinued. Second, low levels of public support may lead to higher opposition to renewable energy installations and related infrastructure. We use data from the Eurobarometer on climate change, considering two aspects measured annually: public perceptions of government actions on climate change in general (“Do you think that the (NATIONALITY) governments are doing enough, not enough or too much to tackle climate change?”). and public perceptions on the expansion of renewable energy. (“How important do you think it is that the following authorities take action and increase the amount of renewable energy used, such as wind or solar power, by 2030?”). We consider the national trend and how it compares with the EU average trend.

Variable 10: Negative electricity prices

Metric 10: Negative prices for electricity (hours and price sum)

Evaluation:
Sufficient: There are no negative prices.
Partially sufficient: Negative prices occur, but the volume is decreasing independently of renewable energy share.
Insufficient: Negative prices occur and do not decrease, or only when the share of renewable energy in electricity mix decreases.

Variable 11: Fossil fuels subsidies

Metric 11: Subsidies for coal and natural gas (USD); trend

Evaluation:
Sufficient: No subsidies are in place for both coal and natural gas.
Partially sufficient: Coal/gas subsidies are in place but are decreasing.
Insufficient: Coal/gas subsidies are in place and are not decreasing (+/- 20%).

Variable 12: Administrative capacity

Metric 12: Average time for permission process, wind power (months)

Evaluation:
Sufficient: Permission time is lower than the EU guidelines limit.
Partially sufficient: Permission time is higher than the EU limit but lower than the EU average.
Insufficient: Permission time is lower than the EU guidelines limit and the EU average.

Variable 13: Public support to the energy transition

Metric 13.1: Support for the expansion of renewable energy (%)

Evaluation:
Sufficient: The majority (>50%) of national residents support the expansion of renewable energy, and their support is stable.
Partially sufficient: The majority of national residents support the expansion of renewable energy, but their support is waning.
Insufficient: Only a minority of national residents support the expansion of renewable energy.

3.5 | Road transport sector

Policy targets

Given the short timeframes, a Paris-consistent zero-carbon transition in road transport requires clear phase-out targets for ICE vehicles. We therefore include such a metric.

The most straightforward type of new technology target is a goal for the share of EVs and other zero-emission vehicles in total car sales by a certain year. This number must be consistent with the aim for a zero-emission sector and follow an expansion timetable that envisages linear or stronger-than-linear growth to be deemed sufficient.

Based on the target for technology deployment, we check whether the targets for infrastructure deployment are built on it. Charging infrastructure bears some uncertainty regarding the needs of different types of charging at different points of the transition, but a key criterion is whether the infrastructure is planned to accommodate (at least) the same number of EVs as the technology targets.

Variable 1: Phase-out target

Metric 1: Target for ICE vehicles phase-out (year)

Evaluation:
Sufficient: Targets to phase out all ICE vehicles by 2045 or earlier.
Partially sufficient: Phase-out targets exist but are set for later than 2045.
Insufficient: No phase-out target exists.

Variable 2: Technology target

Metric 2: Target share of zero-emission vehicles in total car sales (%)

Evaluation:
Sufficient: Final target consistent with zero-carbon by 2045 or earlier, with a linear or stronger-than-linear expansion timetable.
Partially sufficient: Final target is consistent with zero-carbon by 2045, but the expansion timetable is below linear.
Insufficient: Final target is not sufficient for zero-carbon or no target exists.

Variable 3: Infrastructure target

Metric 3: Target for number of public charging points (number per EV)

Evaluation:
Sufficient: Targets are in place and consistent with zero-emission road transport scenarios for 2045.
Partially sufficient: Targets are in place but not consistent with zero-emission road transport scenarios.
Insufficient: There are no targets in place.

Phase-out of carbon-intensive technologies

Similar to the electricity sector, emissions from road transport must decrease and reach zero before 2050. We include a metric to monitor this progress. A closely related variable is the progress in phasing out ICE vehicles. Additionally, a smart transition for road transport may involve a modal shift from cars to other transportation means (bicycles, public transport, etc.), so we include an indicator reflecting such modal shifts in each country compared to the EU average.

Variable 4: Emissions reduction

Metric 4: GHG emissions of road transport (Mt CO2e); trend

Evaluation:
Sufficient: Emissions are decreasing at an equal (+/- 10%) or higher rate than the linear trajectory to zero emissions by 2045.
Partially sufficient: Emissions are decreasing at a rate lower than the linear trajectory to zero emissions by 2045.
Insufficient: Emissions are increasing or stagnating (+/-10%).

Variable 5: Phase-out progress

Metric 5: Share of ICE in total cars (%, trend)

Evaluation:
Sufficient: The share of ICE cars is decreasing at an equal (+/-10%) or higher rate than the linear trajectory to zero emissions by 2045.
Partially sufficient: The share of ICE cars is decreasing at a rate below the linear trajectory to zero emissions by 2045.
Insufficient: The share of ICE cars is stagnating (+/-10%) or increasing.

Variable 6: Modal shift

Metric 6: Share of passenger transport by cars (%, trend)

Evaluation:
Sufficient: The share of cars is decreasing at equal or higher rates than EU/OECD average.
Partially sufficient: The share is decreasing but at lower rates than EU/OECD average.
Insufficient: The share is stagnating or increasing.

Phase-in of zero-carbon technologies

For EVs, the total cost of ownership would be an ideal metric, similar to the LCOE for electricity, as it reflects all or most types of costs related to the uptake of the technology. However, since we are looking at a mass market where buyers are mostly individual citizens with limited cash flow, purchase prices can function as a critical barrier, at least in the early phase of the transition. Therefore, we focus on this metric (Singh et al., 2020). For the national progress to be deemed sufficient, the average purchase price for EVs at present needs to be cheaper than the average price for ICE cars.

Deployment is measured similarly to electricity. In this case, we consider both the share of EVs in total car sales and the share in the entire car fleet. These shares are compared to the linear trend toward the respective target. While there is some uncertainty about the total number of cars needed in a zero-carbon future, it depends on factors such as the degree of a possible shift to other means of transportation. However, it is clear that the car fleet, regardless of its final size, must be 100% zero-emission vehicles, which is why we measure shares and not absolute numbers of cars.

Variable 7: Technology cost

Metric 7: Average purchase prices of EVs and ICE cars (EUR); trend

Evaluation:
Sufficient: EVs (average) are cheaper than ICE vehicles nationally.
Partially sufficient: EVs (average) are more expensive than ICE vehicles nationally, but the gap is narrowing.
Insufficient: EVs (average) are more expensive than ICE vehicles nationally, and the gap is not narrowing.

Variable 8: Technology deployment

Metric 8.1: Share of EVs in total car sales (%); trend

Evaluation:
Sufficient: EV sales share is close (within +/-20%) to the linear trajectory toward the national target and growing.
Partially sufficient: EV sales share is below the linear trajectory toward the national target but growing.
Insufficient: EV sales share is below the linear trajectory toward the national target and not growing.

Metric 8.2: Share of EVs in total car fleet (%); trend

Evaluation:
Sufficient: Share of EVs in the total fleet is growing at a rate approximately 20% above/below the linear trajectory toward the zero-emissions vehicle benchmark for 2045.
Partially sufficient: EVs' share is below the linear trajectory toward the zero-emissions vehicle benchmark for 2045 but growing.
Insufficient: EVs' share is below the liner trajectory toward the zero-emissions vehicle benchmark for 2045 and not growing.

Infrastructure

The infrastructure needed for EVs can use the road network already constructed as part of the ICE regime. Apart from repairs and renewals, the road network exists and does not present a barrier. What is lacking but equally important for EVs is charging infrastructure.

There are different modes of charging, and assessing their respective roles is not trivial. Charging occurs at home, at the workplace, and in public places. Among early adopters, charging was and still is largely done at home, and it remains the most important type of charging to this day (IEA, 2022a). However, as the number of EVs on the roads grows and they start to replace ICE cars, a larger network of charging opportunities is needed to allow for more flexible driving habits. Public charging, in particular, is critical for taking the system to the next level, removing "range anxiety" and facilitating driving habits beyond commuting and short trips (Funke et al., 2019).

Given that data availability is satisfactory only for public charging, we focus on public charging. However, future comprehensive analysis (as well as comprehensive policy) should include all types of charging infrastructure.

To measure the state of infrastructure, we compare the number of installed charging points to the number of registered EVs, including PHEVs) and evaluate it based on the European Commission's recommendation of one charging point per ten EVs. PHEVs are included in the calculation because they are considered in the recommendation for the EV-to-charging-points ratio.

Another option would be to measure public charging based on the installed power of charging opportunities. This would account for the fact that it makes a difference whether the majority of charging points are alternative current or direct current. However, at present, data availability is better, and targets are clearer for the number of charging points.

The deployment trend, similar to electricity, looks at the recent growth of charging points compared to the linear path to target.

Variable 9: State of infrastructure

Metric 9: Public charging points density (Nb per EV)

Evaluation:
Sufficient: 10 EVs or fewer per charging point, on national and transnational levels.
Partially sufficient: 10 BEVs or fewer per charging point on a national, but not on a transnational level.
Insufficient: More than 10 EVs per charging point on a national level.

Variable 10: Deployment of infrastructure

Metric 10: Public charging points installed per year; trend (number/year)

Evaluation:
Sufficient: The growth in charging points is within 20% of the linear trajectory toward the national target.
Partially sufficient: The growth rate is below the linear trajectory toward the target but is increasing.
Insufficient: The growth rate is below the trajectory toward the target and is not increasing.

Market regulation

Administrative capacity is not considered a barrier for EVs, as the institutions and administrative bodies already exist for ICE cars, and the infrastructure is not subject to significant bureaucratic hurdles, unless regulatory and permission issues around charging infrastructure become a problem in the future. Regarding market regulation, pricing design is not an issue. However, subsidies can present a barrier and need to be eliminated sooner rather than later for EVs to break through in the mass market. This applies to subsidies favoring ICE cars and undifferentiated subsidies.

Variable 11: Market regulation

Metric 11: Subsidies for ICE cars (EUR); trend

Evaluation:
Sufficient: No subsidies for oil/ICE cars are in place.
Partially sufficient: Subsidies are in place but decreasing.
Insufficient: Subsidies are not increasing or stagnating (+/-20%).

3.6 | Building sector

Policy targets

Regarding technology targets, we focus on the target for zero-carbon heating, including all heating technologies compatible with climate-neutral heating, such as heat pumps (HPs), solar thermal, or biogas. We also consider the specific target for heat pumps, the main emerging technology. The targets for infrastructure refer to the buildings subsystem and include the number of buildings renovated per year, an efficiency target (heat required per m^2 or similar), and the percentage of buildings with energy storage. As in previous sections, we assess the extent to which such targets are consistent with zero-emission heating by 2045 or earlier.

Variable 1: Phase-out target

Metric 1: Targets for phase-out oil and gas heating systems (year)

Evaluation:
Sufficient: There are targets for the phase-out of oil and gas heating that are consistent with zero emissions by 2045.
Partially sufficient: There are phase out targets, but they are not consistent with zero emissions by 2045 or earlier.
Insufficient: There are no phase-out targets.

Variable 2: Technology targets

Metric 2.1: Target for new heat pumps (number)

Evaluation:
Sufficient: Final target is 2045-consistent, and the expansion timetable is linear/stronger-than-linear.
Partially sufficient: Final target is 2045-consistent, but the expansion timetable below linear.
Insufficient: Final target not 2045-consistent or there is no target.

Metric 2.2: Target for share of zero-carbon heating (%)

Evaluation:
Sufficient: Final target is 2045-consistent, and the expansion timetable is linear/stronger-than-linear.
Partially sufficient: Final target is 2045-consistent, but the expansion timetable is below linear.
Insufficient: Final target is not 2045-consistent.

Variable 3: Infrastructure targets

Metric 3.1: Target for energy consumed for heating per m^2

Evaluation:
Sufficient: Targets for energy efficiency of building are 2045-consistent.
Partially sufficient: Targets for energy efficiency of building are not 2045-consistent.
Insufficient: No targets for energy efficiency of building.

Metric 3.2: Target for building renovations per year (%)

Evaluation:
Sufficient: Targets for building renovations are 2045-consistent.
Partially sufficient: Targets for building renovations are not 2045-consistent.
Insufficient: No targets for building renovations.

Metric 3.3: Target for buildings with thermal energy storage (%)

Evaluation:
Sufficient: Targets for building storage are consistent with zero emissions by 2045.
Partially sufficient: Targets for building storage are not consistent with zero emissions by 2045.
Insufficient: No targets for building storage.

Phase-out of carbon-intensive technologies

Similar to electricity and transportation, emissions from heating must decrease and reach zero by 2050. This goal necessitates the elimination of GHG emissions from heating, which requires phasing out fossil-fuel-based heating technologies such as oil and gas boilers. Therefore, we include phase-out targets and track the progress of this phase-out as key metric.

Variable 4: CO2 emissions from building

Metric 4: CO2 emissions from direct building energy use (Mt CO2); trend

Evaluation:
Sufficient: Emissions are decreasing at a rate equal to (within +/-10%) or higher than the linear trajectory toward achieving zero emissions by 2045.
Partially sufficient: Emissions are decreasing at a rate lower than the benchmark for 2045.
Insufficient: Emissions are increasing or stagnating (+/-10%).

Variable 5: Phase-out progress

Metric 5: Phase-out of oil and gas heating systems

Evaluation:
Sufficient: The decrease rate of the share of gas and oil heating is higher than the linear trajectory toward the target.
Partially sufficient: The share of oil and gas heating is decreasing but at a rate that is below the linear trajectory toward the target.
Insufficient: The share of oil and gas heating is stagnating (+/-10%) or increasing.

Phase-in of zero-carbon technologies

To measure the total cost of the primary technological artifact, HPs, we follow the same logic as in previous sections: we compare the cost of HPs with the main incumbent technology, gas boilers, both nationally and internationally. The deployment trends are measured in relation to the respective targets.

Variable 6: Technology cost

Metric 6: Heat pumps total purchase cost (EUR)

Evaluation:
Sufficient: Heat pumps (average) are cheaper than gas boilers nationally.
Partially sufficient: Heat pumps (average) are more expensive than gas boilers nationally, but the gap is narrowing.
Insufficient: Heat pumps are more expensive than gas boilers nationally, and the gap is not narrowing.

Variable 7: Technology deployment

Metric 7.1: Installed (new) heat pumps (thousands/year) trend

Evaluation:
Sufficient: Number of new HPs is equal to (+/-20%) or higher than the linear trajectory toward the respective target.
Partially sufficient: Number of new HPs is below the linear trajectory toward the target, but growth rates are increasing.
Insufficient: Deployment is stagnating (+/-20%) or growing at a rate below the linear trajectory without increasing growth rates.

Metric 7.2: Share of buildings with climate-neutral heating (%); trend

Evaluation:
Sufficient: Share of climate-neutral heating is increasing at a rate equal to (+/-20%) or above the linear trajectory toward zero emissions by 2045.
Partially sufficient: Share is increasing below the linear trajectory, but growth rates are increasing.
Insufficient: Share is stagnating (+/-20%), falling, or growing without increasing growth rates and below the linear trajectory.

Infrastructure

Variable 8: Infrastructure deployment

Metric 8.1: Energy consumed for heating per square meter (kWh/m^2); trend

Evaluation:
Sufficient: Rate of decline of energy consumption is equal to (+/–20%) or above the linear trajectory toward the respective target.
Partially sufficient: Rate of decline is below the linear trajectory toward the target, but rates are improving.
Insufficient: Rate of decline is below the linear trajectory toward the target and not improving.

Metric 8.2: Homes treated with (high) energy efficiency measures (thousands/year); trend

Evaluation:
Sufficient: Growth rate is equal to (+/–20%) or above the linear trajectory toward the respective target.
Partially sufficient: Growth rate is below the linear trajectory toward the target, but growth rates are increasing.
Insufficient: Growth is below the lineartrajectory toward the target, and growth rates are either not increasing or stagnating (+/–20%).

Metric 8.3: Share of households with energy storage (%); trend

Evaluation:
Sufficient: Growth rate is equal to (+/–20%) or above the linear trajectory toward the respective target.
Partially sufficient: Growth rate is below the linear trajectory toward the target, but growth rates are increasing.
Insufficient: Growth rate is below the linear trajectory toward the target and growth rates are either not increasing or stagnating (+/–20%).

Market and regulation

We have incorporated a metric assessing the "Share of buildings using smart tariffs," which is a pivotal element in decarbonizing heating and reducing energy-related emissions. Smart meters and smart tariffs play a crucial role in aligning electricity consumption with generation patterns and promoting energy conservation (Guo, 2023). Decarbonizing the heating sector is expected to increase electricity demand and create new demand peaks, particularly affecting the unmanaged use of heat pumps and electric vehicles. Effective consumption management is essential in this context (Gupta & Morey, 2022). Dynamic electricity tariffs, which adjust consumer rates based on market prices rather than fixed-rate billing per kilowatt-hour, enhance flexibility and efficiency.

Regarding subsidies, we consider the trend of subsidies for investments in fossil-fuel-based heating, which need to be phased out as soon as possible.

Variable 9: Regulation for flexibility

Metric 9: Share of buildings with smart meters (%)

Evaluation:
Sufficient: The share is higher than the EU/OECD average and increasing.
Partially sufficient: The share is not higher than the EU/OECD average but is increasing.
Insufficient: The share is lower than the OECD average and is not increasing.

Variable 10: Subsidies for heating

Metric 10: Subsidies for investment in fossil-fuel heating (EUR); trend

Evaluation:
Sufficient: No fossil-fuel subsidies in place.
Partially sufficient: Subsidies are in place, but the amount per capita is decreasing.
Insufficient: Subsidies are in place, and the amount per capita is increasing or stagnating (+/–20%).

4

4 | COUNTRY SELECTION FOR CASE STUDIES

We aim to apply this analytical framework to Germany along with a selected group of countries for each sector. To maintain a systemic inter-sector view of decarbonization, we have chosen to analyze the same countries across the three sectors, rather than selecting different countries for each sector. This approach is crucial because countries that base their transport and building decarbonization strategies on electrification must also rapidly decarbonize their electricity sources and adapt their infrastructure accordingly. For instance, electricity networks and storage are essential for ensuring the reliability of power supply, particularly as the transport and heating sectors become increasingly electrified.

Through these case studies, we aim to showcase examples demonstrating the feasibility of transitioning quickly from a fossil-fuel-based (carbon-intensive) system to a zero-carbon paradigm. While no country has fully completed the energy transition, some have made significant advancements in specific sectors. For the reasons outlined below, **we chose Norway, Denmark, and the United Kingdom alongside Germany as case studies**.

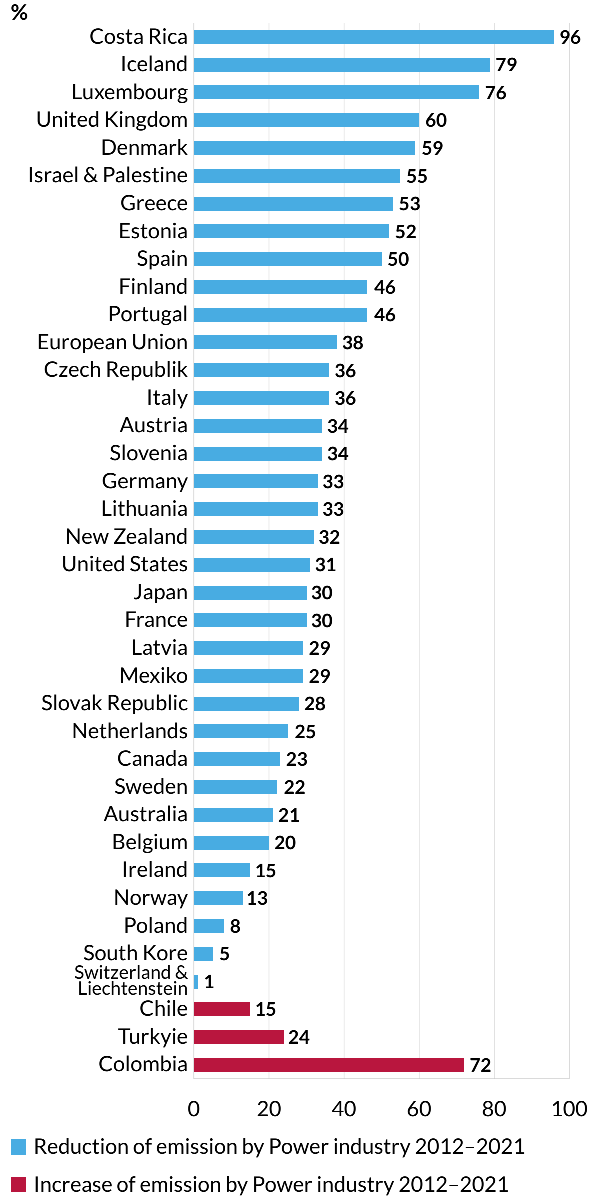
All these countries have policy targets for significantly reducing their GHG emissions and reaching net-zero emissions around 2050. They have also implemented various climate mitigation policy packages, initially for electricity and, more recently, for the transport and residential sectors. **Norway** stands out as a leader in deploying low and zero-carbon technologies in heating and transport, with an electricity system that is nearly decarbonized. Although the country appears to be on track to reach zero CO2 emissions in the coming decades, our analysis will explore the extent to which Norway is adapting its critical infrastructure and institutions to sustain sectoral transitions and phase out fossil fuel consumption. **Denmark** provides an excellent example of transitioning from a heavily fossil-fuel-based electricity system to one that increasingly relies on renewable energy sources, particularly wind power, which accounted for 84% of its electricity generation in 2022. The **United Kingdom**, while not leading in any specific sector, has made rapid progress in decarbonizing its electricity sector through a swift coal phase-out and possesses an economy comparable in size and diversity to Germany. This makes the UK a valuable additional case study.

Among the world's largest economies, China and the United States stand out for their ambitions to become global leaders in zero-carbon industries. However, we did not select the United States as a case study because its progress is very recent and not yet reflected in the data. Although there is early evidence that the 2022 Inflation Reduction Act is triggering substantial investments in zero-carbon technologies and related manufacturing capacities, these impacts may only become apparent in future data. Additionally, the United States lacks specific sectoral decarbonization targets, such as a target for phasing out sales of new ICE vehicles, and its decarbonization policies face high political risks, particularly with the potential for policy reversals in the 2024 elections. Regarding China, while it has made considerable strides in renewable energy, electric cars, and other low-carbon technologies, its continued strong investment in the coal sector poses a significant challenge. Furthermore, China is not an OECD country, which is the primary focus of this study.

4.1 | Electricity sector

Norway has significantly reduced its CO2 emissions (Figure 3) and boasts the lowest carbon intensity (gCO2/kWh) from the power sector in Europe (Figure 4). With the highest share of electricity produced from renewable energy sources, Norway relies heavily on hydropower and related storage capacity. As electricity demand is expected to rise to meet the needs of sectors like transport and heating, Norway is accelerating investments in other renewable energy sources, including floating wind farms. Despite being an oil and gas producer, Norway has almost completely phased out fossil fuel-based electricity generation, with the remaining gas units used only exceptionally. The country has also maintained a low level of electricity cur-

Figure 3 | CO2 emissions reduction in the power sector over the last 10 years



Source: European Environment Agency (2023a).

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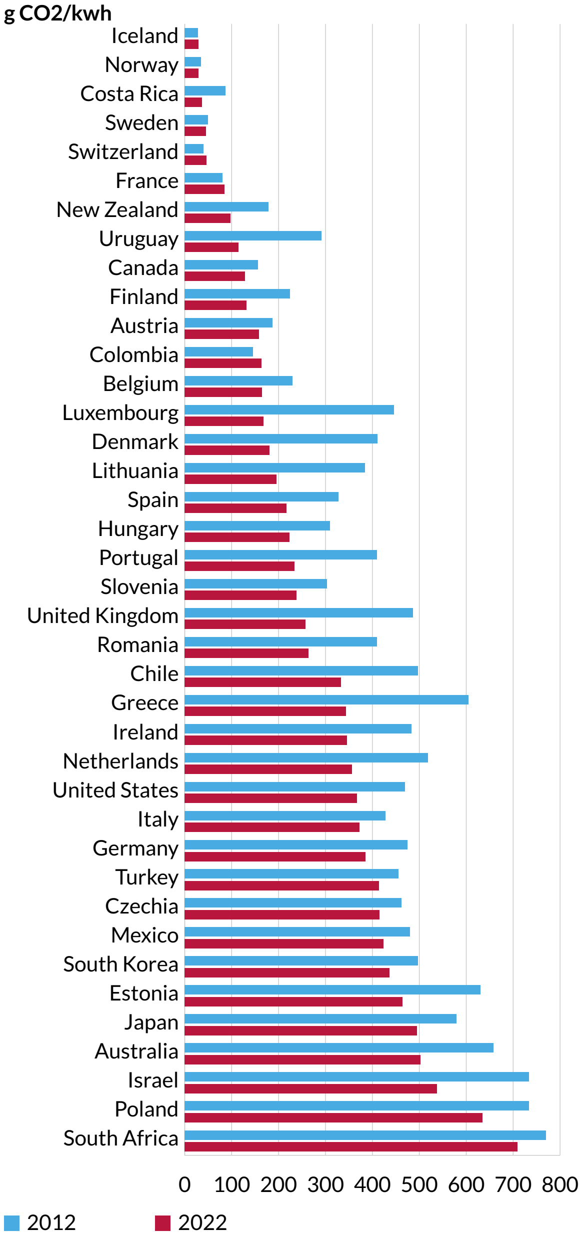
Figure 4 | Carbon intensity of electricity generation (2012 vs 2022)



Note: Carbon intensity is measured in grams of carbon dioxide-equivalents emitted per kilowatt-hour of electricity.
Source: EMBER (2023).

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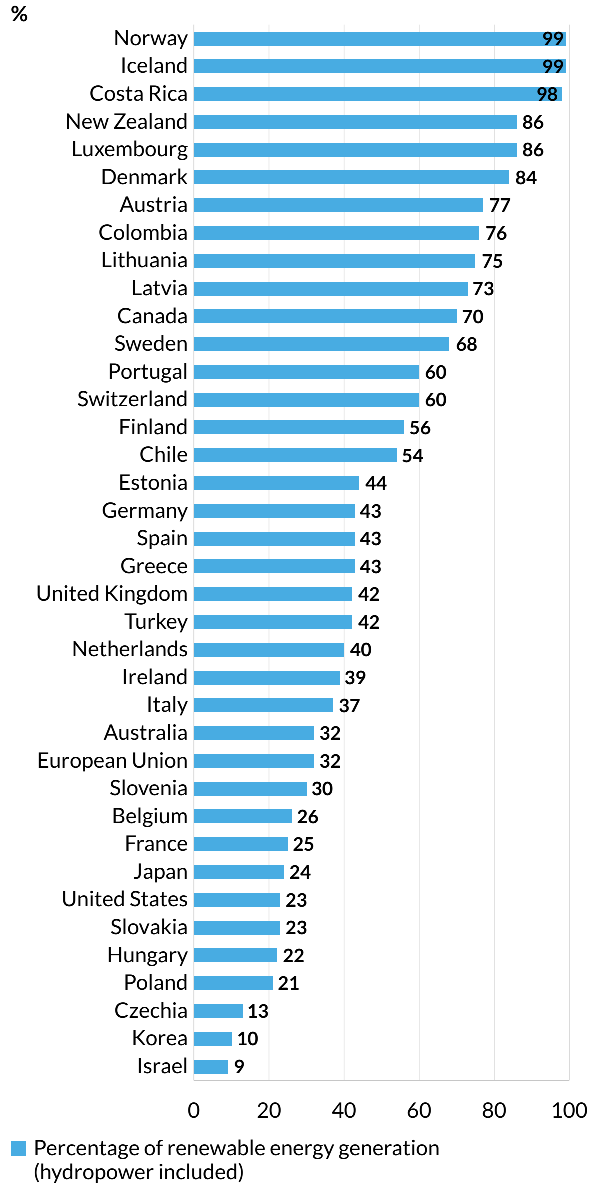
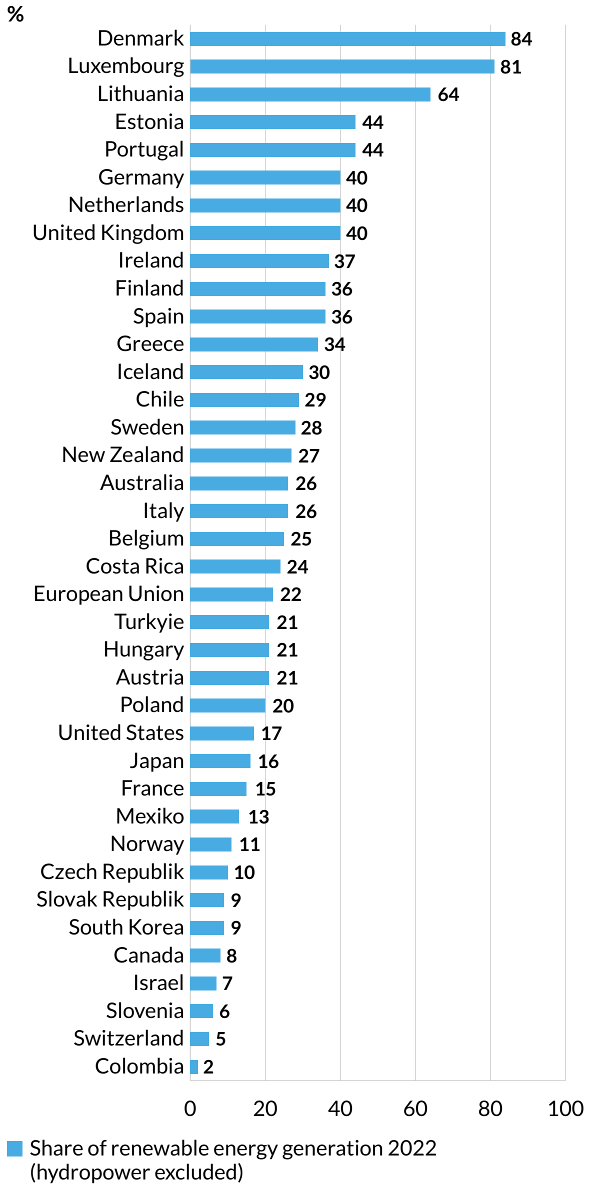
Figure 5 | Share of total renewable energy in the electricity mix



Source: EMBER (2023).

Figure 6 | Share of renewable energy in the electricity mix excluding hydropower



Source: EMBER (2023).

tailment (i.e., a reduction in the output of a generator from what it could otherwise produce given available resources) (Yasuda et al., 2022), indicating a robust state of electricity infrastructure, which will be further discussed in the case study analysis.

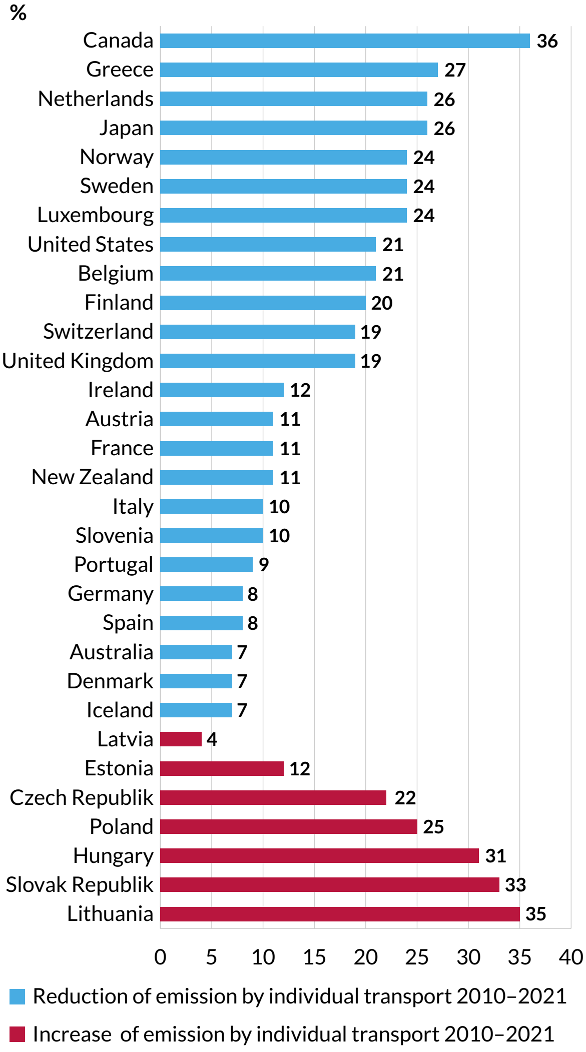
In contrast, **Denmark** and the **UK** have historically relied on fossil fuel-based electricity due to their limited geographical potential for hydropower production, resulting in relatively high carbon intensities (Figure 4). However, both countries have made rapid progress in expanding renewable energy, particularly wind power, and phasing out fossil fuels, leading to faster emissions reductions compared to other countries (Figure 3).

Denmark has the highest share of non-hydro renewable energy generation at around 84%, combined with a significant emission reduction of nearly 60% between 2011 and 2021 in its power industry. Denmark achieved this status by significantly reducing energy intensity and utilizing a high share of wind power. This progress is attributed to consistent support policies for renewable energy expansion and energy efficiency measures, fostering innovation through public and private sector cooperation (Barker, 2022; Climate Analytics; New Climate Institute, 2023).

The **United Kingdom**, with an economy comparable to Germany in size and GDP per capita, has achieved a 60% reduction in power industry-related emissions (Figure 3) and utilizes around 40% non-hydro renewable energies for power generation (Figure 6). This success is largely due to a politically enforced coal phase-out and a supportive policy framework incentivizing renewable energy expansion. The Contract for Difference policy instrument, which provides revenue certainty to renewable energy developers, has been particularly effective in reducing the cost of capital (Barrs, 2023). However, increasing energy curtailment (Yasuda et al., 2022) casts doubt on the electricity system's capacity to accommodate a growing share of variable renewables in the coming years.

Outside Europe, **Costa Rica** is an exemplary case of electricity decarbonization, achieving the most significant reduction of emissions in its power industry over the last decade (Figure 3). This Central American country has the highest share of renewable energy in Latin America, primarily generated from hydropower, complemented by solar and wind energy (Figures 5 and 6). Costa Rica has also strengthened its institutions to support the decarbonization of its economy, including extending a national moratorium on oil exploration and exploitation until 2050, with plans to enshrine it into law to prevent future administrations from reversing the policy (Climate Analytics; New Climate Institute, 2023).

Figure 7 | CO2 emission reduction in individual transport



Source: United Nations Climate Change (2023).

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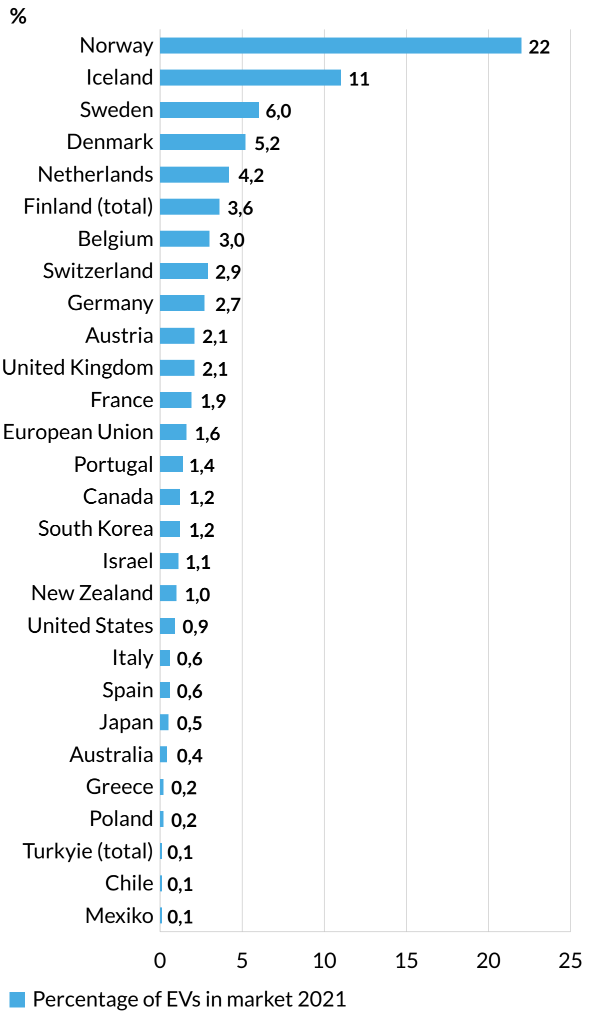
4.2 | Passenger transport sector

Norway boasts an exceptionally high share of EVs in the market and a significant reduction rate in transport-related emissions (Figures 7, 8). The successful rollout of EVs in Norwegian society can be attributed to several policy measures, including a CO2-differentiated registration tax on cars, strong financial incentives such as VAT exemptions for low-carbon intensity cars (Eskeland & Yan, 2021), and a rapid expansion of EV charging infrastructure. In 2022, nearly 90% of newly registered cars in Norway were electric, indicating that in a few years, no new ICE cars will be sold in the country (European Environment Agency, 2023b). Indeed, has set a target to phase out sales of new ICE vehicles by 2025, the earliest in the world (Wappelhorst, 2020). A high share of EVs, combined with an almost completely decarbonized electricity sector, gives Norway a very low carbon intensity of new cars compared to other countries (Figure 9).

Figure 8 | Deployment of EVs



Source: (IEA, 2023b).

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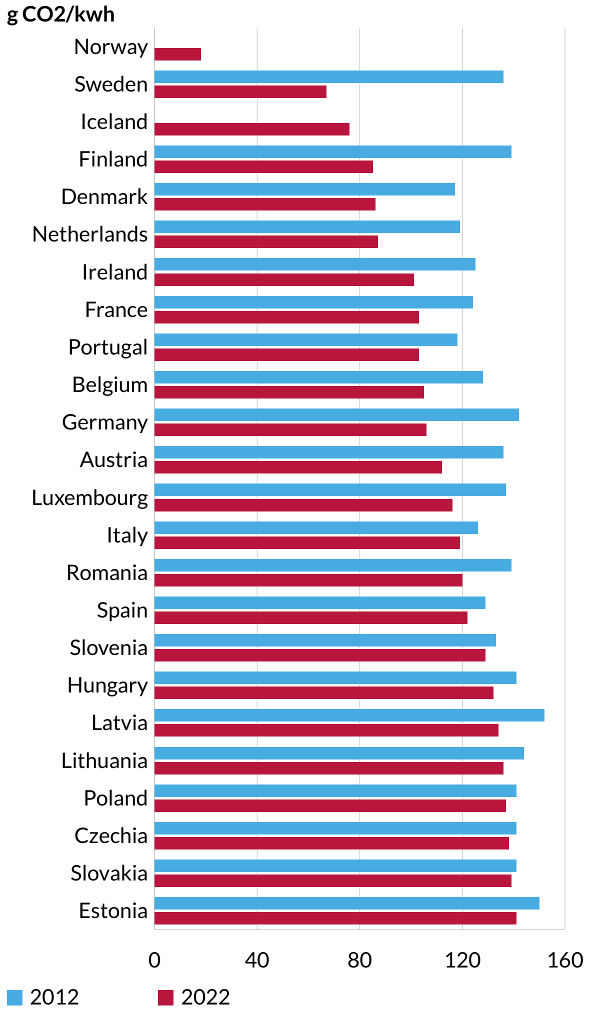
Figure 9 | Carbon intensity of new registered cars (2012 vs. 2022)



Source: European Environment Agency (2023a).

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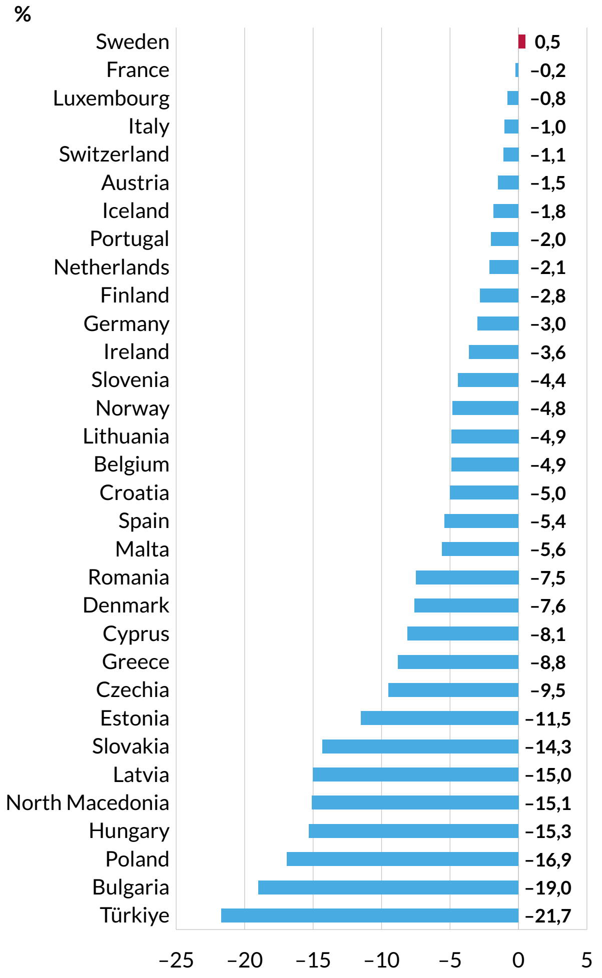
Denmark is accelerating the deployment of EVs, with 40% of new cars in 2022 being electric or hybrid while expanding the infrastructure of available charging points (IEA, 2023a). The country has substantially decreased the carbon intensity of newly sold cars (Figure 9) and has set a target to phase out sales of new ICE vehicles by 2030 (Wappelhorst, 2020). Conversely, the UK lags in electromobility but has managed to decrease its CO2 emissions from transport by 20% over the last decade. Further analysis will explore the drivers behind this emissions reduction and potential acceleration strategies.

Regarding a modal shift to other means of transportation, no country is clearly leading a transport decarbonization strategy based on moving away from individual cars. In all EU countries except for **Sweden** (+0.5%), the share of collective modes in total inland passenger transport decreased between 2005 and 2021, with the decline exceeding 3% in 19 countries and exceeding 5% in 14 countries (Figure 10). For all other European Environment Agency member countries and cooperating countries with available data, the share is decreasing, with figures varying from −1.1% to −21.7% (European Environment Agency, 2023a). In the EU-27, cars still represented 86% of passenger transport in 2022 (DESTATIS, 2023).

Figure 10 | Bus and train transport share change (percentage point)



Note: Figures depict changes in share of inland passenger transport between 2005 and 2021. Source: European Environment Agency (2023a): https://www.eea.europa.eu/en/analysis/indicators/share-of-buses-and-trains

Canada has shown a strong reduction in emissions from individual transportation between 2011 and 2021, largely due to a temporary drop during the COVID-19 pandemic. The government has implemented several measures to incentivize the use of EVs, including the Action Plan for Clean On-Road Transportation. The focus is on reducing EV costs, developing a nationwide EV charging network, and conducting public education campaigns about the relevance of EVs. Although the overall share of EVs remains relatively low (1.2%), the share of light-duty EVs in the first half of 2022 nearly reached 8% (Government of Canada, 2022). The federal government has set 2040 as the target year for phasing out sales of new ICE vehicles (Wappelhorst, 2020). Overall, national and sectoral targets and policy measures are not yet fully aligned with the Paris Agreement (Climate Analytics, 2023a; Climate Analytics; New Climate Institute, 2023).

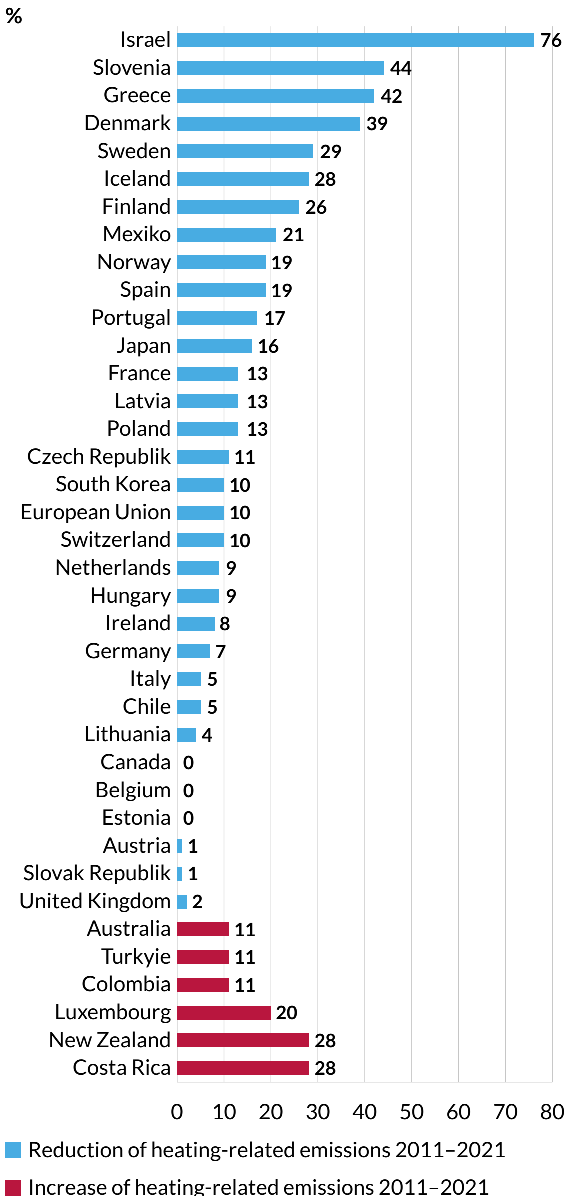
4.3 | Heating sector

The decarbonization of the heating sector is well-advanced in **Norway** (Agora Energy, 2021), which has significantly reduced its CO2 emissions and has the highest share of heat pumps per capita among European countries (Figures 11 and 12). Norway achieved this high-level rollout by implementing subsidies for residential heat pumps, high taxes on fossil fuels, and a carbon tax for heating. While the share of renewable energy consumption in buildings is still lower than in some neighboring countries (Figure 13), it is expected to increase, assuming the country manages to continue the rapid deployment of heat pumps. Regarding policy targets, Norway has also established a ban for the use of oil and gas heating in new and existing homes.

Denmark is performing relatively well regarding the share of renewable energy in building energy consumption, the deployment of heat pumps, and emission reductions. Current government plans aim for about 50% of buildings to be heated by district heating by 2028, with the remainder heated by heat pumps by 2029. The **UK** lags in heat pump deployment and has not decreased CO2 emissions for heating over the last decade (Figure 11). The UK government has established a ban on gas and oil boilers in new buildings starting in 2025.

Other interesting cases for further assessment of the heating sector include **Sweden**, which has the second-highest share of renewable energy sources for heating and has reduced its heating-related emissions by about a third. Sweden achieved low-carbon heating by using a high share of biofuels and district heating. The country also initiated an energetic renovation campaign in the 1980s and, more recently, it has implemented carbon-differentiated taxation and performed well in the deployment of heat pumps (Kerr & Winskel, 2021).

Figure 11 | CO2 emission reduction in heating



Source: European Environment Agency (2023a): https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer

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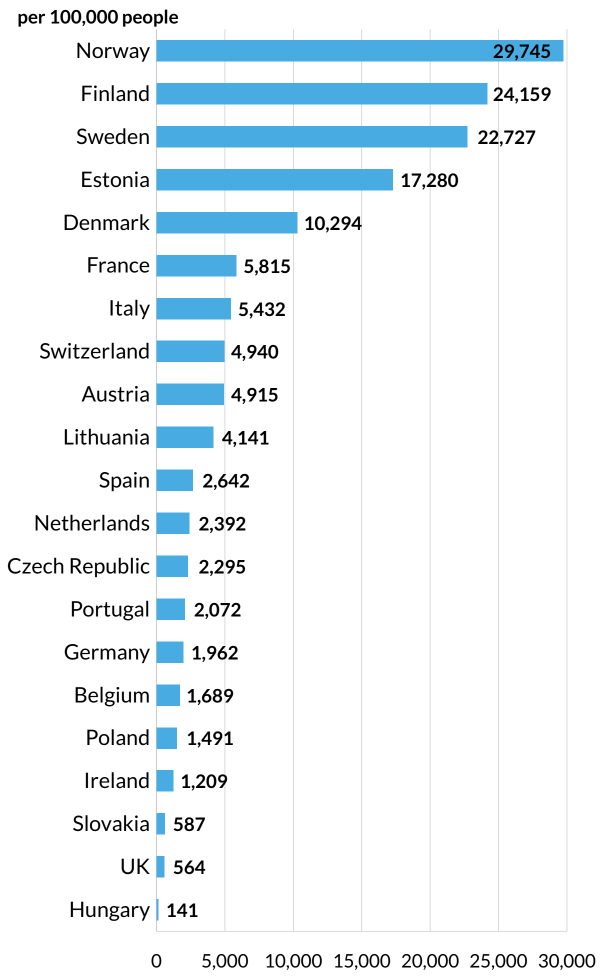
Figure 12 | Diffusion of heat pumps in Europe



Source: Jackman (2023): www.theecoexperts.co.uk/heat-pumps/top-countries

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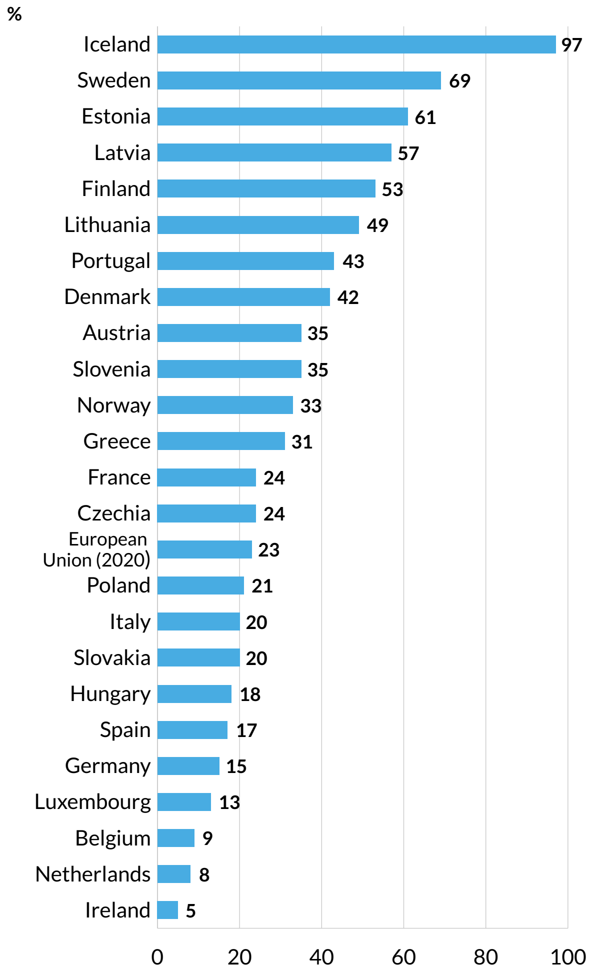
In 2016, **Estonia** already had one of the highest shares (60%) of people using district heating. Over the years, many fossil (mainly oil and gas) district heating systems were substituted by biomass systems. In numbers, the share of biomass in heating increased from 23% to 66% between 2012 and 2022, while natural gas reduced from 43% to 14%, and shale oil decreased from 21% to 6%. While renewables contributed 34% to Estonia's total final energy consumption in 2020, it was 55% in the heating and cooling sector, with over 90% of renewable energy sources coming from biomass (TRINOMICS & SEI, 2022).

Latvia ranks third in Europe by the percentage of the population connected to district heating. In both district heating and individual heating (80%), wood biomass is the most important fuel. Dependence on fossil gas for heating has been reduced due to EU-funded investments in biomass combined heat and power plants (CHP) plants and boiler houses for district heating. While biomass use is prominent, other renewable energy sources remain relatively low. Most of Latvia's renewable energy for total energy consumption is generated by hydropower. Recently, the government has been incentivizing the installation of private PV plants (Petersone, 2023).

Since the 2000s, **Finland** has implemented a wide range of government policies, targets, and taxes to encourage inhabitants to switch to carbon-neutral heating systems. For example, fossil fuel taxation has tripled since 2011, and since 2014, heat pumps have been mandatory in new buildings. Furthermore, a high percentage of households connected to district heating has facilitated more efficient heating systems. Energy-efficient measures have also led to a 15% reduction in energy consumption since 2000. By 2018, Finland's 2.7 million households owned one million heat pumps (Kerr & Winskel, 2021). As of 2022, the electricity required for these systems is generated by nuclear power (38%), hydropower (19%), wind (18%), biomass (9%), fossil gas (3%), as well as coal (6%).

Figure 13 | Share of renewable energy in building



Source: Eurostat (2023a).

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5

5 | FINDINGS

5.1 | Germany

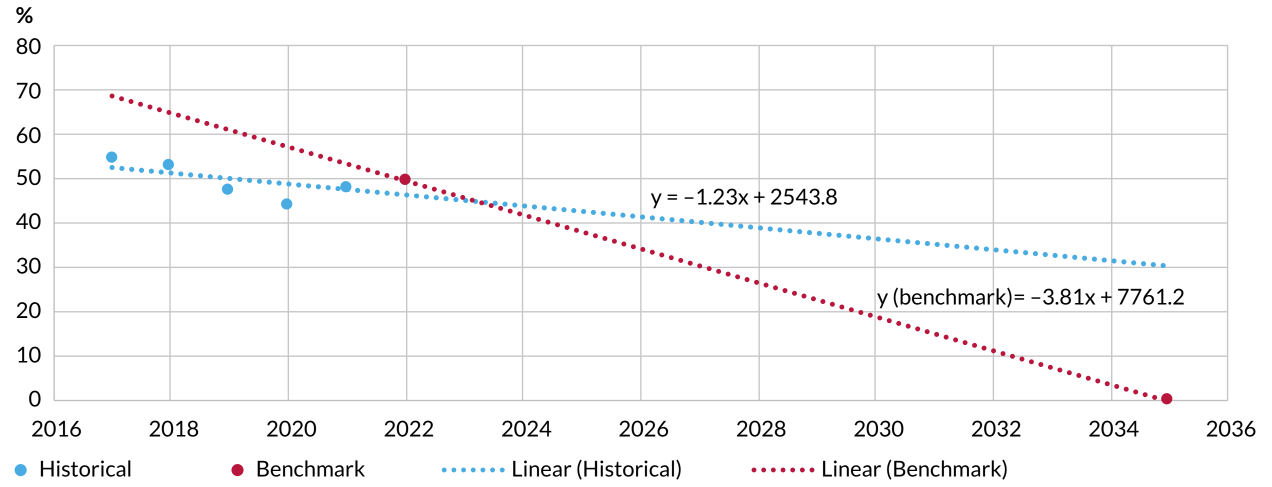
5.1.1 Electricity sector

Germany's transition exhibits significant progress, notable setbacks, and ongoing challenges across various aspects of its renewable energy and decarbonization efforts. Out of twenty metrics, developments are deemed sufficient in four, partially insufficient in nine, and insufficient in seven (see Table 5).

In terms of targets, Germany has made strides in setting ambitious goals for renewable energy adoption, such as doubling the share of renewables in total electricity consumption by 2030 and aiming for 100% renewable electricity by 2035. However, aligning transmission and distribution network development with these targets remains a challenge. The absence of official targets for distribution networks and insufficient transmission capacity planning underscores the need for clearer objectives and robust infrastructure planning. Additionally, while a first electricity storage strategy is under discussion (as of the end of 2023), there are still no official targets.

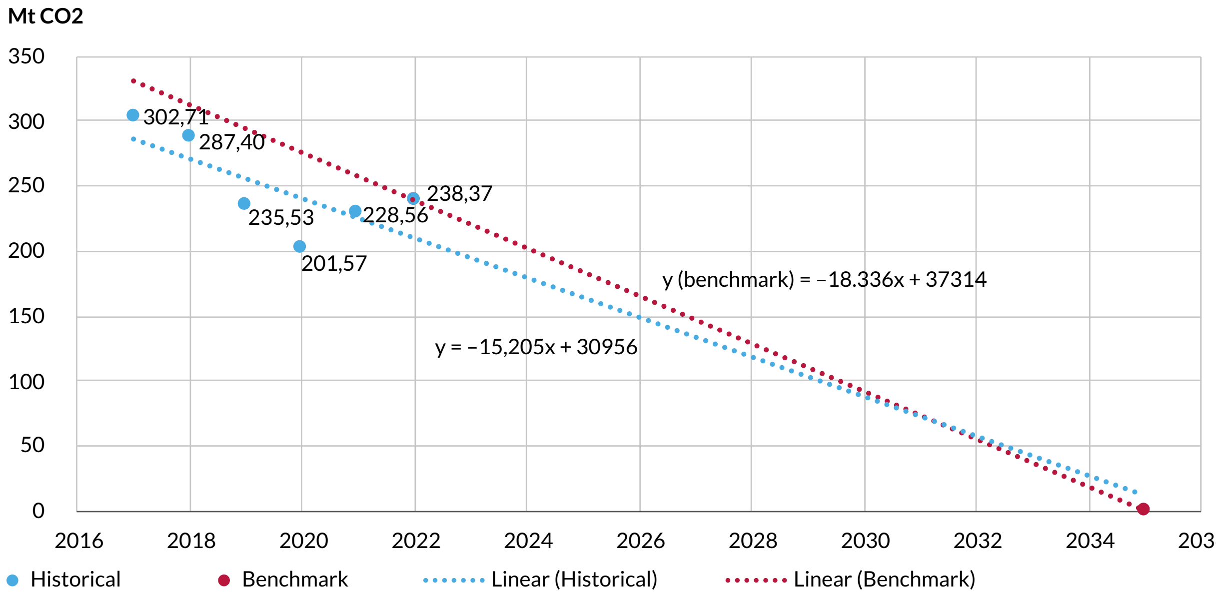
The phase-out of carbon-intensive power generation presents a mixed picture. There are commitments to coal phase-outs and agreements with industry players to expedite regional coal phase-outs. However, recent events, such as the Russia-Ukraine war, have led to temporary reactivations of coal power capacity, highlighting the complexities and tensions in transitioning away from carbon-intensive technologies. The share of fossil fuels in the electricity mix decreased by 1.23 percentage points per year between 2017 and 2022, which

Figure 14 | Share of fossil-fuels in the electricity mix – Germany



Source: EMBER (2024).

Figure 15 | CO2 emissions from electricity generation in Germany



Source: EMBER (2024).

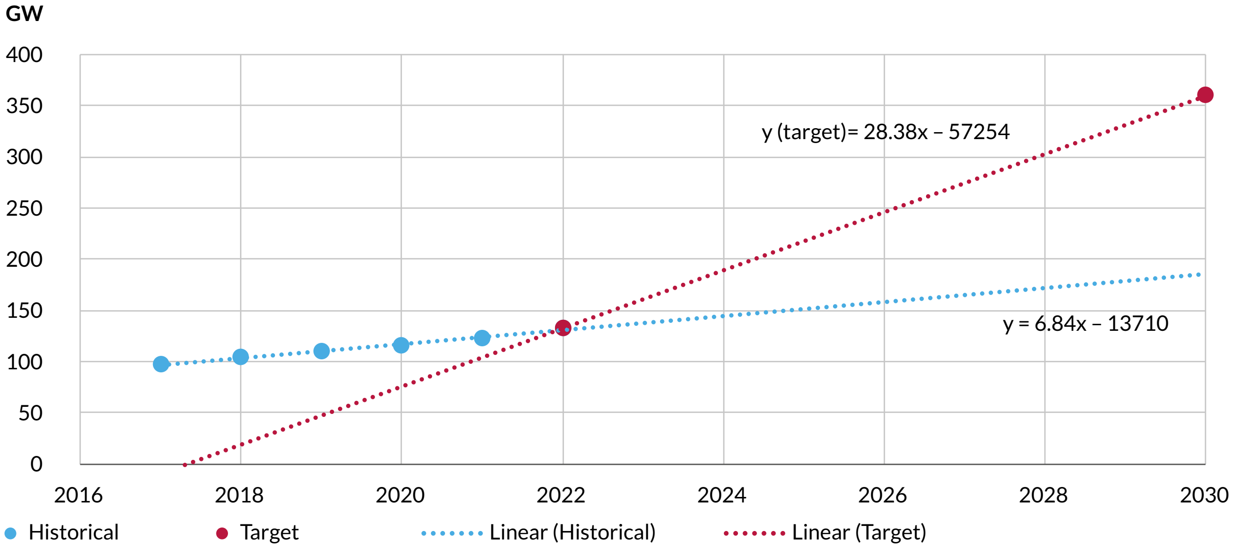
is too slow compared to the benchmark of a total phase-out of fossil fuels by 2035. The share should decrease by at least 3.81 percentage points per year, which is three times faster than the current rate (Fig. 14). Between 2017 and 2022, CO2 emissions from electricity fell by around 20%, and the carbon intensity of electricity was reduced from 454 to 420 gCO2/kWh. However, carbon intensity is still too high and is decreasing at a slower pace than the OECD and EU averages. As shown in Figure 15, the reduction of CO2 emissions from electricity between 2017 and 2022 was slightly below the benchmark for a zero-emissions electricity system by 2035.

Regarding the phase-in of zero-carbon technologies, particularly solar photovoltaics and onshore wind energy, there are promising trends in declining LCOE and capacity additions. Nevertheless, the pace of capacity additions still falls short of the targets necessary to meet future renewable energy goals, indicating a need for accelerated deployment efforts. Indeed, the new installed solar and wind capacity in 2018–2022 was 6.8 GW per year, while 28.4 GW per year are needed to reach the 2030 capacity targets of 360 GW (Figure 16). Similarly, progress in the share of renewable energy mix in 2018–2022 was too slow, although the situation improved in 2023 when renewables covered more than 50% of power generation.

Infrastructure development remains a critical pillar of Germany's energy transition. While there has been an expansion of distribution grids and increasing deployment of battery storage, challenges persist, particularly in transmission line development, which has stagnated (Table 2). The insufficiency of existing grid infrastructure is reflected by the persistent curtailment of renewable energy generation, which increased in 2018–2022. Stagnation in transmission line development and rising curtailment due to grid limitations underscore the urgency of enhancing grid infrastructure to accommodate growing renewable capacities effectively.

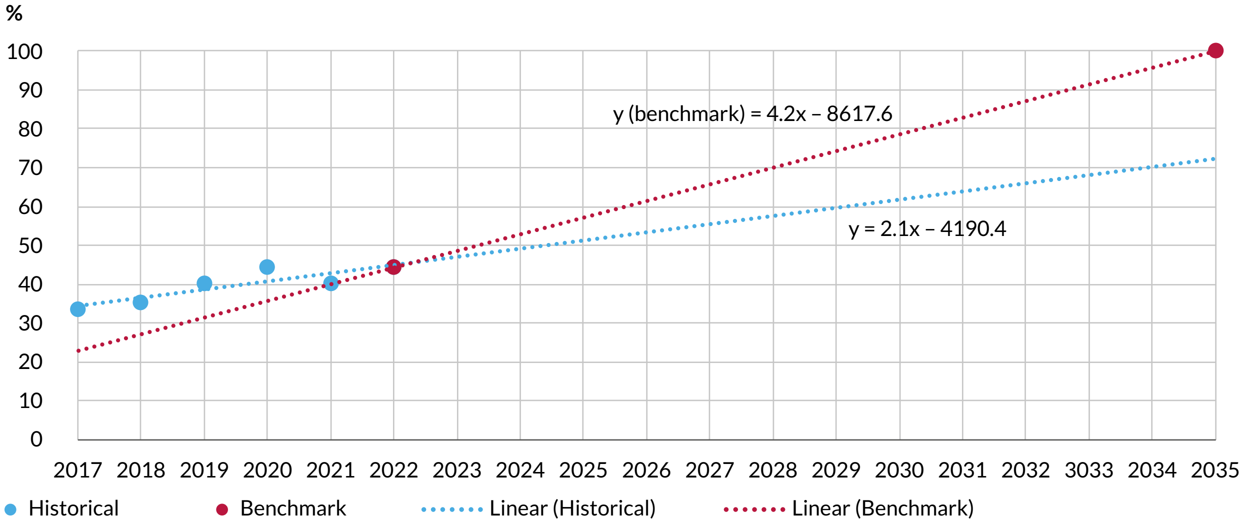
Institutional factors also play a crucial role in shaping Germany's energy transition trajectory. While there have been reductions in subsidies for coal, recent increases in natural gas subsidies due to the 2022 energy crisis highlight the complexities of transitioning away from fossil fuels amidst evolving energy market dynamics (Table 3). Additionally, persistent occurrences of negative electricity prices underscore the need for policy interventions to address market distortions (Table 4). On a positive note, public support for transitioning to a 100% renewable energy system remains very high (Table 5).

Figure 16 | Progress in renewable energy targets – Germany



Note: Wind and solar installed capacity (GW).
Source: EMBER (2024).

Figure 17 | Progress toward zero-emission electricity by 2035 in Germany



Note: Wind and solar installed capacity (GW).
Source: EMBER (2024).

Table 2 | Length of German transmission grid (2017–2022)

	2017	2018	2019	2020	2021	2022
Grid length in thousand km	37.49	36.8	37.30	37.50	37.81	36.3

Source: Bundesnetzagentur/Bundeskartellamt (2019–2023).

Table 3 | Subsidies for coal and natural gas in Germany (2017–2022)

	2017	2018	2019	2020	2021	2022
Coal	4,570,212	3,802,646	4,105,281	5,247,040	3,369,532	2,978,178
Natural gas	921,462	874,747	867,611	874,964	778,825	9,993,540

Note: All values are presented in thousands of USD, nominal terms.
Source: OECD, IISD (2023).

Table 4 | Negative electricity prices in Germany

	2018	2019	2020	2021	2022	2023
Hours	133	211	298	139	88	351
Price (EUR/MWh), summ	–1,835	–3,645	–4,621	–2,273	–1,273	–4,928

Source: EMBER (2024).

In sum, Germany's electricity transition reflects a complex interplay of ambitious goals, evolving challenges, and ongoing efforts to accelerate the shift toward renewable energy and an associated zero-emissions system while phasing out coal and gas. Achieving 100% renewable electricity generation by 2035 is feasible but requires addressing identified challenges, such as aligning infrastructure development with renewable energy targets, providing more flexibility to the grids, and continuously adapting regulations.

Table 5 | Assessment results – Electricity, Germany

Variable/metric	Evaluation	Explanation	Sources
		A) Policy targets	
1. Targets for phase-out fossil fuel-based power generation (year)	Partially sufficient	The 2020 German Coal Exit Act set a deadline for phasing out coal by 2038, with an option to move the date forward to 2035. However, following the onset of the Russian war of Aggression against Ukraine, Germany resorted to its coal power reserves, reactivating 8 GW of coal power and extending the operation of another 1,200 MW of coal capacity. This temporary return to coal was agreed upon with the German coal giant RWE, which committed to advancing its regional coal phase-out to 2030.	Bloomberg (2024): Global Coal Countdown
2. Targets for renewable electricity capacity and/or generation share (%, year)	Sufficient	In April 2022, the coalition government introduced the "Easter Package" and the EEG 2023, aiming to nearly double the share of renewables in total electricity consumption to 80% by 2030 (up from 65% previously), and to reach 100% by 2035. The package includes specific capacity targets for solar PV, onshore wind, and offshore wind.	IRENA (2024); Climate Analytics (2023a)
3.1. Targets for transmission development national (km)	Partially sufficient	The current National Network Development Plan for 2022–2035 outlines targets for transmission lines (44.16 million km), based on a much lower installed renewable energy capacity of 233 to 261 GW, compared to the Renewable Energy government's targets of 360 GW by 2030. International transmission line targets are also based on these less ambitious renewable energy goals.	Bundesnetzagentur (2022)
3.2 Targets for distribution network (km)	Insufficient	Currently, there are no official targets for electricity storage.	

3.3 Targets for energy storage (GW or GWh)	Partially sufficient	The first German strategy for electricity storage, proposed by the Economic and Environment Ministry (BMWK), is under discussion, but no specific targets have been set yet, except for hydrogen. The domestic electrolysis capacity target by 2030 is at least 10 GW.	EURELECTRIC (2023) Bundesministerium für Wirtschaft und Klimaschutz (2023)
B) Phase-out of carbon-intensive technologies			
4.1: CO2 emissions of electricity generation (Mt CO2e), trend	Partially sufficient	CO2 emissions from electricity in Germany decreased by 21% between 2017 and 2022. However, the average yearly decrease (15.2 million tons of CO2) was below the necessary benchmark of 18.3 million tons of CO2 needed to achieve zero emissions by 2035.	EMBER (2023), own calculations
4.2: carbon intensity of electricity (gCO2e/kWh), trend	Insufficient	The carbon intensity of electricity in Germany is 420 gCO2/kWh, which is higher than the OECD average of 373 gCO2/kWh. Although it is decreasing, the rate of decline is slower than that of the OECD.	EMBER (2023), own calculations
5. Share of fossil fuel-based power generation (%)	Partially sufficient	The share of fossil-fuel-based electricity is also decreasing, but at a yearly rate of −1.23%, which is below the required benchmark of −3.81% to achieve zero fossil-fuel electricity by 2035.	EMBER (2023), own calculations
C) Phase-in of zero-carbon technologies			
6.1: LCOE (USD/kWh), national trend; solar PV.	Sufficient	The average LCOE of solar PV decreased from USD 0.101/kwh in 2017 to USD 0.08/kwh in 2022, making it cheaper than the LCOE from new fossil-fuel plants.	IRENA (2024) Kost et al. (2021)
6.2: LCOE (USD/kWh), national trend; wind power.	Sufficient	The average LCOE for onshore wind decreased from USD 0.08/kWh in 2017 to USD 0.05/kWh in 2022, also making it more economical than new fossil-fuel plants. In 2022, the average LCOE for new offshore wind was 0.078 USD/kWh.	IRENA (2024); Kost et al. (2021)
7.1: Capacity added (GW/year) trend; average for solar and wind power	Partially sufficient	Between 2018 and 2022, the average yearly new installed solar and wind capacity was 6.8 GW. However, to meet the national capacity targets for 2030, an annual installation rate of 28.4 GW is required. The current yearly rate is low but showing an upward trend (Fig. 16).	EMBER (2023), own calculations
7.2: Share of renewables in electricity generation (%), trend; average for RE technologies	Insufficient	The share of RE generation grew by an average of 2.1% per year between 2017 and 2022. This growth rate is more than 20% lower than the minimum required annual growth rate of 4.2% to achieve the target of 100% renewable energy by 2035.	EMBER (2023), own calculations
D) Infrastructure			
8: Curtailment of RE (%), trend	Insufficient	Curtailment of RE generation has increased from 5,403 GWh in 2018 to 8,071 GWh in 2022 due to insufficient electricity grid capacity.	(Bundesnetzagentur & Bundeskartellamt, 2020, 2021, 2022a, 2022b, 2023)
9.1: Transmission lines (km)	Insufficient	The development of transmission lines has stagnated, with the length decreasing slightly from 37.5 thousand km in 2017 to 36.3 thousand km in 2022.	(Bundesnetzagentur & Bundeskartellamt, 2020, 2021, 2022a, 2022b, 2023)
9.2: Distribution lines (km), trend	Partially sufficient	The distribution grid expanded slowly, growing from 1.8 million km in 2017 to 2.2 million km in 2022. There is no official target for grid expansion, and it is unclear if the growth rate is sufficient for achieving a zero-emissions system, thus we evaluate it as partially insufficient.	(Bundesnetzagentur & Bundeskartellamt, 2020, 2021, 2022a, 2022b, 2023)
9.3: Energy storage as a % of variable renewable capacity (%)	Partially sufficient	In 2023, the share of energy storage (operational and under construction) was 7.2% (9.6 GW), which is lower than the EU average of 13%. The primary source of energy storage is pumped hydro, followed by electrical and mechanical storage. An additional 7.6 GW of energy storage, including hydrogen production, is currently in development.	ENERDATA (2024)

E) Market regulation			
10: Negative prices for electricity (EUR/MWh); trend	Insufficient	Negative prices are not decreasing; they occurred for 211 hours in 2019, costing €3.6/MWh, and for 351 hours in 2023, costing €4.9/MWh on average.	EMBER (2023)
11: Subsidies from coal and natural gas (US$); trend	Insufficient	Subsidies for coal decreased from USD 4,570 million in 2017 to USD 3,370 million in 2021. Subsidies for natural gas slightly decreased from USD 921 million in 2017 to USD 779 million in 2021. However, in 2022, subsidies for natural gas increased significantly (to around USD 10 billion) due to the energy crisis.	OECD and IISD (2024)
12: Average time for permission process, wind power (months)	Partially sufficient	Permitting time for wind power installations was 40 months for capacity installed in 2021, which is higher than the EU recommendation of 25 months (Renewable Energy Directive 2018/2001) but lower than in most EU countries with available data (e.g., 65 months in France and 120 months in Croatia).	Fox et al. (2022)
13: Support to the expansion of renewable energy	Sufficient	The 2023 Special Eurobarometer on climate change confirmed that a clear majority of Germans (85%) support public policies encouraging the transition to renewable energy sources, consistent with previous surveys.	European Commission (2023)

5.1.2 Road transport sector

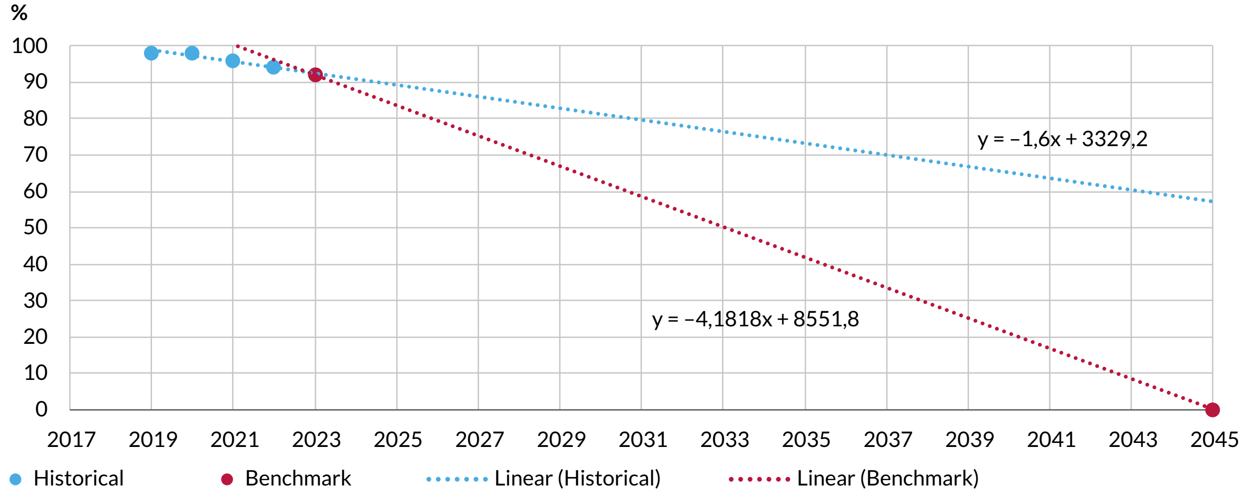
Germany's progress in transitioning road transport to zero CO2 emissions is assessed as partially insufficient to insufficient. Out of the evaluated metrics, five were deemed insufficient, five were partially insufficient, and only two sufficient (see Table 8).

Achieving the 1.5-degree temperature target of the Paris Agreement requires decarbonizing transport by around 2045 or earlier (Plötz et al., 2021). Specifically for road transport, this necessitates implementing strategies to ensure 100% of new car sales are zero-emission and for phasing out remaining ICE cars. While Germany has developed a transition strategy for the transport sector, it still falls short of being fully adequate compared to scenarios aligning with the 1.5-degree target. Notably, the country aims for 100% of car and light-duty vehicle sales to be CO2 emission-free by 2035 (European Parliament, 2023). However, independent modeling suggests this deadline should be advanced to 2030 (Climate Analytics, 2023b). Additionally, there is no clear target or strategy for phasing out remaining ICE cars.

Germany has a strategy for deploying public chargers for electromobility, although it seems too low to meet long-term targets. By 2028, the government intends for every gas station to have at least one fast charger, and public charging points should be available at every public parking area. Models indicate that by 2050, 40 million charging stations will be needed, with 10% being public chargers (Auer, 2019). However, the "Ladeinfrastruktur II" master plan (2023) aims to install only 1 million public chargers by 2030, which is far below a linear trajectory toward the target.

From 2016 to 2021, emissions decreased at nearly the required rate (–3.6% per year) for zero emissions by 2045, which is why Germany receives a rating of "sufficient" on this indicator. However, the 14% decrease in emissions during that period is partially explained by a temporary dip related to the COVID-19 pandemic. On the negative side, the share of ICE vehicles in the total car fleet is decreasing (from 98% in 2019 to 92% in 2023) but at a reduction rate (–1.6% per year) far below the linear path (–4.2%) toward the 2045 benchmark (Figure 18). Furthermore, the share of passenger transport by cars in total passenger transport has not decreased in the last five years but has actually increased by 5%, indicating that this variable is moving in the wrong direction. This suggests a failure in developing alternative modes of transportation, which warrants further investigation. These divergent trends highlight the importance of a framework that considers more than just the direct metric of "CO2 emissions reduction."

Figure 18 | Share of ICE cars in total passenger cars



Source: Statista (2024).

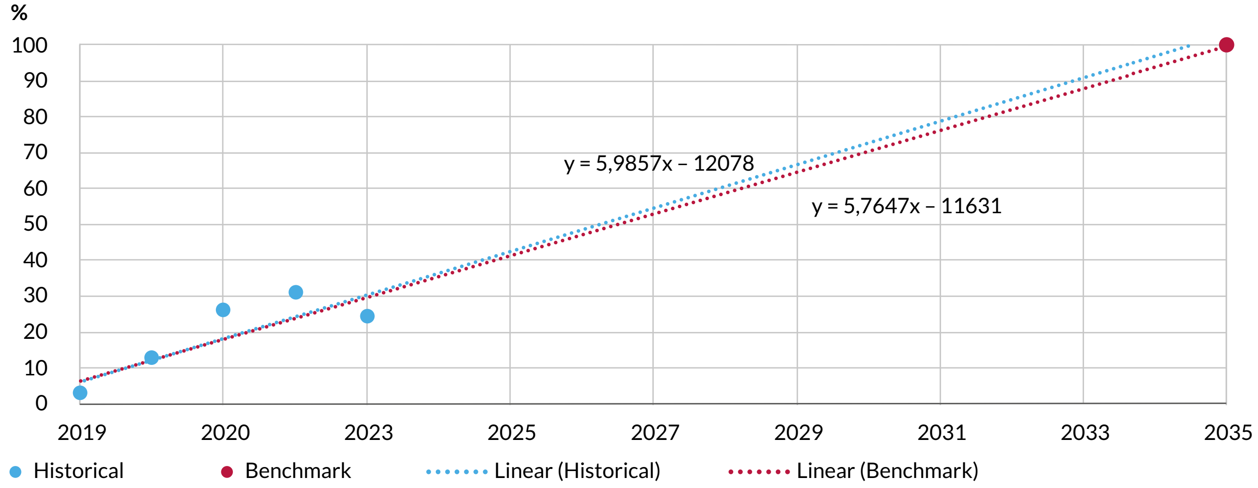
The share of EVs in total car sales reached 31% in 2022 when including plug-in hybrid vehicles but decreased to 24.5% in 2023 (Table 6). This share marks a significant increase compared to only 3% in 2019 and is almost aligned with linear progress toward achieving 100% sales of zero-emission vehicles by 2035. When considering only fully electric cars, the share in 2023 sales was 18.4%. The price of EVs in Germany has remained largely unchanged over the past five years, with an average price of €61,000 in 2019 and €60,000 in 2023, significantly higher than the average price for medium ICE cars, which was €25,000 in 2023. The high upfront cost of EVs raises doubts about the possibility of increasing EV sales in the coming years, particularly when most low- and middle-income families should enter the market. Despite the increasing availability of different models, the price gap between the cheapest ICE car and an EV remains significant.

Table 6 | Car sales share in Germany (first-time registered vehicles)

Car sales	2019	2020	2021	2022	2023
Full electric	1.8%	6.7%	13.6%	17.7%	18.4%
Hybrid	1.3%	6.9%	12.4%	13.7%	6.2%
Hybrid + electric	3.1%	13.6%	26%	31.4%	24.6%

Source: Statista (2024).

Figure 19 | Share of EVs (including plug-in hybrid) in total car sales, Germany



Source: IEA (2023).

The current state of infrastructure, measured by the ratio of battery-electric vehicles to public charging points, is insufficient. The European Commission recommends one charger for every 10 EVs (including plug-in hybrids), but Germany has only one charger for every 25.8 EVs, compared to the EU average of one charger for every 15.5 EVs (in 2021). This infrastructure inadequacy fails to meet the demand from the increasing number of EVs on German roads. Despite the increasing installation of new chargers in Germany, such as 17,700 in 2022 (Table 7), it still falls short of the required numbers to meet targets for 2030–2050, by which approximately 124,000 new chargers per year will need to be installed.

Progress on phasing out subsidies for fossil fuels in the car sector is evaluated as insufficient. Subsidies for fossil fuels in the car sector, such as the reduced tax rate for diesel compared to petrol, have increased over the period between 2014 and 2018. The lower tax rate for diesel led to lower tax revenues of €7.8 billion in 2014, rising to €8.2 billion in both 2016 and 2018. While there is no more recent data, the regulation remains in place. Additionally, there are two undifferentiated subsidies that need to be considered. First, the company car tax allowance, which allows the private use of company cars by applying a flat-rate tax through a provision in the income tax law, making it much cheaper compared to privately owning and using a car (Burger et al., 2021). The Federal Environment Agency estimates revenue losses of “at least” €3.1 billion annually here (ibid.: 146). Second, the commuter allowance subsidizes commuting to the workplace based on distance. Although it also applies to commuting by public transport or other modes of transportation, it is most substantial for cars, where the annual allowance is not capped, and most commuters travel by car.

Progress on Germany’s transition to zero-emissions road transport is clearly insufficient, and more effort is needed to both reduce the share of cars and electrify the remaining fleet.

Table 7 | Number of new EV charging points per year, Germany

2018	2019	2020	2021	2022
8.700	10.400	13.300	16.100	17.700

Source: IEA (2023).

Table 8 | Assessment results – Road transport, Germany

Variable/metric	Evaluation	Explanation	Sources
A) Policy targets			
1. Target for ICE vehicles phase-out (year).	**Insufficient**	Currently, there is no national target for achieving zero emissions in transportation.	
2. Target share of zero-emission vehicles in total car sales (%)	**Partially sufficient**	The goal is to ensure that 100% of car and light-duty vehicle sales are CO2 emission-free by 2035. Reference: To meet the 1.5-degree target in the transport sector, 100% of car sales need to be zero-emission by 2030. The current target is not ambitious enough.	European Parliament (2023); Teske et al. (2022): The Internal Combustion Engine Bubble.
3. Target for number of public charging points (Nb per EV)	**Partially sufficient**	The target is to have 1 million public chargers by 2030. Reference: Calculations for 2050 indicate that 4 million public chargers will be needed for a 100% zero-emission transport system. Following a linear progression from the 2030 target, Germany will have nearly 3 million chargers by 2050. There is a target, but it is not aligned with the requirements for a zero-emissions transport pathway.	Masterplan Ladeinfrastruktur II der Bundesregierung (2022); Auer (2019).
B) Phase-out of carbon-intensive technologies			
4. GHG emissions of road transport (Mt CO2e), trend	**Sufficient**	Trend: A reduction of 14.42 million tons of CO2 (14%) was achieved between 2016 and 2021. During this period, emissions decreased at almost the same rate (–3.6% per year) as the necessary reduction (–3.65% per year) to achieve zero emissions by 2045.	United Nations Climate Change (2023); Own calculation.
5. Share of ICE in total cars (%), trend	**Insufficient**	2023: 92% 2021: 96% 2019: 98% From 2019 to 2023, the annual decrease in the share of ICE cars was –1.6%, significantly lower than the required annual decrease of –4.2% to reach zero emissions by 2045. It decreased by only six percentage points.	Statista (2024f): Anzahl der PKW in DE nach Kraftstoffart 2017–2023; Own calculation.
6. Share of passenger transport by cars (%), trend	**Insufficient**	Trend: An increase of 5% in passenger transport by car from 2016 to 2021. EU: +3% The overall trend for passenger transport by car is increasing across the EU; likely influenced by the COVID-19 pandemic. EU: +3%	Eurostat (2023a): Modal split of inland passenger transport.
C) Phase-in of zero-carbon technologies			
7. Average purchase prices of EVs and ICE cars (EUR); trend	**Partially sufficient**	The average cost of an ICE medium car (€25,000) is significantly cheaper than the average EV (€60,100). Since 2019, the price of EVs has decreased by only 1.5%.	(Statista, 2024b, 2024f).
8.1 Share of EVs (including plug-in hybrid) in total car sales (%); trend	**Sufficient**	2022: 31% 2023: 24.5% The share of EVs in total car sales increased by 5.9% annually from 2019 to 2023, slightly exceeding the required rate of 5.7% to reach the 100% target by 2035. However, the share declined in 2023 compared to 2022, raising concerns about maintaining the necessary pace in the coming years.	IEA (2023b); Own calculation.

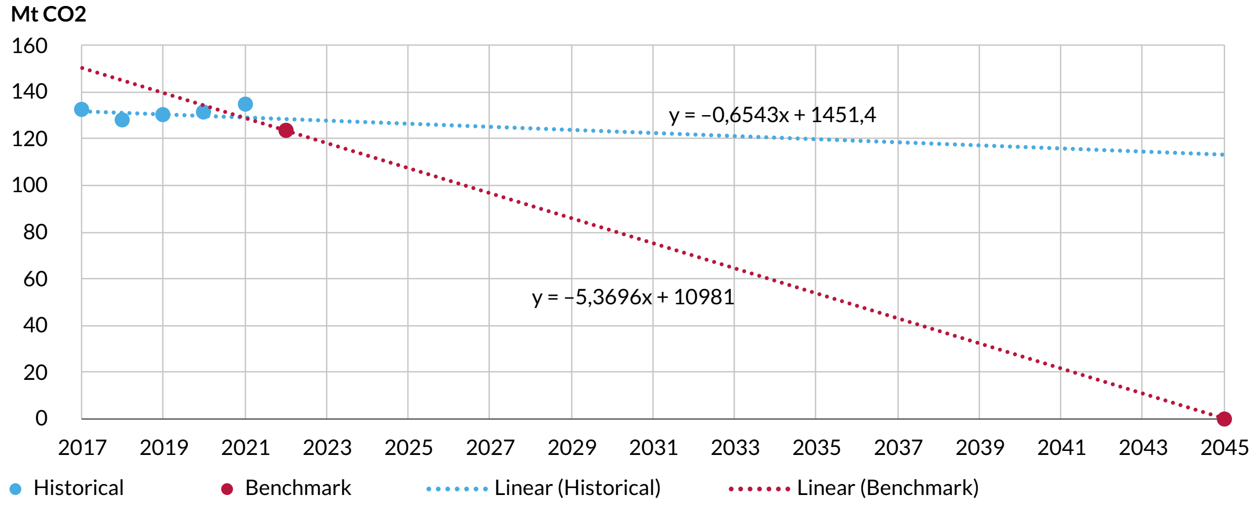
8.2 Share of EVs (including plug-in hybrid) in total car fleet (%); trend	Partially sufficient	2022: 4% Reference: To meet the 2050 target of 75% EVs in the German car stock (considering biofuels, hydrogen, and other zero-emission vehicles), there needs to be at least 10% EVs in the 2022 car stock. As of 2022, the share of EVs is only 4%, but it is still increasing.	IEA (2023b) Climate Analytics (2023b): 1.5°C national pathway explorer Germany; Own calculation.
D) Infrastructure			
9. Public charging points density (Nb per EV)	Insufficient	2021: 25.8 EVs per public charger EU average for 2021: 15.5 The EU guideline recommends one public charger for every 10 EVs.	IEA (2023b): Trends in charging infrastructure; Ref: EU-guideline 2014/94/EU (23).
10. Public charging points installed per year; trend (Nb/year)	Partially sufficient	17,700 chargers installed in 2022 By 2050, a total of 4 million public chargers will be needed. To follow a linear path toward this goal, there should have been an annual installation of 124,000 chargers since 2018. Although the installation rate of public chargers is increasing, it remains below the required linear path.	(IEA, 2023b): EV charging points 2017–2022 worldwide by country: Auer (2019); Own calculation.
E) Market regulation			
11. Subsidies for ICE cars (€); trend	Insufficient	Fossil fuel subsidies are not decreasing. In fact, subsidies, particularly tax reductions for diesel, increased from €5.2 billion in 2012 to €6 billion in 2018. More recent data is not available.	Burger et al. (2021).

5.1.3 Heating sector

The assessment of transition progress in the heating sector reveals a mixed picture, with both successes and areas needing improvement: six metrics are rated sufficient, six insufficient, and two partially insufficient. For the remaining variables, either no data is available or an evaluation was not possible (Table 9).

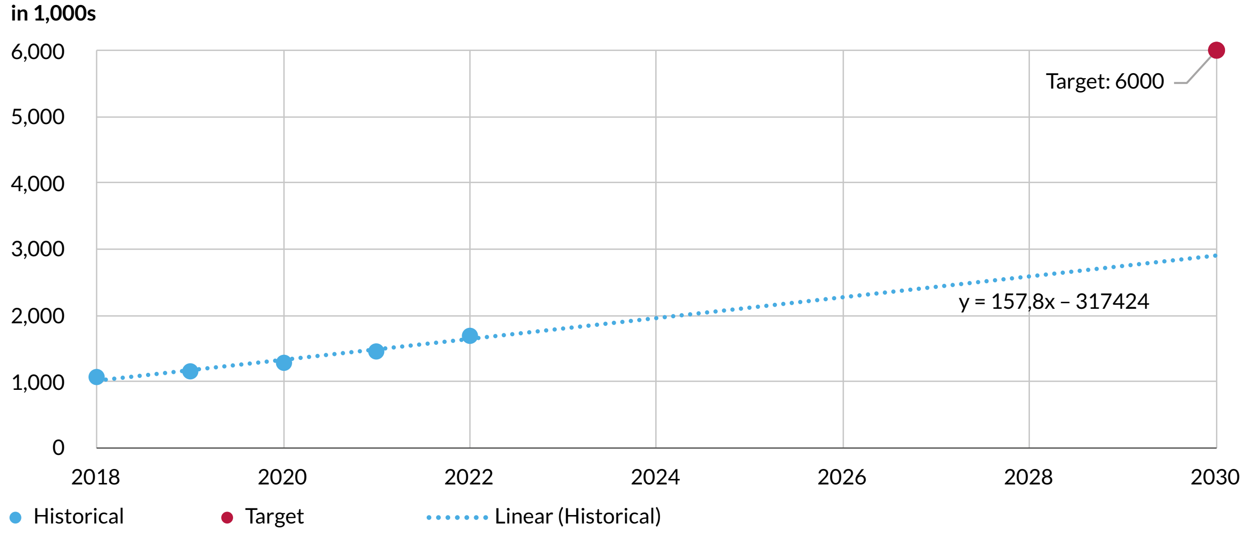
Targets for phasing out oil and gas heating systems remain insufficient, as no specific targets have been set. However, the targets for installing new heat pumps are promising, with ambitious goals set for both the short and mid-term (by 2030). The target for the share of zero-carbon heating is deemed sufficient, aligning in principle with broader climate neutrality strategies, but it will need to be increased to 100% later. Additionally,

Figure 20 | CO2 emissions from direct building energy use, Germany



Source: EDGAR (2023).

Figure 21 | Number of heat pumps in operation in Germany (2018–2022)



Source: Statista (2024),

there is a lack of targets for buildings with energy storage, indicating a potential gap in strategy.

In terms of phasing out carbon-intensive technologies, while CO2 emissions from direct building energy use decreased from 2017 to 2022, the annual reduction (–0.65 MtCO2) is significantly less than needed to achieve zero emissions by 2045 (Figure 20). Moreover, the increase in natural gas consumption (+14% from 2017 to 2021) poses a challenge to reaching emission reduction targets.

In the phase-in of zero-carbon technologies, the total purchase cost of heat pumps remains high compared to gas boilers, although costs have decreased over time. Additionally, while the installation of new heat pumps has increased significantly in recent years (+140% in 2018–2022), it still lags behind the linear path required to meet national targets (Figure 21). The composition of residential total final energy consumption by source also highlights the need for a faster increase in renewable energy/electricity to achieve emission reduction goals.

In terms of building infrastructure, there has been a sufficient reduction in energy consumed for heating per square meter over the past few years, exceeding European benchmarks. This indicates progress in improving energy efficiency in buildings that must be continued in the coming years.

Institutional efforts, such as the rollout of smart meters and tariffs by 2025–2030, show promise in enhancing energy efficiency and adding flexibility to the system. Indeed, the introduction of a new law in 2023 mandating a large-scale rollout of smart meters alongside deadlines for full implementation demonstrates a proactive approach to modernizing energy infrastructure. Furthermore, subsidies for fossil fuel heating investments have been phased out in 2023, aligning with broader decarbonization objectives.

In conclusion, while there are indicators where progress is deemed sufficient, significant challenges and opportunities for improvement remain in transitioning to zero-emissions heating. Addressing gaps in targets, accelerating the adoption of heat pumps, and enhancing institutional support will be crucial in achieving long-term climate goals.

Table 9 | Assessment results – Heating, Germany

Variable/metric	Evaluation	Explanation	Sources
A) Policy targets			
1: Targets for phase-out oil and gas heating systems (year).	Insufficient	No target specified.	“Gebäudeenergiegesetz” (2023).
2.1: Target for new heat pumps (Nb)	Sufficient	2024: Install 500,000 heat pumps per year. 2030: Reach a total of 6 million heat pumps. Reference scenarios (Pronos et al., 2021) indicate achieving 6 million heat pumps by 2030.	OECD and IEA (2022) The Future of Heat Pumps; Prognos et al. (2020).
2.2: Target for share of zero-carbon heating (%).	Sufficient	2024: Ensure 65% renewable energy heating in new homes constructed in new development areas. 2026: All new buildings must have a heating system with at least 65% renewable energy. 2026 (2028): In cities with more (or less) than 100,000 existing buildings, heating systems must have at least 65% renewable energy.	“Gebäudeenergiegesetz” (2023).
3.1: Target for energy consumed for heating per m²	Sufficient	Germany follows EU targets: 2030: Energy efficiency for all new and deeply renovated buildings: Mediterranean climatic zone: 60 kWh/m² Nordic climatic zone: 75 kWh/m² Current energy consumption: One- and two-family houses: 80–85 kWh/m² Non-residential buildings: 60–65 kWh/m² Projected energy consumption by 2050 through renovation: One- and two-family houses: 60 kWh/m² Non-residential buildings: 40–45 kWh/m² All new buildings: 25 kWh/m²	Climate Analytics; New Climate Institute (2023); Prognos et al. (2020).
3.2: Target for building renovation per year (%)	Sufficient	Germany follows the EU target to “at least double the annual energy renovation rate of residential and non-residential buildings by 2030 and to foster deep energy renovations.”	EU: Renovation Wave communication COM 2020 662 final.
3.3: Target for buildings with thermal energy storage (%).	Insufficient	No target specified.	
B) Phase-out of carbon-intensive technologies			
4: CO2 emissions from direct building energy use (Mt CO2e), trend	Insufficient	In 2017, CO2 emissions were 132.4 million tons (mtCO2), and by 2022, they had decreased to 123.5 mtCO2, representing a reduction of 6.7%. This equates to an average annual decrease of 0.65 mtCO2 per year. However, to reach zero emissions by 2045, a minimum annual reduction of 5.4 mtCO2 is required, indicating a shortfall of over 85% compared to the necessary rate.	European-Comission and Joint-Research-Centre (2024): EDGAR database; Climate Analytics, 2023a; Velten, Calipel, et al. (2023).
5: Phase-out oil and gas heating systems	Insufficient	Reduction in fossil-fuel consumption (2017–2021): Natural gas: Increased by 14% to 1,052,063 TJ in 2021. Oil products: Decreased by 31% to 330,868 TJ in 2021. Coal: Decreased by 33% to 14,574 TJ in 2021. The significant increase in natural gas consumption is incompatible with the zero-emissions target by 2045.	IEA (2023d): Evolution of residential total final consumption by source.

C) Phase-in of zero-carbon technologies			
6: Heat pumps total purchase cost (EUR)	**Insufficient**	Acquisition costs in Germany (2022, Statista Data): Heat pump: €18,750 – €37,500 Gas boiler: €7,500 – €12,500 Total investment cost in Germany (2021, IEA Data): Air-air heat pump: USD 9,100 Gas boiler: USD 5,100	Statista (2023); IEA (2021b): Residential Heat Economics Calculator.
7.1: Installed (new) heat pumps; trend	**Partially sufficient**	2018: 97,857 units 2019: 102,270 units 2021: 154,000 units 2022: 236,000 units To reach the target of 6 million heat pumps by 2030, 500,000 heat pumps need to be installed per year. Although installations increased significantly by 140% from 2018 to 2022, the current rate is still below the required linear path.	EHPA (2023): Heat Pumps in Europe; Observ'ER (2020): Heat Pumps Barometer.
7.2: Share of buildings with climate-neutral heating (%), trend.	**Insufficient**	Data on the exact percentage of buildings with climate-neutral heating is not available. However, in 2021, the final energy consumption in the residential sector was: Natural gas: 44% Oil products: 14% Coal: 1% Electricity: 21% Biofuels: 12% District heating: 8% Wind and solar: 1% From 2016 to 2021, the share of renewable sources (including electricity) in the residential sector increased by only 3%, which is insufficient to achieve zero emissions by 2045.	IEA (2023d): Evolution of residential total final consumption by source.
D) Infrastructure			
8.1: Energy consumed for heating per square meter (kWh/m^2), trend	**Sufficient**	Residential energy intensity 2016: 172 kWh/m^2 2021: 161 kWh/m^2 (a reduction of 6.4%) The average reduction trend from 2016 to 2021 is 2.2 kWh/m^2 per year, which is above the EU benchmark of –1.3 kWh/m^2 per year (ECNO). 2016: 172 kWh/m^2 2021: 161 kWh/m^2 (a reduction of 6.4%) The average reduction trend from 2016 to 2021 is 2.2 kWh/m^2 per year, which is above the EU benchmark of –1.3 kWh/m^2 per year (ECNO).	IEA (2023d): Residential Energy intensity per country 2000–2020; IEA (2023d): Residential Energy intensity per country 2000–2020; Velten, Calipel, et al. (2023).
8.2: Homes treated with (high) energy efficiency measures (thousands/year), trend	Evaluation not possible	Data not available.	
8.3: Share of households with energy storage (%), trend.	Evaluation not possible	Battery Energy Storage Systems (BESS): A total of 270,000 BESS units have been installed, representing 1.4% of the 19.5 million residential buildings equipped with a BESS.	Solar Power Europe (2021): European Market Outlook for residential energy storage.

		E) Market regulation	
9: Share of buildings using smart tariffs/ smart meters (%)	**Insufficient**	The share of homes equipped with smart meters is extremely low (0.3% in 2021). A new law, which came into force in the spring of 2023, facilitates the immediate start of a large-scale smart metering rollout. This rollout will become mandatory from 2025 and includes a roadmap with binding deadlines to achieve near-complete coverage by 2030 (20% rollout by the end of 2025, 50% by 2028 and 95% by 2030). Starting in 2025, all electricity suppliers will be required to offer dynamic tariffs, regardless of the number of customers. Currently, only larger suppliers with more than 100,000 customers are required to offer dynamic tariffs with smart metering.	Bundesnetzagentur and Bundeskartellamt (2022b).
10: Subsidies for investment in fossil-fuel heating (EUR); trend	**Sufficient**	As of 2023 all support schemes exclude fossil fuel heating.	Williams et al. (2023): Subsidies for fossil heating appliances in the EU and UK.

5.2 | Norway

5.2.1 Electricity sector

Norway's pathway toward zero-carbon electricity and increasing electrification of its economy marks a significant shift in its energy landscape, with substantial progress observed across various indicators. Unlike the other countries analyzed, Norway's electricity production is already almost completely decarbonized. The primary challenge now is to continue expanding the power system and integrating new flexibility to meet the rising demand resulting from the rapid electrification of other sectors like transport, heating, and partially industry. Our evaluation shows ten indicators as sufficient, five as partially insufficient, and none as insufficient. For the remaining metrics, either the evaluation was not possible, or no data was publicly available (Table 13).

Norway has successfully phased out coal from its electricity mix since 2023, marking a pivotal milestone in its transition to cleaner energy sources. Ambitious targets for renewable energy capacity and generation share by 2030 have been set, representing nearly 100% of projected generation/capacity and encompassing various renewable technologies (Table 10). Additionally, in May 2022, the government presented a large-scale plan for offshore wind, targeting 30 GW of offshore wind capacity by 2040, nearly matching Norway's current power generation capacity (IEA, 2022b). This positions Norway to become a significant electricity exporter to Europe, enhancing supply security.

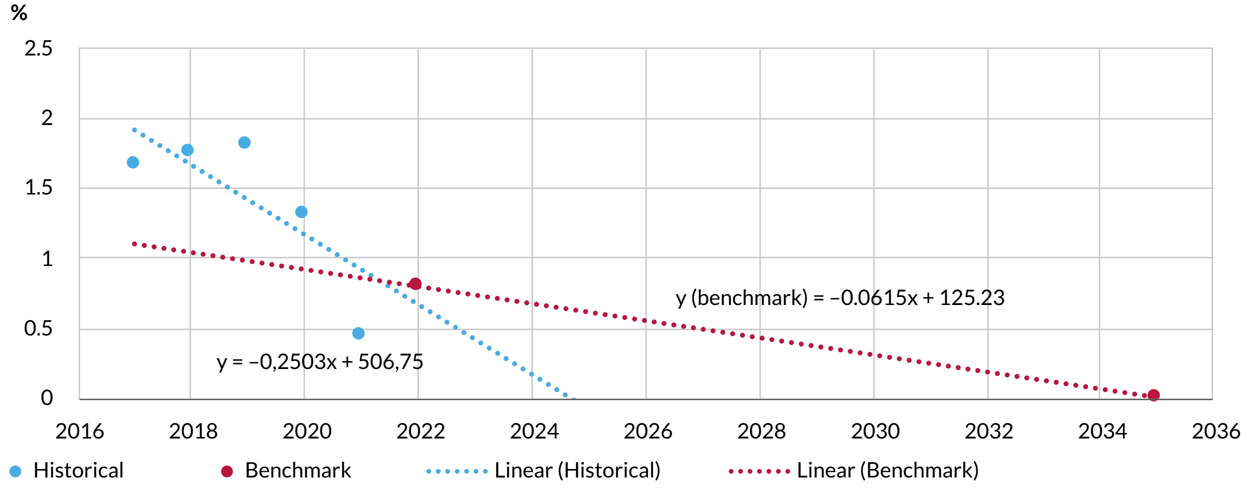
While formal targets for transmission and distribution network expansion have yet to be established, initiatives outlined in the 2023 System Development Plan emphasize the importance of enhancing grid infrastructure to accommodate the growing share of renewable energy sources. These measures aim to ensure that

Table 10 | Renewable energy targets by 2030, Norway

	Total capacity (GW)	Generation (Twh)	Generation (%)
Hydropower	34.69	148.79	82.98
Bioenergy	0.19	1	0.56
Wind	9.17	21.17	11.81
Solar	5.39	5.99	3.34

Source IRENA (2024).

Figure 22 | Share of fossil fuels in the electricity mix, Norway



Source: EMBER (2023).

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the transmission grid has sufficient capacity to support zero-emission objectives by 2050. Similarly, while specific targets for electricity storage are lacking, efforts highlighted in the System Development Plan underscore the critical role of storage capacity in enabling the transition to zero emissions by 2050. Investments in storage technologies will be essential to mitigate intermittency and ensure grid stability, facilitating the integration of renewables into the energy mix.

From 2017 to 2022, CO2 emissions decreased by 14%, with an average annual reduction of 0.13 MtCO2, slightly below the necessary benchmark of 0.26 MtCO2 for zero emissions by 2035. However, given its already low emission level, Norway could quickly eliminate the remaining emissions. The indicator “share of fossil fuels for electricity generation” shows that, following recent trends, fossil fuels could be completely phased out in the coming years (Figure 22). The carbon intensity of electricity in Norway (26 gCO2/kWh) is substantially lower than in the OECD (373 gCO2/kWh) and continues to decrease.

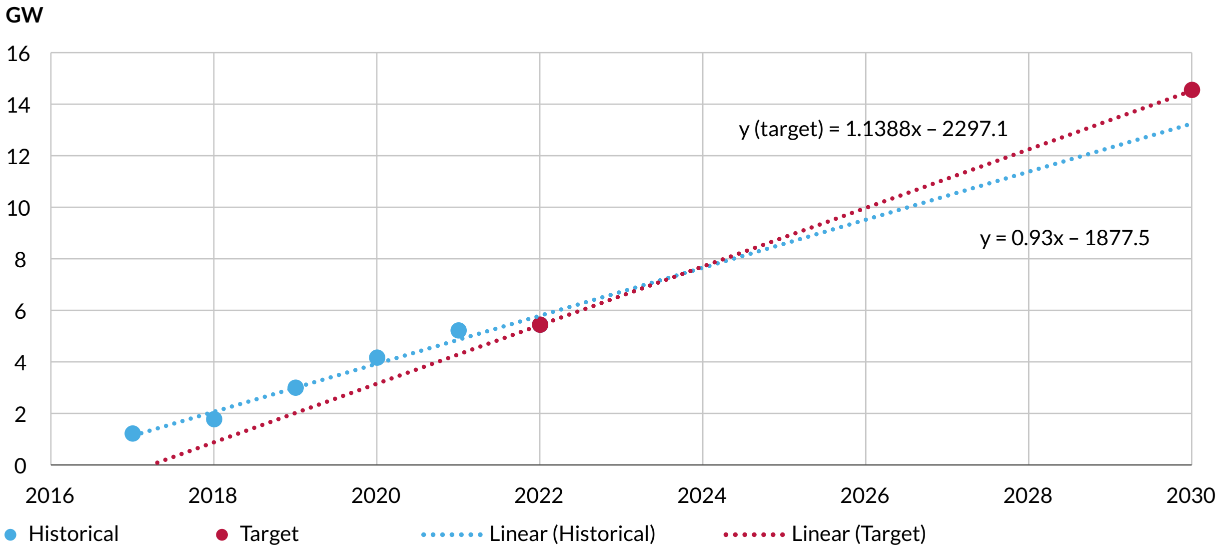
Publicly available data on the LCOE for different sources is not available, but it is not considered a barrier for investment, given that new fossil fuel power plants and nuclear power in Norway are no longer options. Different renewable energy sources now compete among themselves rather than against fossil fuel generation. As Table 11 shows, hydropower is – and will remain – the dominant source. However, the relative importance of other renewable energy sources, particularly wind, is rising, adding more resilience to the power system. The new installed solar and wind power capacity has increased close to the benchmark for the 2030 capacity targets (Figure 23). Capacity addition will need to accelerate, considering the increasing demand for electricity in the coming years to supply the rapid electrification of other economic sectors. Norway has faced strong local opposition to onshore wind power projects due to perceived impacts on landscapes and ecology. Following a pause on new licenses for onshore wind in 2019, the government announced in April 2022 that it would resume licensing for new projects where local municipalities are supportive (IEA, 2022b). The government is also working on different measures to operationalize the targets for offshore wind generation.

Table 11 | Electricity generation by source, Norway

Energy (GWh)	2017	2018	2019	2020	2021	2022	(%)
Coal/Lignite	186	178	163	182	192	224	0.2%
Gas	2,060	2,180	2,056	1,605	305	1,146	0.8%
Oil	489	436	341	220	400	241	0.2%
Biomass	455	375	451	434	403	402	0.3%
Hydro	143,112	139,714	126,030	142,471	144,339	129,408	88.4%
Wind	2,854	3,877	5,525	9,913	11,769	14,811	10.1%
Solar	0	2	13	136	175	175	0.1%
Total	149,156	146,762	134,579	154,961	157,583	146,407	

Source ENERDATA (2024).

Figure 23 | Progress in renewable energy targets, Norway

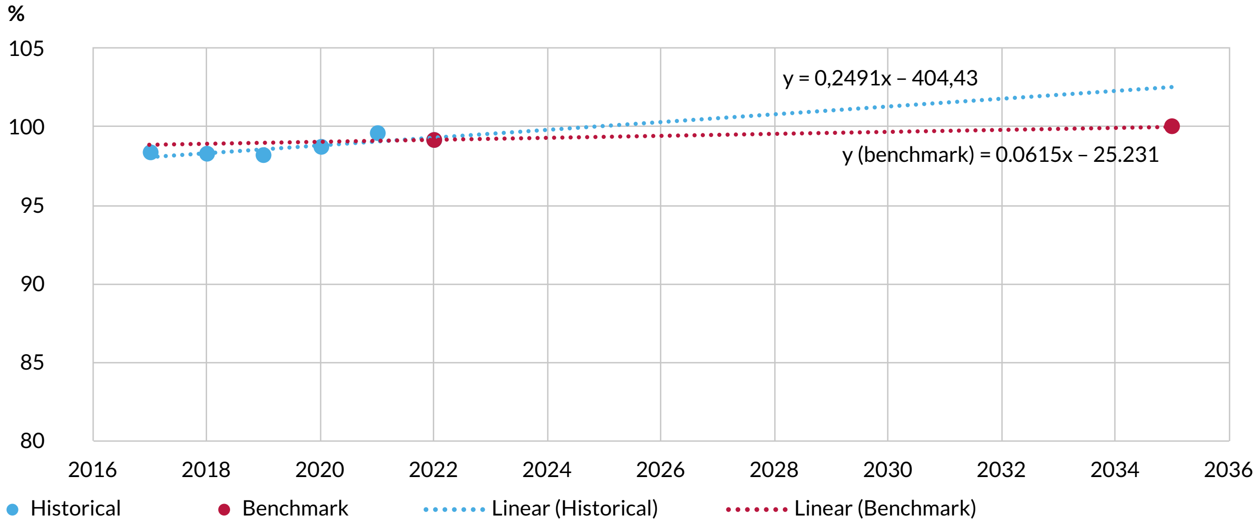


Source: EMBER (2023).

The state of electricity grids is generally good, with no reported curtailment of renewable production. However, the grid must continue developing and integrating new flexibility options to accommodate increasing renewable generation. Statnett, owned by the Ministry of Petroleum and Energy, is Norway's sole TSO and owns 98% of the transmission grid. It has a sizable transmission network, attributable to Norway's geographic length and the locations of its hydropower stations. The transmission network has almost doubled in the last 5 years (2018–2023), growing from 6,850 to 13,250 km (circuit length ≥ 220kv). Additionally, Norway has been expanding its interconnections with neighboring countries, which stood at 8.85 GW in 2022. This expansion is crucial for domestic energy security and contributes to the security of the entire European network.

Negative electricity prices in Norway have been uncommon but increased in 2022–2023. While consumers may appreciate the occasional negative prices – such as in September 2023 when residents from Oslo and Bergen enjoyed several hours of free electricity – it highlights the need for more storage capacity and flexibility options to accommodate increasing variable electricity generation. Subsidies to coal have been almost completely phased out, and subsidies to natural gas have remained minimal without an increase during the 2022 energy crisis (Table 12).

Figure 24 | Progress toward zero-emissions electricity by 2035, Norway



Source: EMBER (2023).

Table 12 | Subsidies for coal and natural gas in Norway (2017–2022; in millions of USD, nominal)

	2017	2018	2019	2020	2021	2022
Coal	17	0	2	0	5	5
Natural gas	79	50	41	35	41	43

Source: (OECD & IISD, 2024).

In summary, Norway's transition to zero-carbon electricity is well underway, with significant achievements in phasing out coal, expanding renewable energy capacity, and reducing carbon emissions. Continued efforts in infrastructure development, digitalization to enhance grid flexibility, and wind energy deployment will be essential to sustain and accelerate this positive trajectory.

Table 13 | Assessment results – Electricity, Norway

Variable /Metric	Evaluation	Explanation	Sources
A) Policy targets			
1. Targets for phase-out fossil fuel-based power generation (year)	Sufficient	No coal in the electricity mix since 2023, when the last small coal power plant was closed. Remaining gas plants are only used for emergency situations.	Jonassen (2023).
2. Targets for renewable electricity capacity and/or generation share (%, year)	Sufficient	The renewable energy generation targets for capacity and generation by 2030 represent almost 100% of projected generation/capacity. They are desegregated by technology. New target for offshore wind by 2040: 30GW.	IRENA (2024); IEA (2022b).
3.1. Targets for transmission development national (km))	Partially sufficient	For solar and wind combined, the transmission grids targets developed by the TSO are based on technology capacities planned (11.2 GW by 2030) that are less ambitious than the latest national target for solar and wind (14.4 GW). The 2023 System Development Plan intends investment for NOK 100–150 billion (EUR 10–15 billion) during 2023–2032 (up from NOK 70 in the previous decade). The plan aims to allow the connection of 15 GW of offshore wind by 2040.	EMBER (2023); (IEA, 2022b); Statnett (2023).
3.2 Targets for distribution network (km)	Partially sufficient	No official targets but, the 2023 System Development Plan includes measures to assure that "the transmission grid must have sufficient capacity to enable zero emissions by 2050."	Statnett (2023).
3.3 Targets for electricity storage (GW or GWh)	Partially sufficient	No official targets but, the 2023 System Development Plan includes measures to assure that "the transmission grid must have sufficient capacity to enable zero emissions by 2050."	Statnett (2023).
B) Phase-out of carbon-intensive technologies			
4.1: CO2 emissions of electricity generation (Mt CO2e), trend	Partially sufficient	CO2 emissions from electricity in Norway decreased by 14% between 2018 and 2022. However, the average yearly reduction of –0.14 mtCO2 is below the necessary benchmark of –0.31 mtCO2 to achieve zero emissions by 2035. Given its already low emission levels, Norway could eliminate the remaining emissions relatively easily.	EMBER (2023); Own calculations.
4.2: carbon intensity of electricity (gCO2e/kWh), trend	Sufficient	The carbon intensity of electricity in Norway is 26 gCO2/kWh, significantly lower than the OECD average of 373 gCO2/kWh and the EU average, and it is decreasing.	EMBER (2023); Own calculations.
5. Share of fossil fuel-based power generation (%)	Sufficient	The share of fossil fuel generation has been decreasing at a rate of –0.25% per year from 2018 to 2022, which is compatible with phasing out fossil fuel generation completely by 2035, potentially as early as 2025/26 if the trend continues.	EMBER (2023); Own calculations.
C) Phase-in of zero-carbon technologies			
6.1: LCOE (USS/kWh), national trend; solar PV.	Evaluation not possible	Data not available	
6.2: LCOE (USS/kWh), national trend; wind power.	Evaluation not possible	Data not available	

7.1: Capacity added (GW/year) trend; average for solar and wind power	Sufficient	From 2018 to 2022, the annual new installed solar and wind capacity was 0.93 GW per year, close (<20%) to the linear benchmark of 1.1 GW needed to reach the 2030 capacity target of 14.6 GW.	EMBER (2023); Own calculations.
7.2: Share of renewables in electricity generation (%), trend; average for RE technologies	Sufficient	The share of RE generation grew by 0.25% on average between 2018 and 2022, surpassing the minimum required growth of 0.06% to achieve 100% renewables by 2035. At this rate, Norway could reach 100% renewables before the national target of 2030. In 2022, the RE share was 99%.	EMBER (2023); Own calculations.
D) Infrastructure			
8: Curtailment of RE (%), trend	Sufficient	There has been no curtailment of renewable energy generation in Norway as of 2020. To avoid curtailment in the future, dedicated grid-connected storage, vehicle-to-grid power, and interconnections with neighboring countries are critical.	Nycander et al. (2020); DNV (2023).
9.1: Transmission lines (km) and NTC (GW), trend	Sufficient	The transmission network has almost doubled in the last 5 years (2018–2023), growing from 6850 to 13250 km (circuit length ≥ 220kv). The interconnection capacity with neighboring countries was 8.85 GW in 2022 and is increasing.	IEA (2022b); ENERDATA (2024).
9.2: Distribution lines (km), trend	Evaluation not possible	Data not available.	
9.3: Energy storage as a % of variable renewable capacity (%)	Sufficient	The rate of energy storage (operational and under construction) in 2023 was 40% (2.2 GW), substantially higher than the EU average of 13%, with pumped hydro being the main source. An additional 350 MW of hydrogen storage is in development.	ENERDATA (2024).
E) Market regulation			
10: Negative prices for electricity (EUR/MWh); trend	Partially sufficient	Negative electricity prices are uncommon but increasing, with 199 hours in 2023 compared to only 7 hours in 2022 and none in 2018.	EMBER (2023).
11: Subsidies from coal and natural gas (USS); trend	Sufficient	Subsidies for coal decreased from USD 17 million in 2017 to zero in 2022. Subsidies for natural gas decreased from USD 53 million to near zero over the same time period, and they remained almost unchanged during the 2022 energy crisis.	OECD and IISD (2024).
12: Average time for permission process, wind power (months)	Evaluation not possible	Data on wind energy is available from WindEurope, but it requires a fee.	
13: Support to the expansion of renewable energy	Evaluation not possible	Data not available	

5.2.2 Transport

Norway leads the world in transitioning to a zero-emissions road transport sector. Our evaluation shows progress on seven indicators as sufficient, three as insufficient, and two as partially insufficient (Table 15).

The Norwegian National Transport Plan 2018–2029 and the Climate Plan 2021–2030 set ambitious sales targets for zero-emission vehicles:

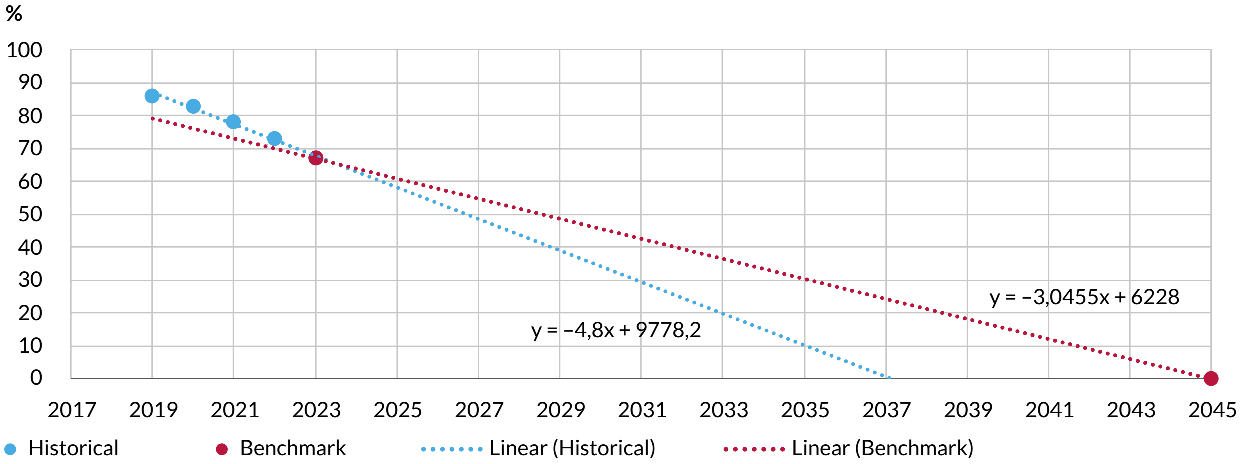
- As of 2025, new passenger cars and light vans must be zero-emission vehicles.
- Beginning in 2030, new heavy-duty vans must be zero-emission vehicles.
- As of 2025, new city buses must use zero-emissions technology or biogas.
- By 2030, 75% of new buses and 50% of new trucks must use zero-emissions technology.

The target for new passenger cars is sufficient for a transition compatible with Paris Agreement scenarios. However, Norway lacks a national target for phasing out remaining ICE vehicles. The total phase-out of the remaining ICE fleet will depend on several factors, particularly consumer decisions and market dynamics. Considering that by 2025 all new car sales should be zero-emission vehicles, and the historical lifespan of vehicles may take 15–18 more years (2035–2038). However, eliminating the remaining fleet of ICE cars could happen faster if consumers face difficulties fueling their cars or see significant advantages in switching to EVs sooner.

Regarding the charging infrastructure, the Norwegian government published a new National Charging Strategy in 2023 to expand charging infrastructure, particularly fast chargers. The strategy considers that “The charging market for light vehicles is now mature, and the infrastructure can be constructed on a commercial basis without further public subsidy” (Norwegian Ministry of Transport, 2023). Instead, it focuses on improving regulatory conditions related to land use and electricity grid access, and on making the charging infrastructure more user-friendly.

Norway is performing well in reducing CO2 emissions from transport and decreasing the share of ICE vehicles. CO2 emissions decreased from 5.3 million tCO2 in 2016 to 4.1 million tCO2 in 2021, which is above the reduction needed on a linear path to zero emissions by 2045. The share of ICE cars in the total car fleet fell from 86% in 2018 to 67% in 2022. However, the share of passenger transport by car is increasing – instead of decreasing – following a negative EU trend. It was stable at around 89% until 2019 and then increased to 93% in 2020 and 2021. More recent data will show if this trend continues or reverses post-pandemic. In response, the government set a target of zero growth in passenger transport by car in large urban areas. Additionally, under agreements with local authorities, the government is exploring options for creating low-emis-

Figure 25 | Share of ICE cars in total passenger cars, Norway



Source: Statistics Norway (2024).

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sion zones to promote sustainable transport and cleaner cities, with funds granted to finance local public transport projects (IEA, 2022b).

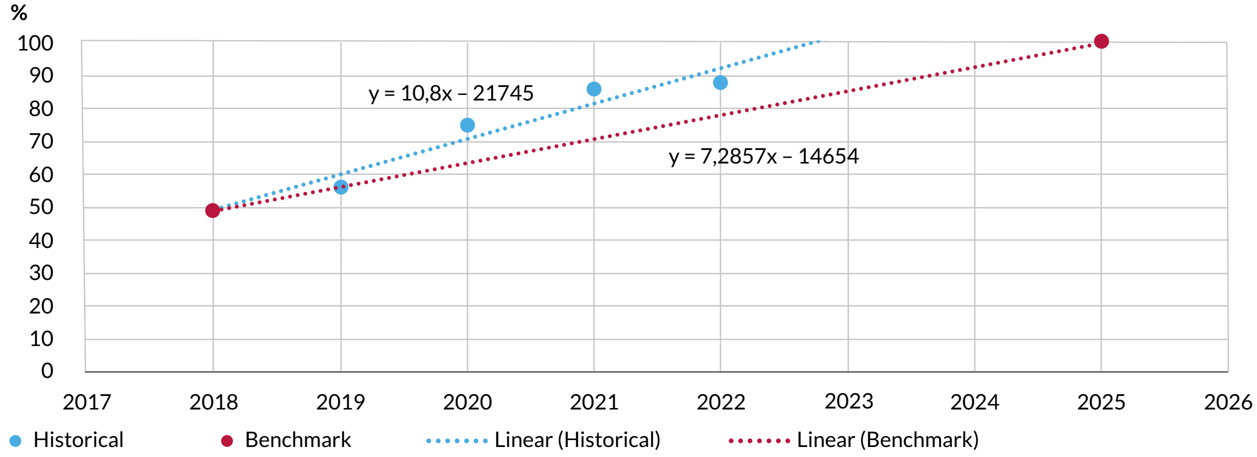
Even though the prices of EVs have decreased by 7% since 2019, the average purchase price of an EV in 2023 was 2.4 times higher than the price of a medium ICE car. Despite the relatively high prices, the sales of EVs have surged in recent years, with 79% of total car sales in 2022 being full EVs and a further 10% being plug-in hybrids (Table 14). Sales of new petrol cars (1.3%) and diesel cars (2.7%) have decreased abruptly in recent years and are disappearing from the market. Consequently, the share of EVs in the total car fleet is increasing rapidly and is now aligned with a linear trend to zero emissions by 2045. Several incentives have supported the rapid deployment of e-mobility. ICE cars are subject to a high registration tax on purchase, as well as a CO2 tax and road use tax on gasoline and diesel. Meanwhile, zero-emission vehicles are subsidized, with support including no VAT, exemption from a one-off registration tax, and reduced toll roads, ferry, and parking fees (IEA, 2022b).

Table 14 | Car sales in Norway (first-time registered vehicles)

Car sales	2019	2020	2021	2022
Full electric	60,246	76,791	113,715	138,283
Plug-in hybrid	19,299	28,909	38,174	16,131
Hybrid + electric	79,545	105,700	151,889	154,414
Total car sales	142,278	141,369	176,201	174,291

Source: Statistics Norway (2024).

Figure 26 | Share of EVs (including plug-in hybrids) in total car sales, Norway



Source: Statistics Norway (2024) .

Finally, the state of public charging infrastructure seems insufficient compared to the EU guideline. In 2021, there was one public charger per 33 EVs. However, the deployment of new charging points has been progressing rapidly alongside the growth of the EV fleet.

Norway's case demonstrates that rapid transition to zero-emission road transport is possible but may require continued public support for new technologies and infrastructure until market dynamics consolidate and consumer preferences change. On the downside, the country is not performing well in reducing the high dependence on cars for passenger transportation.

Table 15 | Assessment results – Road transport, Norway

Variable/ metric	Evaluation	Explanation	Sources
A) Policy targets			
1. Target for ICE vehicles phase-out (year)	Insufficient	No national target.	
2. Target share of zero-emission vehicles in total car sales (%)	Sufficient	2025: All new passenger cars, light vans, and city buses must be zero-emission. 2030: All new heavier vans and 75% of long-distance buses and 50% of trucks must be zero-emission. To reach the 1.5-degree target in the transport sector by 2030, 100% of new car sales should be zero-emission.	Norwegian Ministry of Transport (2021): National Transport Plan 2022-2033; Teske et al. (2022): The Internal Combustion Engine Bubble.
3. Target for number of public charging points (Nb per EV)	Sufficient	The Norwegian government does not see the need for new specific targets or subsidies, as the charging infrastructure is already well developed. The focus is on improving land use, access to the electricity grid, and making the charging infrastructure more user-friendly.	Norwegian Ministry of Transport (2023): National charging strategy. p. 7.
B) Phase-out of carbon-intensive technologies			
4. GHG emissions of road transport (Mt CO2e), trend	Sufficient	From 2016 to 2021, CO2 emissions from road transport decreased by 1.2 MtCO2 (−22%), a reduction rate of 0.25 MtCO2 per year, which is faster than the required linear path of 0.17 MtCO2 per year to achieve net-zero road transport by 2045.	United Nations Climate Change (2023): Greenhouse Gas Inventory Data; Own calculation.
5. Share of ICE in total cars (%), trend	Sufficient	In 2023, the share of ICE cars in the Norwegian car stock was 67%, down from 2019, but the reduction rate of −4.8% per year is higher than the needed −3% per year to achieve zero ICE cars by 2045.	Statistics Norway (2024): Registered Vehicles.
6. Share of passenger transport by cars (%), trend	Insufficient	From 2016 to 2021, passenger transport by car increased by 4%, compared to the EU trend of +3%. This increase is likely due to the COVID-19 pandemic.	Eurostat (2023b): Modal split of inland passenger transport.
C) Phase-in of zero-carbon technologies			
7. Average purchase prices of EVs and ICE cars (€); trend	Partially sufficient	Average price of a medium car in 2023: €28,000 Average price of an EV in 2023: €62,800 (a 7% decrease since 2019) Although the average ICE medium car is cheaper than the average EV, EV prices are decreasing.	Statista (2024g): Medium cars – Norway; Statista (2024c): Electric Vehicles – Norway.
8.1 Share of EVs in total car sales (%); trend	Sufficient	2022: 89% To reach 100% by 2025, the calculated share in 2022 should have been 78%. The increase in EV sales share (10.8% per year) from 2018 to 2022 is faster than the required linear development (7.3%) to meet the national target.	Statistics Norway (2024); Own calculation.
8.2 Share of EVs in total car fleet (%); trend	Sufficient	2022: 27% By 2050, the EV share in Norwegian car stock is projected to be at least 83%. The actual increase in EV share from 2018 to 2022 (18.2%) is faster than the linear pathway needed to achieve the 2045 target.	IEA (2023c): EV stock share 2011–2022; Climate Analytics (2023b): 1.5°C national pathway explorer Norway; Own calculation.
D) Infrastructure			
9. Public charging points density (Nb per EV)	Insufficient	2021: 33.6 EVs per public charger (EU average: 15.5) Norway has one public charger per 34 EVs, which is below the EU average and far from the EU guideline of one charger per 10 EVs.	IEA (2023c): Trends in charging infrastructure; EU-guideline 2014/94/EU (23).

10. Public charging points installed per year; trend (Nb/year)	Sufficient	2022: 4,400 new public chargers installed (up from 1,280 in 2018) In 2022, 2,400 fast public chargers were installed, surpassing the minimum requirement of 950 to reach at least 12,500 by 2030.	IEA (2023c): EV charging points 2017–2022; Ministry of Transport (2023): National charging strategy. p17.
E) Market regulation			
11. Subsidies for ICE cars (EUR); trend	Partially sufficient	Subsidies directed to consumers (not limited to cars) are decreasing, from USD 57 per capita in 2018 to USD 48 in 2022.	OECD and IISD (2024).

5.2.3 Heating sector

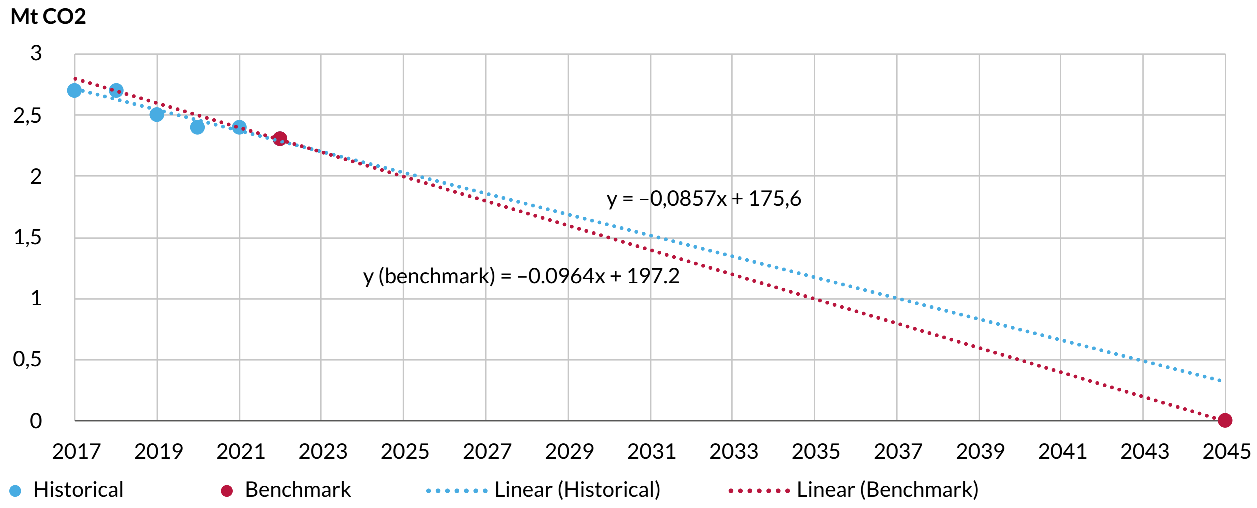
Despite having one of the coldest climates in Europe and being a major producer of natural gas, Norway is rapidly transitioning to zero-emission heating. Our assessment reveals that most metrics have shown sufficient progress, with performance on three rated as partially insufficient or insufficient (Table 16).

A ban on the installation of fossil fuel-based heating systems in new buildings was implemented in 2016. Furthermore, as of January 1, 2020, a new regulation prohibited the use of mineral oil for heating in both new and existing buildings. While natural gas is still permitted in existing buildings, it is only marginally utilized. However, the country would benefit from establishing targets for the renovation of existing buildings and thermal storage systems, as well as setting more ambitious targets for decreasing residential energy consumption.

Norway currently boasts an almost entirely renewable energy-based heating system, resulting in a dramatic reduction in fossil fuel consumption within the residential sector in recent years. Concurrently, CO2 emissions from direct building energy use continue to decline and are poised to be eliminated in the coming years (Figure 27).

Norway leads the global ranking in terms of the number of heat pumps per capita, with 604 installed heat pumps for every 1,000 households (Rosenow et al., 2022). The oil crisis of 1973 prompted Norwegians to seek alternative heating sources, with the heat pump market experiencing gradual growth until the 2000s. Since then, the market has expanded exponentially, with 156,000 heat pumps sold in 2022. Of all heat pumps in Norwegian homes, 90% are air source heat pumps. This rapid growth has been supported by factors such as affordable and clean electricity, high taxes on fossil fuels, generous government subsidies for households,

Figure 27 | CO2 emissions from direct building energy use, Norway



Source: European Commission & Joint-Research Centre, 2024.

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and the ban on fossil fuel-based boilers. The state-owned enterprise Enova has also played a pivotal role in facilitating the deployment of heat pumps. Unlike other Nordic countries, district heating plays a minor role in Norway, and the government anticipates only modest growth in this sector in the coming years (IEA, 2022b).

Another noteworthy aspect of Norway's heating (and electricity) transition is the nearly 100% penetration of smart meters. Smart metering encompasses approximately 2.9 million customers, covering up to 99.5% of national demand. Although there was no support scheme for deploying smart meters, the National Water Resources and Energy Directorate mandated in 2011 that all customers must have smart meters by 2019. These smart meters record electricity consumption every hour and facilitate two-way communication between the metering point and the distribution system operator, enabling consumers to access information about time-of-use consumption and prices via smartphones or in-home displays (IEA, 2022b).

Norway's high share of renewable electricity and nearly fully renewable heating system mean that the country's future efforts to achieve zero emissions will be focused on more challenging sectors, such as industry.

Table 16 | Assessment results – Heating, Norway

Variable/ metric	Evaluation	Explanation	Sources
A) Policy targets			
1: Targets for phase-out oil and gas heating systems (year).	Sufficient	2016: Ban on the installation of fossil fuel-based heating in new buildings. 2020: Ban on the use of mineral oil for heating in both new and existing buildings. Natural gas: Its use is marginal, and new installations based on natural gas are not allowed.	IEA (2022b): Norway 2022 Energy Policy Review.
2.1: Target for new heat pumps (Nb)	Sufficient	No target. But strong phase-out target, therefore the technology target is not that important, because there is no other possibility than to implement a renewable-energy-based heating system.	IEA (2022b); Rapid Transition Alliance (2023).
2.2: Target for share of zero-carbon heating (%).	Sufficient	There is no specific technology target, but a strong phase-out target for fossil fuels.	
3.1: Target for energy consumed for heating per m²	Partially sufficient	2017 targets for new buildings: Single house: 100 kWh/m² Apartments: 95 kWh/m² Offices: 115 kWh/m² Target for existing buildings: Reduce energy use by 10 TWh by 2030, compared to 2015 levels. New targets are under discussion.	Climate Analytics; New Climate Institute (2023); IEA (2022b).
3.2: Target for building renovation per year (%)	Insufficient	No specific targets.	
3.3: Target for buildings with thermal energy storage (%).	Insufficient	No specific targets.	
B) Phase-out of carbon-intensive technologies			
4: CO2 emissions from direct building energy use (Mt CO2e), trend	Sufficient	2018–2022: CO2 emissions decreased by 15%, from 2.7 MtCO2 to 2.3 MtCO2. 2017–2022: Emissions decreased at a rate of 0.08 MtCO2 per year. A minimum reduction of 0.09 MtCO2 per year is needed to reach zero emissions by 2045. Emissions are falling almost in line with the benchmark.	European-Comission and Joint-Research-Centre (2024); Climate Analytics, (2023a); ClimateAnalytics (2022); Velten, Calipel, et al. (2023).

5: phase-out oil and gas heating systems	Sufficient	Reduction of fossil-fuel consumption (2017–2021): Natural gas: –57% (65 TJ in 2021). Oil products: –95% (211 TJ in 2021). Coal: No use since 2006.	IEA (2023d): Evolution of residential total final consumption by source.
C) Phase-in of zero-carbon technologies			
6: Heat pumps total purchase cost (EUR)	Sufficient	Heat pump and installation costs Air-air heat pump: NOK 15,000 – NOK 30,000 (€1,300 – €2,600) Air-water heat pump: NOK 60,000 – NOK 130,000 (€5,300 – €11,500) Ground-source heat pump: NOK 170,000 – NOK 250,000 (€15,000 – €22,000). Installing new fossil fuel-based heaters is prohibited, so there is no price for gas boilers. Norway has relatively low installation costs for heat pumps compared to other countries.	Sadeghi et al. (2022).
7.1: Installed (new) heat pumps (thousands/year); trend	Sufficient	2021: 125,028 units 2022: 156,295 units In 2021, 60% of households were equipped with heat pumps, the highest percentage worldwide. With a residential building stock of 1.6 million, the current installation rate is sufficient to achieve 100% penetration by around 2030.	Rapid Transition Alliance (2023); Rosenow et al., (2022) Statista (2024i).
7.2: Share of buildings with climate-neutral heating (%), trend.	Sufficient	Data on the exact % of building with climate-neutral heating is not available. However, in 2021, the final energy consumption in the residential sector was: Electricity: 83% Biofuels and waste: 13% District heating: 3.6% Fossil-fuel share: Marginal.	IEA (2023d): Evolution of residential total final consumption by source.
D) Infrastructure			
8.1: Energy consumed for heating per square meter (kWh/m²), trend	Sufficient	Residential energy intensity: 2015: 169 kWh/m² 2020: 158 kWh/m² Trend (2015–2020): Reduction of 2.2 kWh/m², above the EU benchmark).	IEA (2023d): Residential Energy intensity per country 2000–2020; Velten, Calipel, et al. (2023).
8.2: Homes treated with (high) energy efficiency measures (thousands/year), trend	Evaluation not possible	Data not available.	
8.3: Share of households with energy storage (%), trend.	Evaluation not possible	Data not available.	
E) Market regulation			
9: Share of buildings using smart tariffs/ smart meters (%)	Sufficient	2022: 99% of households had smart meters, as mandated by Norway's National Water Resources and Energy Directorate in 2011.	IEA (2022b): Norway 2022 Energy Policy Review.
10: Subsidies for investment in fossil-fuel heating (EUR); trend	Sufficient	There are no subsidies for fossil-fuel heating.	Agora Energy (2021).

5.3 | Denmark

5.3.1 Electricity sector

Denmark is widely recognized as a global leader in the transition to zero-emission electricity, showcasing significant advancements across various metrics. Our evaluation highlights Denmark's commendable progress, with nine metrics demonstrating sufficient advancement, five showing partial insufficiency, and only three deemed insufficient.

Denmark has set ambitious renewable energy deployment targets (Table 17), solidifying its position as a pioneer in sustainable energy initiatives. The Nordic nation's strategic plans include a substantial increase in offshore wind capacity and a quadrupling of onshore wind and solar photovoltaic (PV) capacity by 2030. Additionally, Denmark's Power-to-X (PtX) Strategy aims to establish up to 6 GW of hydrogen electrolysis capacity by 2030, demonstrating a robust commitment to innovative renewable energy solutions. These targets not only align with but also exceed benchmarks for scenarios aimed at achieving 100% renewable electricity by 2035. Moreover, Denmark joined the Powering Past Coal Alliance in 2017, the year it was launched, committing to phasing out coal by 2030. The remaining coal plants, totaling 1,560 MW and primarily retained for energy security reasons, all have scheduled closure dates, with the latest being Nordjylland in 2028. Gas use in Denmark is minimal. Denmark also serves as an exemplary model for transmission electricity line planning. Notably, the transmission grid objectives set by the TSO Energinet, accounting for both solar and wind power, are based on technology capacities planned to reach 44 GW by 2030. These targets are more ambitious than the most recent national goals for solar and wind, which aim for 29 GW. This proactive grid development acts as a catalyst for the increased deployment of renewable electricity in the future.

Denmark has seen a continuous decline in the share of fossil fuels in its electricity generation, with a notable reduction in coal use. Consequently, CO2 emissions from electricity decreased by 19.5% from 2018 to 2022. The carbon intensity of Denmark's electricity is significantly lower than the OECD average and continues to decline rapidly (−29% from 2018 to 2022), reflecting the nation's strong commitment to decarbonization. If recent trends persist, fossil fuels for electricity generation could be completely phased out by 2029 (Figure 28).

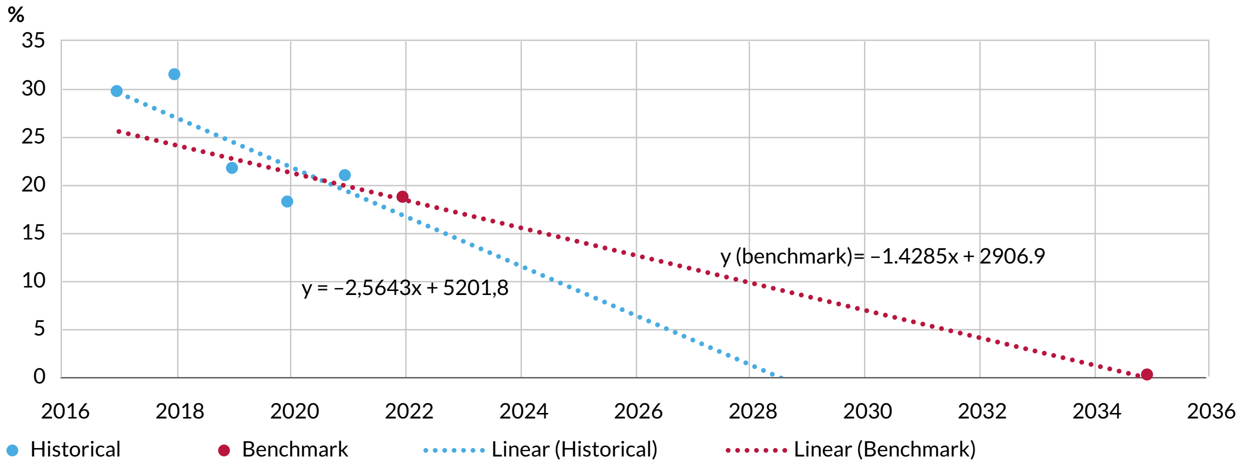
The increasing dominance of variable renewables, particularly wind and solar, underscores Denmark's transition toward cost-effective and sustainable electricity generation. The LCOE for solar PV and wind power has significantly declined (wind offshore LCOE decreased by 26% from 2017 to 2022), facilitating their widespread adoption nationwide. Despite these advancements, the capacity added for solar and wind power remains below national targets, indicating the need for accelerated deployment to meet Denmark's ambitious renewable energy goals (Figure 29). However, considering the evolution of the share of renewable energy in the electricity mix, Denmark could achieve 100% renewables as soon as 2028 (Figure 30).

Table 17 | Renewable energy targets by 2030, Denmark

	Total capacity (GW)	Generation (Twh)	Generation (%)
Bioenergy		4.3	5.96
Hydro		0.02	0.02
Other Renewables		0.57	0.79
Solar	11.7	16.3	22.58
Wind (offshore)	17.2 (11.3)	50.51	69.97

Source: IRENA (2024).

Figure 28 | Share of fossil-fuels in the electricity mix, Denmark



Source: EMBER (2023).

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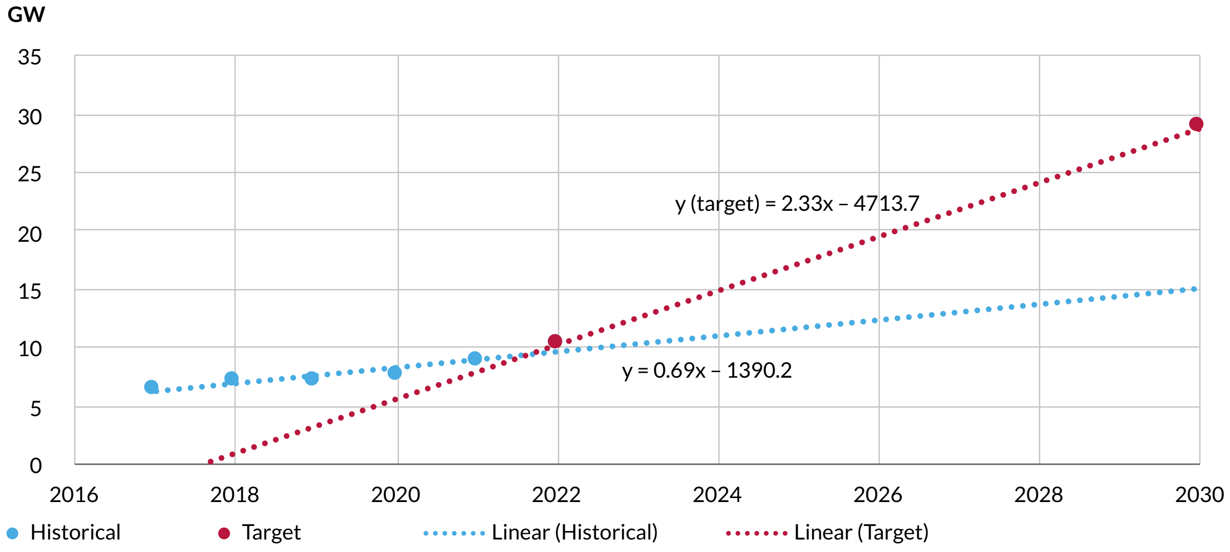
Figure 29 | Progress to the 2030 national renewable energy targets, Denmark



Source: EMBER (2023).

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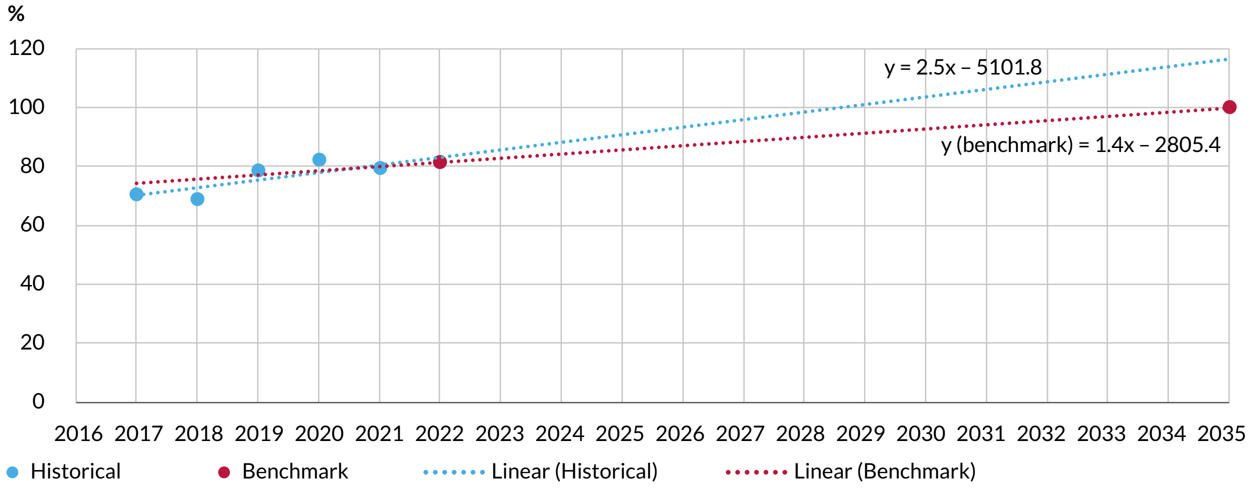
Denmark boasts a robust and interconnected electricity infrastructure, bolstered by interconnectors linking it to neighboring countries such as Norway, Sweden, the Netherlands, and Germany. While these interconnections enhance energy security and facilitate cross-border trade, challenges such as grid bottlenecks have led to instances of wind generation curtailment and negative electricity prices (IEA, 2023a). The transmission grid has grown, but not fast enough. According to the latest grid plans discussed above, this should improve in the coming years. Efforts to enhance grid flexibility are imperative to address these challenges and ensure the reliability and resilience of Denmark's electricity supply. Furthermore, Denmark's strong public support for renewable energy transition policies, as evidenced by the overwhelming majority of citizens favoring renewable energy sources, underscores the nation's commitment to sustainable energy initiatives.

Figure 30 | Progress toward zero-emission electricity by 2035, Denmark



Source: EMBER (2023).

Table 18 | Assessment results – Electricity, Denmark

Variable/Metric	Evaluation	Explanation	Sources
A) Policy targets			
1. Targets for phase-out fossil fuel-based power generation (year)	Sufficient	Denmark joined the Powering Past Coal Alliance in 2017, the year it was launched, committing to phasing out coal by 2030. The remaining coal plants, totaling 1,560 MW and primarily retained for energy security reasons, all have individual closure dates, with the last being Nordjylland in 2028. Gas use is marginal.	Bloomberg (2024): Global Coal Countdown.
2. Targets for renewable electricity capacity and/or generation share (%, year)	Sufficient	Denmark's renewable energy generation target for 2030 is almost 100% of projected generation (99.3%), with gas used only for emergencies. Given the country's geography, it relies mainly on onshore and offshore wind power. The capacity and generation targets are equal to or exceed benchmarks for 1.5°C scenarios.	IRENA (2024); Wråke et al. (2021).
3.1. Targets for transmission development national (km)	Sufficient	For solar and wind combined, the transmission grid targets developed by the TSO are based on planned technology capacities (44 GW by 2030), which are more ambitious than the latest national target for solar and wind (29 GW). Energinet, Denmark's national transmission system operator for electricity and natural gas, is responsible for developing a long-term development plan for the power grid.	Cremona (2024); Energinet (2022).
3.2 Targets for distribution network (km)	Evaluation not possible	The 2021 policy agreement, "A Future-Proof Electricity Infrastructure to Support the Green Transition and Electrification," outlines a new regulatory framework for DSOs to stimulate timely investments and incentivize flexibility.	IEA (2023a).
3.3 Targets for electricity storage (GW or GWh)	Partially sufficient	Denmark has no specific targets for storage capacity, except for hydrogen, with plans to build 4–6 GW of capacity by 2030 under the Agreement on the Development and Promotion of Hydrogen and Green Fuels.	EURELECTRIC (2023).

B) Phase-out of carbon-intensive technologies			
4.1: CO2 emissions of electricity generation (Mt CO2e), trend	Partially sufficient	From 2018 to 2022, CO2 emissions from electricity decreased by 19.5%. However, the annual average reduction of CO2 emissions (–0.4 MtCO2) is below the necessary benchmark (–0.54 MtCO2) to achieve zero emissions by 2035.	EMBER (2023); Own calculations.
4.2: Carbon intensity of electricity (gCO2e/kWh), trend	Sufficient	The carbon intensity of electricity in Denmark (202 gCO2/kWh) is lower than the OECD average (373 gCO2/kWh) and is rapidly decreasing (–29% from 2017 to 2022).	EMBER (2023); Own calculations.
5. Share of fossil fuel-based power generation (%)	Sufficient	The share of fossil fuels was 18.5% in 2022 and is decreasing faster (–2.6% annually) than the benchmark for zero emissions by 2035 (–1.4% annually). The use of coal has significantly decreased, and the use of gas and oil is marginal.	EMBER (2023); Own calculations.
C) Phase-in of zero-carbon technologies			
6.1: LCOE (USD/MWh), national trend; solar PV.	Sufficient	Variable renewables (i.e., wind and solar) are now the cheapest form of electricity generation due to continuous cost reductions. The 2022 LCOE for utility-scale solar PV is USD 44/MWh, compared to USD 124/MWh for second-generation gas technology. T From 2017 to 2022, the LCOE for solar PV decreased by 12%.	ENERDATA (2024).
6.2: LCOE (USD / kWh), national trend; wind power.	Sufficient	The LCOE for onshore wind in 2022 is 38 USD/MWh, and offshore wind is 62 USD/MWh. From 2017 to 2022, the LCOE for onshore wind decreased by 9.5% and offshore wind by 26%.	ENERDATA (2024).
7.1: Capacity added (GW/year) trend; average for solar and wind power	Partially sufficient	The average annual new installed capacity for solar and wind from 2018 to 2022 was 0.7 GW, but 2.3 GW per year is needed to reach the 2030 capacity targets (29 GW). Capacity additions per year are increasing but still below national targets.	EMBER (2023); Own calculations.
7.2: Share of renewables in electricity generation (%), trend; average for RE technologies	Sufficient	The share of RE generation grew by an average of 2.5% from 2018 to 2022, while a minimum of 1.4% is needed for a 100% RE system by 2035. Current trends suggest 100% renewable energy could be achieved by 2028.	EMBER (2023); Own calculations.
D) Infrastructure			
8: Curtailment of RE (%), trend	Insufficient	Wind generation curtailment increased from approximately 1% in 2019 to approximately 4% in 2020, mainly due to grid bottlenecks in neighboring countries' power grids.	Danish Energy Agency (2021).
9.1: Transmission lines (km) and NTC (GW), trend	Partially sufficient	The transmission network experienced a 34% increase from 5,491 km to 7,339 km between 2018 and 2023. Denmark has interconnectors with Norway, Sweden, the Netherlands, and Germany. Recent interconnectors include the COBRA interconnector to the Netherlands and the hybrid interconnector via Kriegers Flak to Germany. The Viking Link Cable to Great Britain is under construction and expected to be operational in 2023.	IEA (2022b); (IEA, 2023a).
9.2: Distribution lines (km), trend	Evaluation is not possible	Denmark has 160,000 km of distribution lines, operated by 38 DSOs, some owned by holding companies, others by consumers or municipalities.	IEA (2023a).
9.3: Energy storage as a % of variable renewable capacity (%)	Partially sufficient	In 2023, the rate of energy storage (operational and under construction) was 10.5% (1.1 GW), lower than the EU average (13%). Denmark is developing an additional 5 GW of hydrogen storage.	ENERDATA (2024).

E) Market regulation			
10: Negative prices for electricity (hours); trend	**Insufficient**	Negative electricity prices increased from 40 hours in 2018 (0.5%) to 235 hours in 2023 (2.7%).	Staffell et al. (2023).
11: Subsidies from coal and natural gas (USS); trend	**Insufficient**	Subsidies for coal were phased out in 2014. However, subsidies for natural gas have continued, increasing by 34% from 2018 to 2021 and by 150% from 2018 to 2022 due to the energy crisis.	OECD and IISD (2024).
12: Average time for permission process, wind power (months)	Evaluation is not possible	Data is available from WindEurope but only for a fee.	
Support to the expansion of renewable energy	**Sufficient**	The special Eurobarometer on climate change (2023) confirmed that a clear majority of Danish people (93%) support public policies encouraging the transition to renewable energy sources.	European Commission (2023): Special Eurobarometer on climate change (May 2023).

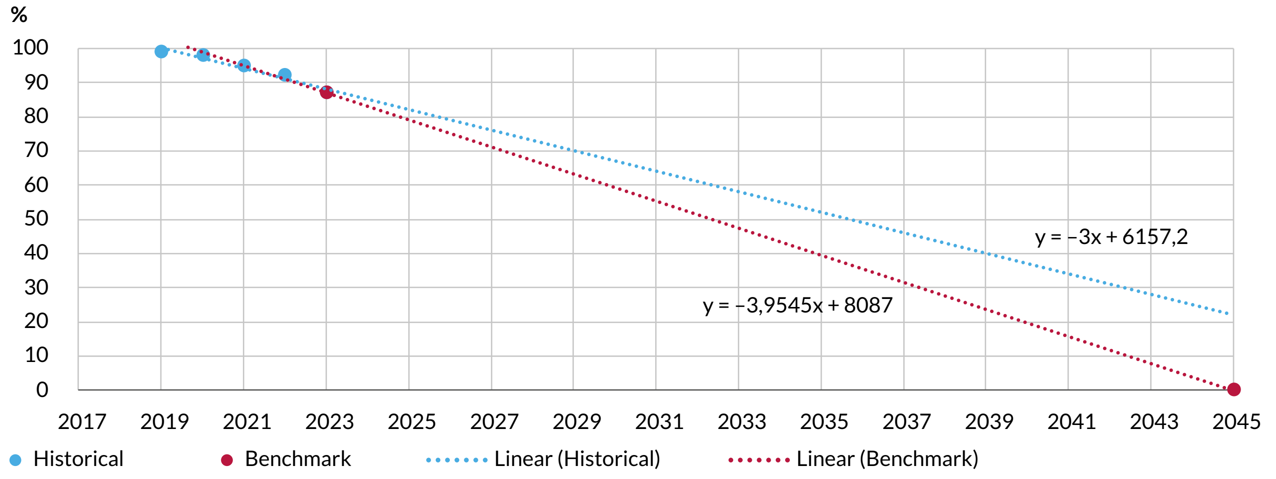
5.3.2 Road transport sector

The overall progress of the Danish road transport transition is deemed insufficient to partially insufficient, as it is still not aligned with the objective of achieving zero emissions in line with the Paris Agreement. Our evaluation shows progress on one indicator as sufficient, seven as insufficient, and four as partially insufficient (Table 20).

Denmark follows EU regulations mandating 100% of new car sales to be zero-emission by 2035; however, this timeline is too late when considering Paris-compatible scenarios. Additionally, the government has not established any target or strategy to phase out ICE cars and lacks specific targets regarding EV charging infrastructure. Local developments, such as, Copenhagen's plan to ban diesel and petrol cars by 2030, are crucial.

CO2 emissions from transport are decreasing too slowly, having dropped from 6.6 metric tons in 2016 to 6.15 in 2021, a 7% decrease over five years. To align with a zero-emission transport sector by 2045, the reduction rate should be at least twice as high. Progress in phasing out ICE cars is also insufficient, with ICE cars comprising 87% of the total car fleet in 2023 (Figure 31). The share of transport by car in total passenger transport has increased in Denmark, rising from 81% in 2016 to 87% in 2021, indicating challenges in advancing a modal shift in transport. More recent data will

Figure 31 | Share of ICE cars in total passenger cars, Denmark



Source: Statistics Denmark (2024a).

Table 19 | Car sales in Denmark (first-time registered vehicles)

Car sales	2019	2020	2021	2022	2023
Full electric	5,501	14,218	24,872	30,797	62,599
Plug-in hybrid	3,880	18,235	40,442	26,441	17,222
Hybrid + electric	9,381	32,453	65,314	57,238	79,821
Total car sales	225,620	198,981	186,584	149,279	173,398

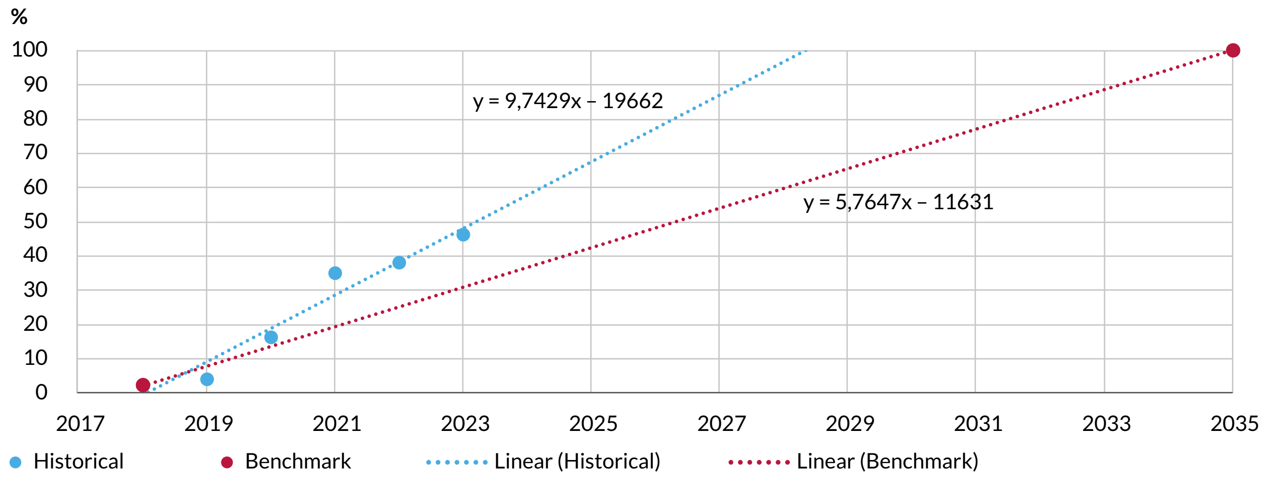
Source: Statista (2024a) and (2024).

reveal if this trend continues or reverses in the years following the COVID-19 pandemic.

The average price for EVs has not decreased substantially and remains higher than that of medium ICE cars (23,000 EUR in 2023). An average EV cost 69,100 EUR in 2019, increased to 72,500 EUR in 2021, and decreased slightly to 69,200 EUR in 2023. Despite this, EV sales have accelerated in recent years amid decreasing total car sales (see Table 19). From 2022 to 2023, EV sales increased by over 100%, representing 36% of car sales (46% including plug-in hybrids). The share of EVs in the total car fleet is increasing due to higher sales shares but is still not on track for long-term decarbonization goals.

The state of public charging infrastructure is insufficient compared to EU guidelines: in 2021, there was one public charger per 35 EVs. The government aims to increase the stock of electric vehicles to 1 million by 2030 (up from 210,000 in 2022). To support this number of electric cars, estimates show that 67,000 public charging points would be needed, meaning the current rate of installation (2,260 new chargers in 2022) must double in the coming years.

Figure 32 | Share of EVs (including plug-in hybrid) in total car sales, Denmark



Source: Statistics Denmark (2024a).

Table 20 | Assessment results – Road transport, Denmark

Variable/metric	Evaluation	Explanation	Sources
A) Policy targets			
1. Target for ICE vehicles phase-out (year).	Insufficient	No national target specified.	
2. Target share of zero-emission vehicles in total car sales (%)	Partially sufficient	2035 target: 100% of car and light-duty vehicle sales to be CO2-emissions-free. 2030 goal: One million EVs on the road. To meet the 1.5-degree target in the transport sector by 2030, there should be 100% zero-emission car sales. Denmark has a target, but it is not ambitious enough.	EU-Regulation 2023/851; Teske et al. (2022).
3. Target for number of public charging points (Nb per EV)	Insufficient	No national target specified.	
B) Phase-out of carbon-intensive technologies			
4. GHG emissions of road transport (Mt CO2e), trend	Insufficient	2016-2021: CO2 emissions reduced by 0.48 MtCO2 (7% reduction). Emissions decreased at an annual rate of 0.12 MtCO2, lower than the benchmark rate of 0.26 MtCO2 needed to achieve zero emissions by 2045.	United Nations Climate Change (2023); Own calculation.
5. Share of ICE in total cars (%), trend	Partially sufficient	2023: 87% of cars still ICE 2019: 99% of cars still ICE 2019–2023: Annual decrease in the share of ICE cars was 3%, lower than the required 4% to meet the 2045 target.	Statistics Denmark (2024a): Stock of means of transportation; Own calculation.
6. Share of passenger transport by cars (%), trend	Insufficient	2018–2021: Passenger transport by car increased by 6% in Denmark, compared to a 3% EU average increase, likely due to COVID-19 impacts.	Eurostat (2023b).
C) Phase-in of zero-carbon technologies			
7. Average purchase prices of EVs and ICE cars (EUR); trend	Insufficient	2023 average prices: medium ICE car: €23,000; EV: €69,200. EV prices have increased slightly, while ICE car prices have decreased.	Statista (2024e); Statista (2024a).
8.1 Share of EVs in total car sales (%); trend	Sufficient	2022: 38% of new car sales were EVs. 2023: 46% of new car sales were EVs. To reach 100% zero-emission car sales by 2035, the share of EVs needs to increase by 5.8% annually. Currently, it is increasing by 9.7% annually.	Statistics Denmark (2024b); Own calculation.
8.2 Share of EVs in total car fleet (%); trend	Partially sufficient	2022: 7.8% No projection for EV share in 2050 is available, therefore we use the prediction for NOR as they have a comparable transport sector. In 2050 there will be a share of 83% EVs in the zero-emission transport sector. Starting from 0.6% EVs in car stock in 2018 a linear path toward 2050 calculation, in 2022 there should be at least 11% EVs in the Danish car stock. The share of EVs is only 7.8%, but still increasing.	IEA (2023c): EV stock share 2011–2022; Climate Analytics (2023b); Own calculation.
D) Infrastructure			
9. Public charging points density (Nb per EV)	Insufficient	2021: 35.5 EVs per public charger EU average 2021:15.5 Compared to the EU guideline that for 10 EVs one public charger is needed.	IEA (2023c): Trends in charging infrastructure; EU-guideline 2014/94/EU (23).

10. Public charging points installed per year; trend (Nb/year)	Partially sufficient	2022: 2.260 By 2030 67,000 charge points would be needed to supply one million EVs. Starting in 2018 with 4,300 charging points around 5,250 new chargers should be installed each year; 2260 were installed in 2022, up from only 100 in 2018.	IEA (2023c): EV charging points 2017–2022 worldwide by country; www.fuse-project.dk
E) Market regulation			
11. Subsidies for ICE cars (EUR); trend	Insufficient	There are still subsidies for petroleum directed to consumers (not limited to cars); in 2018–2022 they have stagnated around USD 200 per capita.	OECD and IISD (2024).

5.3.3 Heating sector

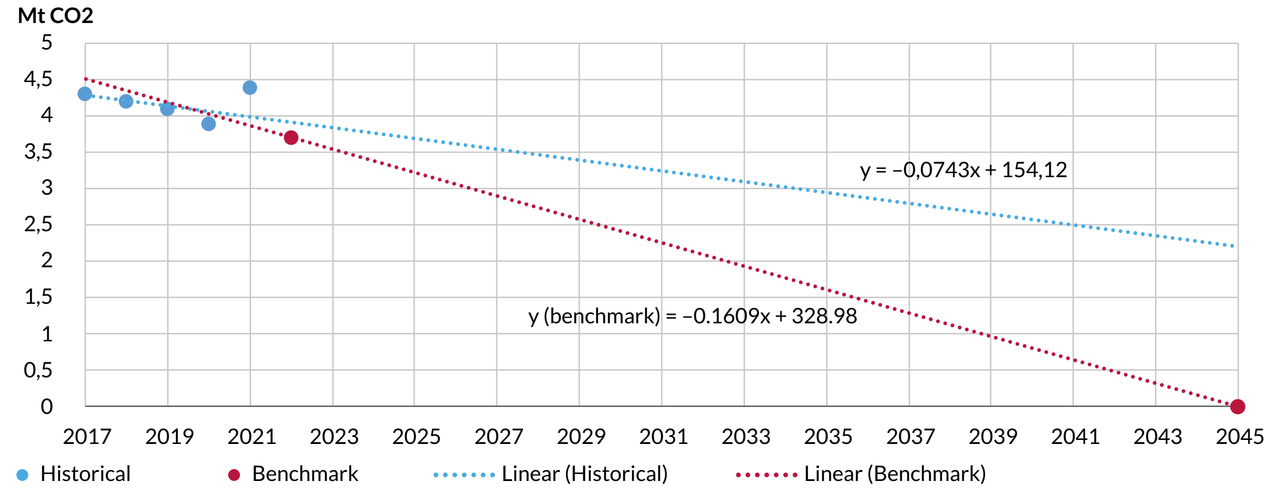
Overall, Denmark is progressing well in its transition to zero-emission heating. Our assessment reveals ten metrics as sufficient, three as partially insufficient and only one as insufficient (Table 21, below).

Early-established policy targets have played a crucial role in driving the transition, with Denmark implementing measures to phase out oil and gas heating systems. Key initiatives include a ban on the installation of fossil oil and gas boilers in new buildings since 2013 and a general obligation for renewable heating in both new and existing buildings. More recently, Denmark has set ambitious targets for the share of zero-carbon heating, aiming for the complete decarbonization of heat supply for buildings by 2035.

The phase-out of fossil fuels and CO2 emissions is progressing but not fast enough, with Denmark achieving a reduction in CO2 emissions at a rate (–14% in 2017–2022) that is still not fully compatible with a linear trajectory toward zero emission by 2045 (Figure 33). Moreover, the decline in natural gas consumption has been slow and will need to accelerate in the coming years, particularly to reach the national stricter target (2035).

Denmark has made significant strides in adopting zero-emission technologies, particularly with the notable 78% increase in heat pump installations from 2018 to 2022. The country ranks among the world leaders in heat pumps per capita, trailing only behind other Nordic countries. Although exact data on the percentage of buildings with climate-neutral heating is not available,

Figure 33 | CO2 emissions from direct building energy use, Denmark



Source: European-Comission and Joint-Research-Centre (2024).

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the growing share of renewable energy sources and electricity in the residential sector indicates substantial progress in this area. Additionally, district heating plays a vital role in Denmark, with government plans to expand its coverage in certain regions.

Energy consumption in buildings has also improved, evidenced by a consistent reduction in energy used for heating per square meter over recent years. Regulatory measures have been crucial in promoting energy efficiency, achieving a 100% implementation of smart meters in buildings by 2022. Furthermore, Denmark has phased out subsidies for fossil-fuel heating investments, redirecting support toward renewable energy solutions.

Denmark's transition to zero-emission heating is well underway, driven by robust policy targets, effective regulations, and significant progress in zero-emission technology adoption. Continued efforts to promote renewable energy heating and enhance energy efficiency will be essential to achieving zero emissions.

Table 21 | Assessment results – Heating, Denmark

Variable/metric	Evaluation	Explanation	Sources
		A) Policy targets	
1: Targets for phase-out oil and gas heating systems (year).	Sufficient	2013: ban on installation of fossil oil and gas boilers in new buildings introduced. 2018: general obligation for renewable heating introduced with following measures: – New and existing buildings in district heating (DH) areas can only be heated by DH or RE – In areas with a gas grid, houses can still be heated with gas but not with oil – Outside of these areas, existing buildings are not required to use RE, but it is expected that homeowners will gradually switch from oil heating to heat pumps and biomass for economic reasons – New buildings must use RE for heating – During renovations, RE must be integrated In 2020, it was decided to phase out gas use in heating by 2035. In 2022, Denmark set a target to convert 200,000 households using natural gas heating systems (half of all gas users) to DH by 2028.	IEA (2023a): Denmark 2023. Policy Review; Braungardt et al. (2021); Kerr and Winskel (2021).
2.1: Target for new heat pumps (Nb)	Sufficient		
2.2: Target for share of zero-carbon heating (%).	Sufficient	By 2035, Denmark aims to achieve 100% decarbonization of heat supply for buildings.	Kerr and Winskel (2021).
3.1: Target for energy consumed for heating per m²	Sufficient	Denmark also aligns with the EU 2030 Energy Efficiency targets for all new and deeply renovated buildings: Mediterranean climatic zone: 60 kWh/m² Nordic climatic zone: 75 kWh/m².	Climate Analytics; New Climate Institute (2023).
3.2: Target for building renovation per year (%)	Sufficient	Denmark supports the EU targets to "at least double the annual energy renovation rate of residential and non-residential buildings by 2030 and to foster deep energy renovations."	EU: Renovation Wave communication COM 2020 662 final.
3.3: Target for buildings with thermal energy storage (%).	Insufficient	No target.	

B) Phase-out of carbon-intensive technologies			
4: CO2 emissions from direct building energy use (Mt CO2e), trend	Partially sufficient	From 2017 to 2022, Denmark's CO2 emissions decreased from 4.3 million metric tons to 3.7 million metric tons, a 14% reduction. This translates to an annual reduction rate of 0.074 million metric tons of CO2 per year. However, to achieve zero emissions by 2045, a minimum annual reduction of 0.16 million metric tons is required.	European-Comission and Joint-Research-Centre (2024); Climate Analytics (2023a); Velten, Calipel, et al. (2023).
5: Phase-out oil and gas heating systems	Partially sufficient	The reduction in fossil fuel consumption between 2017 and 2021 is as follows: – Natural gas: decreased by 7% (24,245 TJ in 2021) – Oil products: decreased by 32% (6,601 TJ in 2021) – Coal: no change (0%) While there has been a significant reduction in oil consumption, the decrease in natural gas usage has been slower.	IEA (2023d): Evolution of residential total final consumption by source.
C) Phase-in of zero-carbon technologies			
6: Heat pumps total purchase cost (EUR)	Sufficient	Total investment costs in 2021: Air-to-air heat pump: USD 2,900 Gas boiler: USD 4,500	IEA (2021b): Residential Heat Economics Calculator.
7.1: Installed (new) heat pumps; trend	Sufficient	Installation rates: 2018: 49,818 units 2019: 60,249 units 2021: 73,941 units 2022: 88,833 units Figures for the 2022 installation rate indicate that nearly 3.5% of Danish residential houses purchased a heat pump in that year. Although there is no reference scenario available, the high number of sales (+78%) and the significant share of district heating indicate a strong trend toward climate-neutral heating.	EHPA (2023): Heat Pumps in Europe; Observ'ER (2020): Heat Pumps Barometer.
7.2: Share of buildings with climate-neutral heating (%), trend.	Partially sufficient	Data on the exact % of building with climate-neutral heating is not available. However, in 2021 the final energy consumption in the residential sector was: Natural gas: 13.6% Oil products: 3.7% Coal: 0% Electricity: 21.9% Biofuels: 19.2% District heating: 41.3% Wind and solar: 0.3% Between 2016 and 2021, the share of renewable sources (including electricity) increased by only 2%. Despite this modest growth, the overall share of renewables is already high.	IEA (2023d): Evolution of residential total final consumption by source.
D) Infrastructure			
8.1: Energy consumed for heating per square meter (kWh/m²), trend	Sufficient	Residential energy intensity 2016: 133 kwh/m² 2021: 119 kwh/m² (–6.4%). From 2016 to 2021, the average annual reduction in residential energy intensity was 2.8 kWh/m² per year, which is significantly above the EU benchmark (ECNO) of –1.3 kWh/m² per year.	IEA (2023d) Residential Energy intensity per country 2000–2020; Velten, Calipel, et al. (2023).
8.2: Homes treated with (high) energy efficiency measures (thousands/year), trend	Evaluation not possible	No data available.	

8.3: Share of households with energy storage (%), trend.	Evaluation not possible	No data available.	Solar Power Europe (2021) European Market Outlook for residential energy storage.
E) Market regulation			
9: Share of buildings using smart tariffs/ smart meters (%)	Sufficient	2022: 100%.	ACER/CEER (2022): Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets.
10: Subsidies for investment in fossil-fuel heating (EUR); trend	Sufficient	No subsidies are in place.	Williams et al. (2023): Subsidies for fossil heating appliances in the EU and UK.

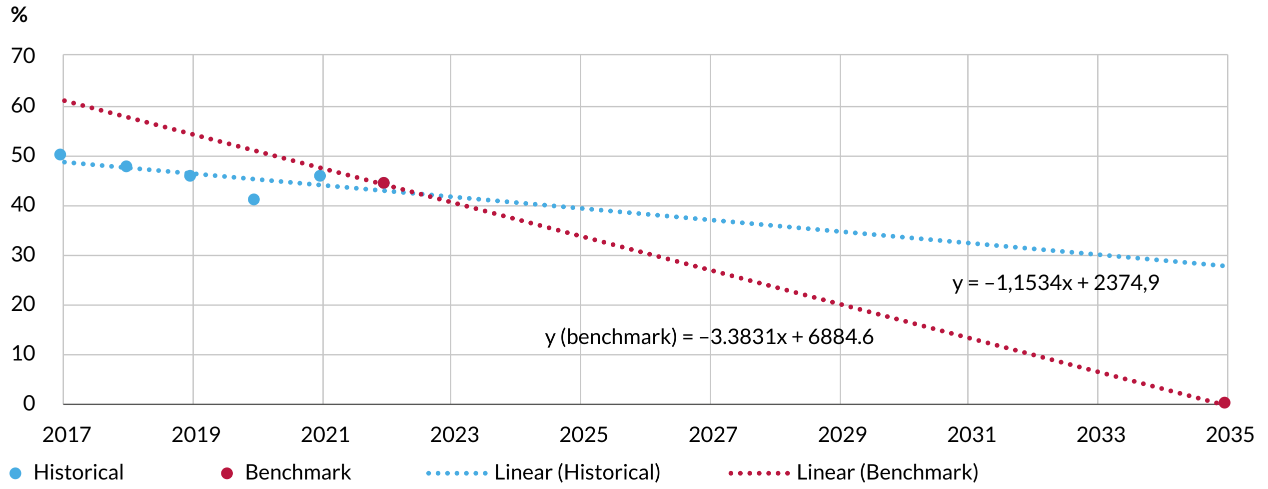
5.4 | United Kingdom

5.4.1 Electricity sector

The evaluation of the UK's progress in transitioning to zero-emission electricity shows significant advancements, especially with the rapid phase-out of coal, leading to a marked decrease in carbon intensity. However, the assessment reveals a mixed landscape, with five metrics deemed sufficient, seven partially insufficient, and four considered insufficient. Evaluation for the remaining factors was not feasible (Table 22).

The UK has set commendable targets for phasing out fossil fuel-based power generation, including unabated coal, by 2024 and achieving 100% low-carbon electricity (renewable energy complemented by nuclear power) by 2035. However, there is a need for clearer strategies on phasing out unabated gas. While the targets for renewable electricity capacity and generation share are adequate, further clarity is needed regarding transmission and distribution grids and energy storage. There is an ongoing consultation on a Centralised Strategic Network Plan. According to current plans, nuclear power will play a role in the future energy system, though it will be substantially minor compared to the central role of renewable energy sources, particularly offshore wind. The UK aims to be a global leader in offshore wind, targeting 50 GW by 2030, which is higher than Norway's target of 30 GW by 2040 and Denmark's target of 11.3 GW by 2030.

Figure 34 | Share of fossil fuels in the electricity mix, United Kingdom



Source: EMBER (2023).

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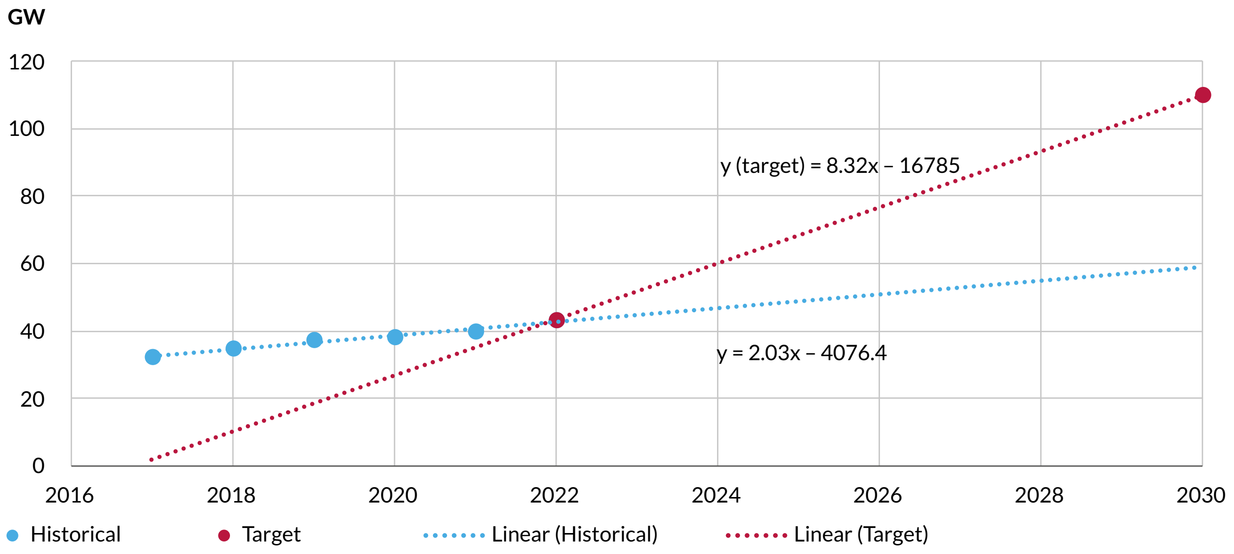
Figure 35 | Progress in renewable energy targets, United Kingdom

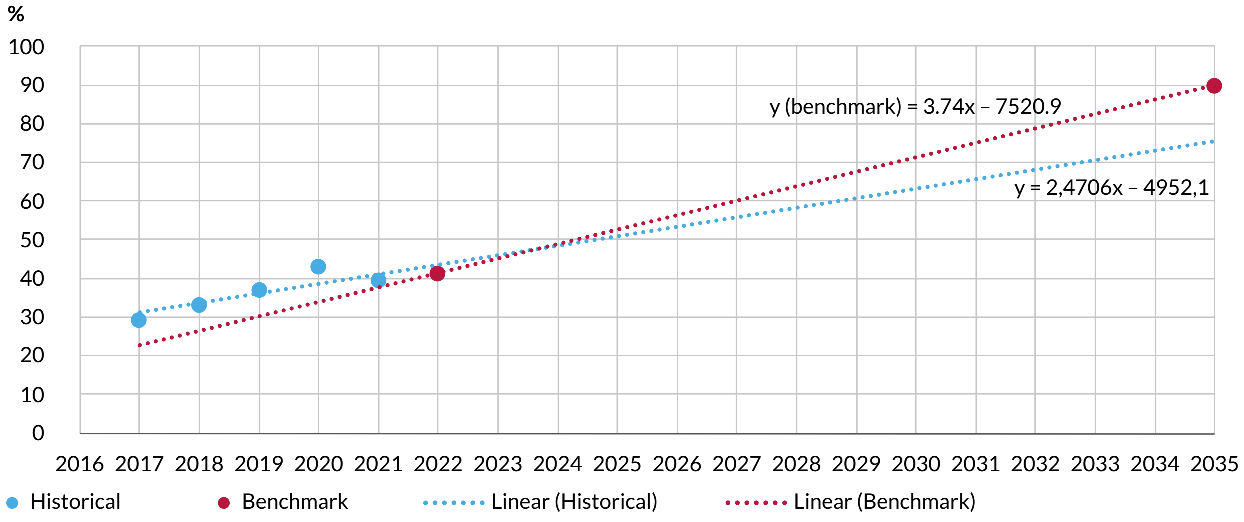


Source: EMBER (2023).

While the carbon intensity of UK electricity is lower than the OECD average and declining, the pace of emissions reduction needs to accelerate to achieve zero-emission status by 2035. Although there has been a significant reduction in CO2 emissions (–18.5% from 2017 to 2022), the annual average reduction still falls short of the necessary benchmark to achieve zero emissions by 2035. Coal usage has been nearly eliminated, but there is still resistance to phasing out gas (EMBER, 2023).

Variable renewables, such as wind and solar, have become the most cost-effective sources of electricity generation due to continuous cost reductions (–30% of the LCOE for onshore and offshore wind from 2017 to 2022). However, the rate of capacity additions for solar and wind power remains below the benchmark needed to reach 2030 capacity targets (Figure 35). Similarly, the growth in the share of renewable generation has not kept pace with the linear benchmark to achieve

Figure 36 | Progress toward zero-emission electricity by 2035 – United Kingdom



Source: EMBER (2023).

zero-emission electricity by 2035 (Figure 36). However, 2023 may mark a shift, with renewables covering more than 50% of electricity generation, indicating positive progress.

Regarding the state and expansion of electricity infrastructure, while the transmission system in England and Wales has seen some expansion, curtailment of renewable electricity highlights infrastructure insufficiencies, particularly in Scotland. Although higher than the EU average, energy storage capacity must continue to expand to meet future needs.

The occurrence of negative prices and high subsidies for fossil fuels underscore regulatory challenges. While subsidies for coal are low and will disappear with the phase-out of coal, subsidies for natural gas increased, particularly spiking in 2022 due to the energy crisis. This indicates the need for a more coherent regulatory framework.

In summary, while progress has been made in transitioning to zero-emission electricity, addressing challenges related to policy clarity, expanding and upgrading a flexible electricity grid, and improving regulatory frameworks will be crucial to accelerate the pace toward a zero-emission electricity system in the UK.

Table 22 | Assessment results – Electricity, United Kingdom

Variable/metric	Evaluation	Explanation	Sources
		A) Policy targets	
1. Targets for phase-out fossil fuel-based power generation (year)	Partially sufficient	Complete phase-out of unabated coal by 2024. All electricity must be derived from low-carbon sources by 2035. A clear strategy for the phase-out of unabated gas is required.	Bloomberg (2024): Global Coal Countdown; Climate Change Committee (2023): (Climate Change Committee, 2021) Independent Assessment: The UK's Net Zero Strategy.
2. Targets for renewable electricity capacity and/or generation share (%, year)	Sufficient	Generation share: 85% from renewable energy Sources by 2030. Capacity: Total renewables target of 110 GW, with 50 GW from offshore wind (including 1 GW from floating wind). There are no specific targets for onshore wind and solar power. The UK plans to continue developing nuclear power, maintaining its share around 10–15%.	IRENA (2024): Independent Assessment: The UK's Net Zero Strategy.
3.1. Targets for transmission development national (km)	Partially sufficient	For solar and wind combined, the transmission grids targets developed by the TSO are based on planned technology capacities of 120.4 GW by 2030, which are less ambitious than the latest national target for solar and wind (118 GW). In 2023, the Climate Change Committee recommended a new long-term cross-sectoral infrastructure strategy. A Centralised Strategic Network Plan is under consultation by OFGEM as of December 2023.	EMBER (2023); Climate Change Committee (2023): Delivering a reliable decarbonised power system.
3.2 Targets for distribution network (km)	Partially sufficient	No official targets. However, the government launched the Great Grid Upgrade plan in 2024, providing financial support for the extension of the transmission and distribution grid.	
3.3 Targets for electricity storage (GW or GWh)	Partially sufficient	The UK has no specific targets for storage capacity, except for hydrogen, with a goal of 5 GW of low-carbon hydrogen production capacity by 2030. The national grid operator ESO estimated that the UK will need over 50 GW of energy storage installed by 2050 to achieve net-zero emissions in a best-case scenario.	National Grid ESO (2023): Future Energy Scenarios; Government of the United Kingdom (2023b): UK hydrogen strategy.

B) Phase-out of carbon-intensive technologies			
4.1: CO2 emissions of electricity generation (Mt CO2e), trend	Partially sufficient	CO2 emissions from electricity decreased by 18.5% from 2018 to 2022. However, the average yearly reduction of CO2 emissions (–3.9 mtCO2) falls short of the necessary benchmark (–6.4 mtCO2) needed to achieve zero emissions by 2035.	EMBER (2023); Own calculations.
4.2: carbon intensity of electricity (gCO2e/kWh), trend	Sufficient	The carbon intensity of electricity in the UK of 256 gCO2/kWh is lower than the OECD average of 373 gCO2/kWh, and it decreased by 15% from 2017 to 2022.	EMBER (2023); Own calculations.
5. Share of fossil fuel-based power generation (%)	Partially sufficient	While the share of fossil fuel-based power generation is decreasing, it is doing so at a slower rate (–1.15% per year) than the benchmark needed for zero emissions by 2035 (–3.38% per year). There has been a substantial reduction in coal use, but there is ongoing resistance to phasing out gas.	EMBER (2023); Own calculations.
C) Phase-in of zero-carbon technologies			
6.1: LCOE (USS/MWh), national trend; solar PV.	Sufficient	Variable renewables, such as wind and solar, have become the cheapest form of electricity generation due to continuous cost reductions. LCOE in 2022: Solar PV (utility-scale): USD 68.4/MWh Gas (1st gen. technology): USD 113/MWh Gas (2nd gen. technology): USD 94/MWh Nuclear (2020): USD 106/MWh Cost reduction (2017–2022) of solar PV: LCOE decreased by 15%.	ENERDATA (2024).
6.2: LCOE (USS/kWh), national trend; wind power.	Sufficient	Wind Onshore: LCOE decreased by 30% (2017–2022), now at $52.4/MWh. Wind Offshore: LCOE decreased by 28% (2017–2022), now at $91.4/MWh. The LCOE for both onshore and offshore wind is now lower than that of fossil fuel technologies.	ENERDATA (2024).
7.1: Capacity added (GW/year) trend; average for solar and wind power	Partially sufficient	From 2018 to 2022, the yearly new installed solar and wind capacity was 2.03 GW. An annual 8.3 GW are needed to reach the 2030 capacity targets (110 GW). While the capacity added per year is increasing, it remains below the required benchmark.	EMBER (2023); Own calculations.
7.2: Share of renewables in electricity generation (%), trend; average for RE technologies	Partially sufficient	From 2017 to 2022, the share of RE generation grew by an average of 2.47% per year. To achieve 90% renewables and 10% nuclear power by 2035, a minimum annual growth rate of 3.74% is needed. This growth has been below the linear path to the target. However, in 2023, the situation improved significantly, with renewables covering more than 50% of electricity generation.	(EMBER, 2023); Own calculations.
D) Infrastructure			
8: Curtailment of RE (%), trend	Insufficient	In 2020 and 2021, there were 5.8 TWh of wind curtailments due to system actions, enough to power 800,000 homes. This issue primarily affects wind generation in Scotland.	Nycander et al. (2020) Insight Clarity Advice (2022).
9.1: Transmission lines (km)	Evaluation is not possible	The transmission system in England and Wales includes approximately 7,200 kilometers of overhead lines and 1,400 kilometers of underground cables, operating at 275kV and 400kV. As of 2022, the UK had 7.4 GW of interconnector capacity, with several plans for expansion.	IEA (2022).

9.2: Distribution lines (km), trend	Evaluation is not possible	In 2021, the onshore electricity network comprised approximately 800,000 kilometers of lower voltage distribution lines.	Government of the United Kingdom (2022): British energy security strategy.
9.3: Energy storage as a % of variable renewable capacity (%)	Sufficient	In 2023, the rate of energy storage (both operational and under construction) was 22.4% (9.7 GW), higher than the EU average of 13%. The primary storage sources are electricity storage and pumped hydro. The storage capacity needs to continue expanding to meet future demands.	ENERDATA (2024).
E) Market regulation			
10: Negative prices for electricity (hours); trend	Insufficient	Negative electricity prices have increased from 112 (1.3% of hours) in 2019 to 214 (2.4%) in 2023.	Staffell et al. (2023).
11: Subsidies from coal and natural gas (US$); trend	Insufficient	Subsidies for coal remained stable at around USD 800 million from 2016 to2021. Subsidies for natural gas increased from USD 5.4 billion to USD 6 billion (+ 12%) from 2016 to 2021. Natural gas subsidies surged to almost USD 17 billion in 2022 due to the energy crisis.	OECD and IISD (2024).
12: Average time for permission process, wind power (months)	Evaluation is not possible	Data is not available.	
Support to the expansion of renewable energy	Evaluation is not possible	Data is not available.	

5.4.2 Road transport

The overall progress of the UK's road transport transition is deemed partially insufficient, as it is not yet aligned with the objective of achieving zero emissions in line with the Paris Agreement. The evaluation reveals two indicators as sufficient, four as insufficient, and six as partially insufficient (Table 24).

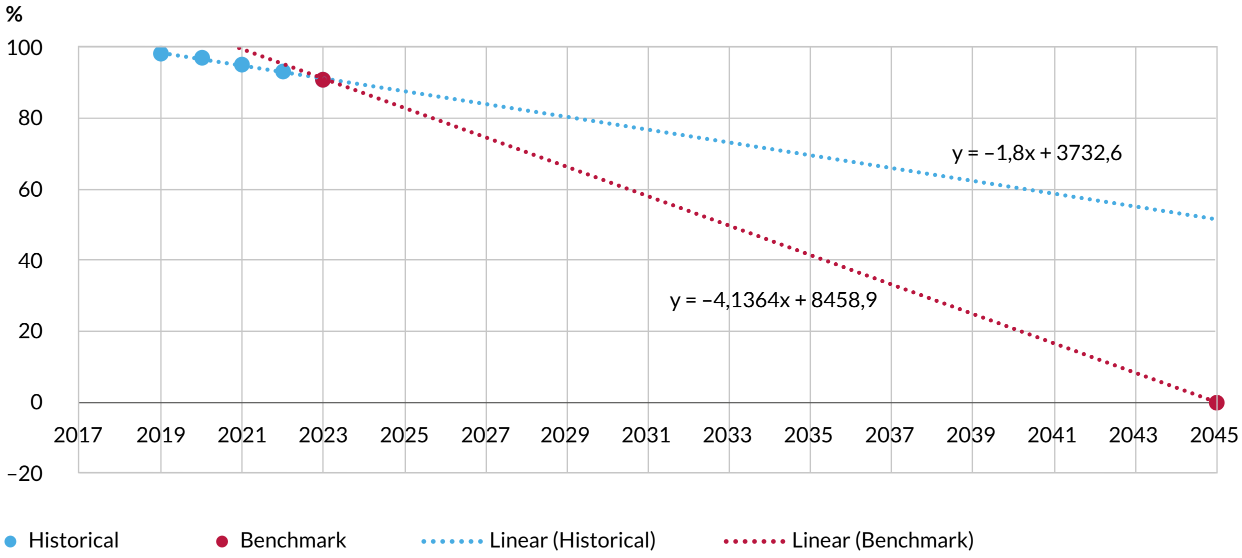
In 2023, the government enacted a zero-emission vehicles mandate for 2035 (originally planned for 2030), aiming to increase the share of zero-emission sales from 22% in 2024 (for cars) to 80% in 2030 and 100% in 2035. However, these targets are evaluated as partially insufficient because a trajectory compatible with the 1.5°C temperature target would require 100% zero-emission sales by 2030 at the latest (Plötz et al., 2021). Moreover, like other countries, the UK has no target or regulation to phase out the remaining ICE vehicles in the coming years.

In 2023, the UK government developed a new strategy aiming for 300,000 public charging points by 2030. While this is a positive step, the intermediate target is not high enough compared to the infrastructure needed for a zero-emission car transport system.

The UK is making progress in reducing CO2 emissions from transport. CO2 emissions decreased from 71.8 metric tons in 2016 to 57.8 metric tons in 2021, which exceeds the reduction needed on a linear path to zero emissions by 2045. However, it is worth noting that 2021 was still partially affected by the COVID-19 pandemic. The phase-out of ICE cars, which still represented 91% of the total car fleet in 2023, is progressing too slowly and is thus considered partially insufficient for long-term targets. Additionally, the share of transport by car in total passenger transport has slightly increased, highlighting the difficulty in advancing a modal shift in transport.

The average price of EVs has only decreased by 2% since 2019, reaching EUR 50,500 in 2023, which is considerably more expensive than a medium ICE car (EUR 26,000 in 2023). Despite this, sales of EVs are rapidly increasing amidst a context of decreasing total car sales (Table 23). In 2022, battery-electric car registrations rose by around 40.1% to approximately 267,200 units, while diesel car registrations slumped to nearly 83,000 units. The share of total EVs is almost in line with the linear pathway to achieving 100% zero-emission car sales by 2035. The share of EVs in the total car fleet is still small but increasing.

Figure 37 | Share of ICE cars in total passenger cars, United Kingdom



Source: Government of the United Kingdom (2024).

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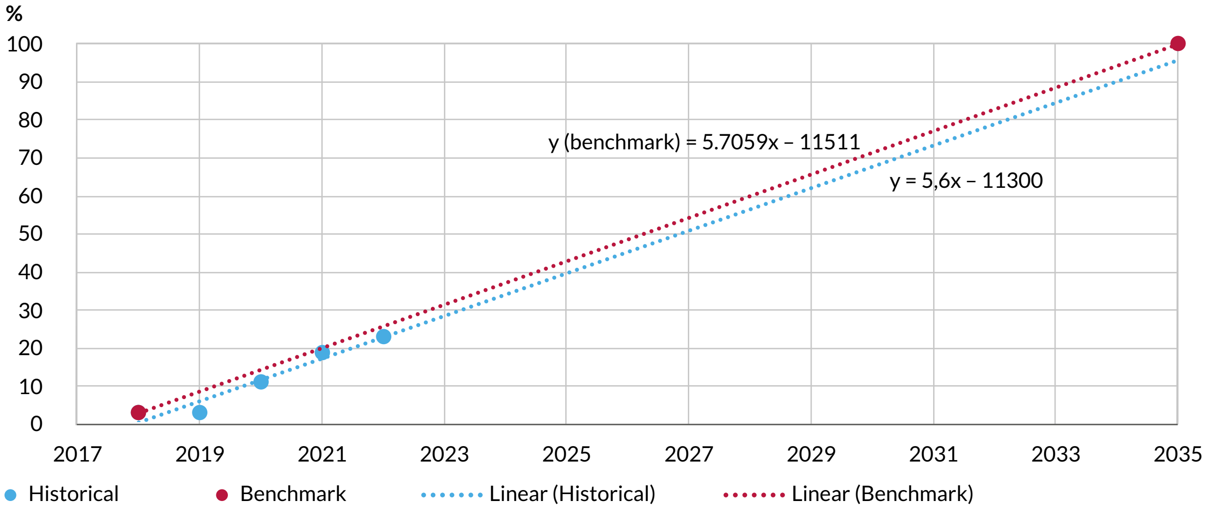
Table 23 | Car sales in the United Kingdom (first-time registered vehicles)

Car sales	2018	2019	2020	2021	2022
Full electric (EVs)	15,510	37,850	108,210	190,730	267,200
Plug-in hybrid	42,230	34,980	66,880	114,550	101,410
Plug-in + EVs	57,740	72,830	175,090	305,280	368,610
Total car sales	2,367,140	2,311,140	1,630,470	1,647,180	1,614,050

Source: SMMT UK (2023).

Figure 38 | Share of EVs (including plug-in hybrid) in total car sales, United Kingdom



Source: IEA (2023c).

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Finally, the state of public charging infrastructure is deemed insufficient compared to the EU guideline. In 2021, there was one public charger per 21 EVs. The installation of public chargers increased from 2,500 in 2018 to 13,900 in 2022, but this remains insufficient.

Table 24 | Assessment results – Road transport, United Kingdom

Variable/metric	Evaluation	Explanation	Sources
A) Policy targets			
1. Target for ICE vehicles phase-out (year).	Insufficient	No national target set.	
2. Target share of zero-emission vehicles in total car sales (%)	Partially sufficient	2035: 100% of car sales must be zero-emission To meet the 1.5-degree target for the transport sector by 2030, all car sales should be zero-emission. Although the UK has a target, it is not ambitious enough.	UK Gov. (2023): Zero Emission Vehicle Mandate and CO2 Regulations; Teske et al. (2022).
3. Target for number of public charging points (Nb per EV)	Partially sufficient	2030: 300,000 public chargers 2050: 37.4 million EVs in the UK, requiring around 3.7 million chargers to maintain a ratio of 10 EVs per public charger. Calculating a linear path from the 2030 target, the UK would have nearly 720,000 chargers by 2050. This indicates that the current target is not on a linear path to meet the needs of a net-zero transport system by 2045.	Government of the United Kingdom (2023a): the EV infrastructure strategy; Electricity System Operator and Octopus Energy Group (2023): EVs and Electricity; Own calculation
B) Phase-out of carbon-intensive technologies			
4. GHG emissions of road transport (mt CO2e), trend	Sufficient	From 2016 to 2021, 14.3 mtCO2 reduction (20% decrease). Emissions have decreased at a faster rate (–3.7 mtCO2 per year) than the benchmark rate (–2.4 mtCO2) needed for zero emissions by 2045.	United Nations Climate Change (2023); Own calculation.
5. Share of ICE in total cars (%), trend	Insufficient	2019: 98% 2023: 91% From 2019 to 2023, the yearly decrease in the share of ICE cars was –1.8%, significantly lower than the benchmark rate of –4.14% needed to reach zero emissions by 2045.	Government of the United Kingdom (2024): Vehicle licensing statistics tables. Table: VEH0105; Own calculation.
6. Share of passenger transport by cars (%), trend	Insufficient	From 2015 to 2019, passenger transport by car increased by 1%. From 2016 to 2021, the EU average increase was 3%. The overall trend for passenger transport by car is increasing EU-wide and is likely influenced by the COVID-19 pandemic.	Eurostat (2023b).
C) Phase-in of zero-carbon technologies			
7. Average purchase prices of EVs and ICE cars (EUR); trend	Partially sufficient	In 2023, the average price for a medium ICE car was €26,000, while the average price for an EV was €50,500. Although EV prices are higher, they have been slowly decreasing at a rate of –2% from 2019 to 2023.	Statista (2024h): Medium cars – United Kingdom; Statista (2024d): Electric Vehicles – United Kingdom.
8.1 Share of EVs in total car sales (%); trend	Partially sufficient	In 2022, EVs constituted 23% of total car sales, which is an increase of 5.6% per year from 2018 to 2022. This growth rate is nearly aligned with the necessary 5.7% annual increase needed to achieve a 100% EV target by 2035.	IEA (2023c): EV sales share 2011–2022; Own calculation.

8.2 Share of EVs in total car fleet (%); trend	Partially sufficient	In 2022, EVs comprised 2.8% of the total car fleet. To meet the 2050 target of having a minimum of 66% of all cars as EVs, at least 9% of the car stock should have been EVs by 2022. Although the current share of EVs is still low, it is increasing.	IEA (2023c): EV stock share 2011–2022; Climate Analytics (2023b): 1.5°C national pathway explorer United Kingdom; Own calculation.
D) Infrastructure			
9. Public charging points density (Nb per EV)	Insufficient	In 2021, the UK had 21 EVs per public charger, compared to the EU average of 15.5 EVs per public charger. This falls short of the EU guideline, which recommends one public charger for every 10 EVs.	IEA (2023c): Trends in charging infrastructure; EU-guideline 2014/94/EU (23).
10. Public charging points installed per year; trend (Nb/year)	Partially sufficient	Looking ahead, the UK will need approximately 3.7 million public chargers by 2050, requiring an annual installation rate of 125,000 chargers. Although the rate of charger installation is increasing, it is still below the necessary linear path to meet future demands.	IEA (2023c): EV charging points 2017–2022 worldwide by country; Electricity System Operator and Octopus Energy Group (2023): EVs and Electricity; Own calculation.
E) Market regulation			
11. Subsidies for ICE cars (EUR); trend	Partially sufficient	Subsidies for petroleum, which are directed to consumers and not limited to cars, are decreasing. They have dropped from USD 94 per capita in 2018 to USD 77 per capita in 2022.	OECD & IISD, 2024.

5.4.3 Heating sector

The progress in transitioning to zero-emission heating in the UK is currently insufficient. Of the assessed variables, only two are considered sufficient, four are partially insufficient, eight are insufficient, and two lack adequate data (Table 25).

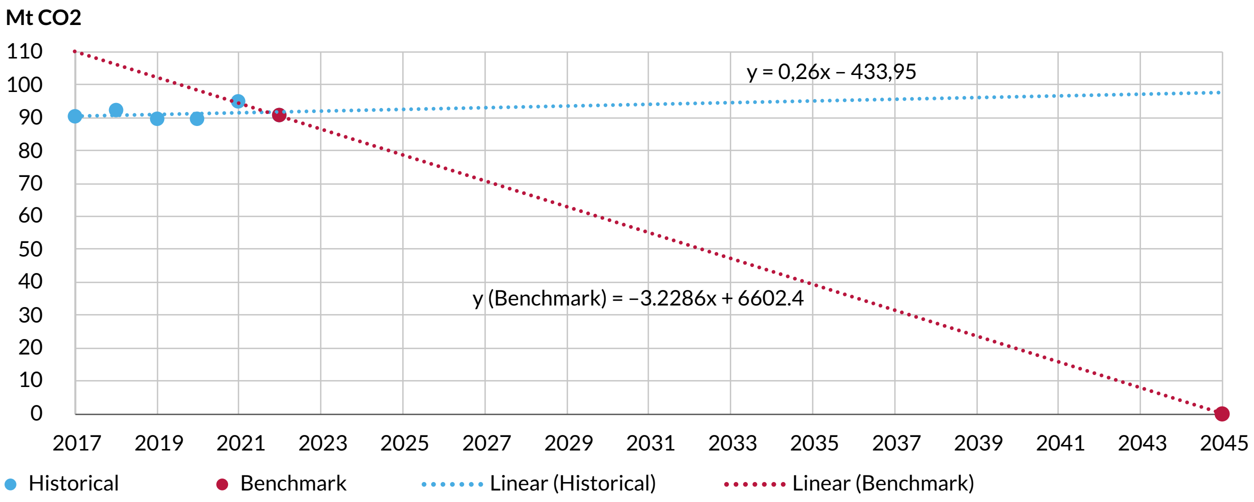
The UK's approach to heating decarbonization reflects a mixed picture. While there are set goals, such as the cut-off dates for new fossil boilers (2026/2035, see Table 25) and ambitious targets for heat pump deployment (600,000 per year by 2028), some critical aspects remain lacking. Notably, there are no explicit targets for energy consumption per square meter or building renovation rates, indicating an incomplete decarbonization strategy. In September 2023, planned regulations for minimum energy efficiency standards for rental properties (MEES) were scrapped, among other plans canceled or paused by the government. This lack of specificity raises concerns about achieving a 100% net-zero heating sector by 2045, especially given the ongoing extensive use of gas heating systems and the relatively late phase-out date of 2035 for buildings on the gas grid.

CO2 emissions from direct building energy use have increased by 0.3 metric tons of CO2 per year from 2017 to 2022. This trend is not aligned with the zero-emission linear benchmark, which requires a decrease of 3.2 metric tons per year. Efforts to phase out fossil fuel consumption in the heating sector have faced challenges. While there has been a decrease in oil and coal consumption, natural gas usage has increased and remains the primary source for heating.

The cost dynamics and deployment rates of climate-friendly technologies, particularly heat pumps, remain a concern. Although there has been a relative increase in heat pump installations (+130% from 2018 to 2022), the total numbers fall short of national targets. Moreover, the cost comparison between heat pumps and traditional gas boilers still favors the latter, posing a barrier to the widespread adoption of heat pumps. To boost the deployment of heat pumps, the government is discussing a market-based approach instrument by the end of 2023, a new "low-carbon heat scheme." This scheme will place an obligation on manufacturers of fossil fuel heating appliances to meet a rising standard for heat pump sales as a proportion of their total appliance sales. Manufacturers can meet the new standard either through their own heat pump sales, by purchasing credits from other heat pump manufacturers, or a mix of both.

Energy efficiency in residential buildings, a cornerstone of the transition to zero-emissions heating, has shown signs of stagnation. The failure to meet bench-

Figure 39 | CO2 emissions from direct building energy use, United Kingdom



Source: European Commission & Joint Research Centre, 2024.

marks for yearly reductions in energy consumption per square meter, which remained constant at around 167 kWh/m² from 2016 to 2021, indicates a lack of progress in improving infrastructure efficiency. This stagnation corresponds to a clear decline in building renovations over the last decade (IEA, 2023). On the positive side, 56% of homes were equipped with smart meters in 2022, and the government aims to install over 50 million smart meters (electricity and gas) by the end of 2024, which may enable demand flexibility.

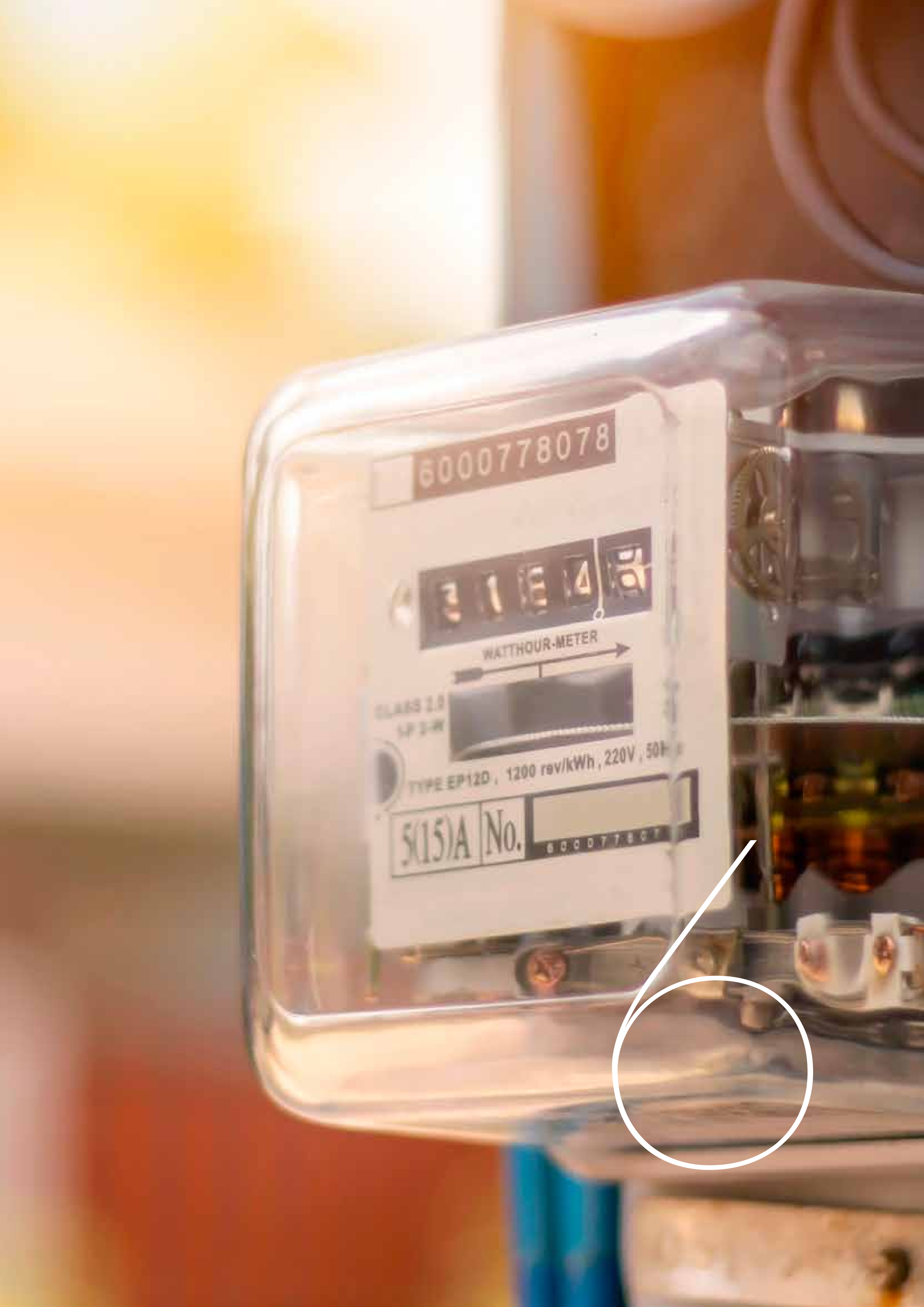
The regulatory landscape surrounding heating subsidies and investments is complex. While subsidies are available for climate-friendly heating systems (particularly heat pumps), a portion of the budget continues to support fossil fuel alternatives. This discrepancy between policy objectives and investment priorities underscores the need for greater alignment to accelerate the transition to zero-emission heating.

In summary, despite the government setting a decarbonization strategy in 2021, the journey toward zero-emissions heating in the UK faces significant challenges. These range from policy ambiguities and infrastructure limitations to insufficient deployment dynamics.

Table 25 | Assessment results – Heating, United Kingdom

Variable/metric	Evaluation	Explanation	Sources
A) Policy targets			
1: Targets for phase-out oil and gas heating systems (year).	Partially sufficient	Cut-off dates for installing new fossil boilers: 2026 for off-grid homes 2035 for buildings on the gas grid Due to the relatively late phase-out date and the remaining stock of fossil heating systems, it is questionable whether a 100% net-zero heating sector will be achieved by 2045.	Government of the United Kingdom (2021): Heat and Buildings Strategy; Climate Change Committee (2020): trajectories for residential heat decarbonization.
2.1: Target for new heat pumps (Nb)	Sufficient	600,000 heat pump installations per year by 2028, with a third coming from new buildings 1.9 million installations per year by 2035 Current projections suggest 16.2 million heat pumps will be installed by 2050, in line with the CCC (2021) benchmark.	Government of the United Kingdom (2021): Heat and Buildings Strategy; OECD and IEA (2022): The Future of Heat Pumps; Climate Change Committee (2020).
2.2: Target for share of zero-carbon heating (%)	Partially sufficient	While no explicit targets have been set, there is a plan for achieving total decarbonization by 2050. Anticipated heat production from low-carbon district heat networks: 15–29 TWh by 2035 and 70 TWh by 2050. In 2026, a strategic decision about hydrogen in the heating system will be made. The current plan is to reuse the gas grid for low-carbon heating. Meanwhile, the UK is prioritizing building markets and supply chains, testing options, and ensuring support is available to households on the gas grid who want to switch to low-carbon heat now.	Government of the United Kingdom (2021): Heat and Building Strategy.
3.1: Target for energy consumed for heating per m²	Insufficient	While no target has been set, there are the following anticipated regulations: 2025 Future Homes Standard: new homes are to produce 75–80% less emissions than current building regulations. By 2030, all fuel-poor homes should be upgraded to Energy Performance Certificate (EPC) Band C (66–100 kWh/m²). The UK aims to reduce its final energy consumption by 15% by 2030, compared to 2021 levels.	Government of the United Kingdom (2018): Clean Growth Strategy.
3.2: Target for building renovation per year (%)	Insufficient	Though no specific target has been set, the aim is to upgrade all fuel-poor homes to EPC Band C by 2030.	Government of the United Kingdom (2018): Clean Growth Strategy.
3.3: Target for buildings with thermal energy storage (%).	Insufficient	No specific target has been set.	
B) Phase-out of carbon-intensive technologies			
4: CO2 emissions from direct building energy use (mtCO2e), trend	Insufficient	2017: 90.4 mtCO2 2022: 90.5 mtCO2 (+0.11%) From 2017 to 2022, emissions increased at an average rate of 0.3 mtCO2 per year. To achieve zero emissions by 2045, a minimum reduction of 3.2 mtCO2 per year is needed. This current trend is moving in the wrong direction.	European-Comission and Joint-Research-Centre (2024); Climate Analytics, (2023a); Velten, Calipel, et al. (2023).
5: Phase-out oil and gas heating systems	Insufficient	Fossil fuel consumption from 2017 to 2021: Natural gas: +4% (1,031,589 Tj in 2021) Oil products: –6% (92,772 Tj in 2021) Coal: –21% (17,953 Tj in 2021) While there has been a decrease in the consumption of oil and coal, the use of natural gas, which is the main fuel for heating, has increased.	IEA (2023d) Evolution of residential total final consumption by source.

C) Phase-in of zero-carbon technologies			
6: Heat pumps total purchase cost (USD)	**Insufficient**	Total investment cost for 2021: Air-to-air heat pump: USD 9,500 Gas condensing boiler: USD 3,200	IEA (2021b): Residential Heat Economics Calculator.
7.1: Installed (new) heat pumps; trend	**Partially sufficient**	2018: 25,925 2019: 31,315 2021: 42,759 2022: 59,862 Despite a strong relative increase in heat pump sales, the total numbers are still well below the national target of 600,000 by 2028 and the goal for zero emissions by 2045.	EHPA (2023): Heat Pumps in Europe; Observ'ER (2020): Heat Pumps Barometer; Climate Change Committee (2020): Trajectories for Residential Heat Decarbonization.
7.2: Share of buildings with climate-neutral heating (%), trend.	**Insufficient**	Data on the exact percentage of buildings with climate-neutral heating is not available. However, in 2021, the final energy consumption in the residential sector was as follows: Natural gas: 66% Oil products: 6% Coal: 1% Electricity: 25% Biofuels: 2% District heating: 0.7% Wind and solar: 0.1% From 2016 to 2021, the share of renewable sources (including electricity) remained around 28%, showing no progress.	UK Energy Statistics (2023): Renewables' shares.
D) Infrastructure			
8.1: Energy consumed for heating per square meter (kWh/m^2), trend	**Insufficient**	Residential energy intensity: 2016: 0.6 gj/m^2 (167 kwh/m^2) 2021: 0.6 gj/m^2 (167 kwh/m^2) No progress has been made in energy efficiency, failing to meet the benchmark of at least a 1.3 kWh/m^2/year reduction.	IEA (2023d): Residential Energy intensity per country 2000–2020; Velten, Calipel, et al. (2023).
8.2: Homes treated with (high) energy efficiency measures (thousands/year), trend	Evaluation not possible	No data available.	
8.3: Share of households with energy storage (%), trend.	Evaluation not possible.	Annual installation of BESS: 2019: 65 MWh 2020: 81 MWh Insufficient data is available to determine a trend.	Solar Power Europe (2021).
E) Market regulation			
9: Share of buildings using smart tariffs/ smart meters (%)	**Sufficient**	2021: 49% 2022: 56% By 2024, 80% of all households should be equipped with a smart meter.	ACER/CEER (2022).
10: Subsidies for investment in fossil-fuel heating (EUR); trend	**Partially sufficient**	Subsidies in 2022: Total subsidies: €260 million 11% (EUR 28.6 million) for fossil fuel heating systems 17% (EUR 44.2 million) for biomass 72% (EUR 187.2 million) for low-carbon systems The subsidies supporting fossil fuel systems were provided through the Warm Home Discount (EUR 9 million) and Energy Company Obligation (ECO) Schemes (EUR 18 million) in 2022.	Williams et al. (2023).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6

6 | ACHIEVING ZERO EMISSIONS: SECTORAL LEADERS AND KEY ISSUES

6.1 | Electricity

Norway shows the best performance overall when it comes to the transition to a zero-emission electricity system (Figure 40). The country has made significant progress across most metrics, driven by its historically decarbonized electricity production, which relies on hydropower and, more recently, offshore wind. Norway has completely phased out coal and nearly phased out gas, resulting in an exceptionally low carbon inten-

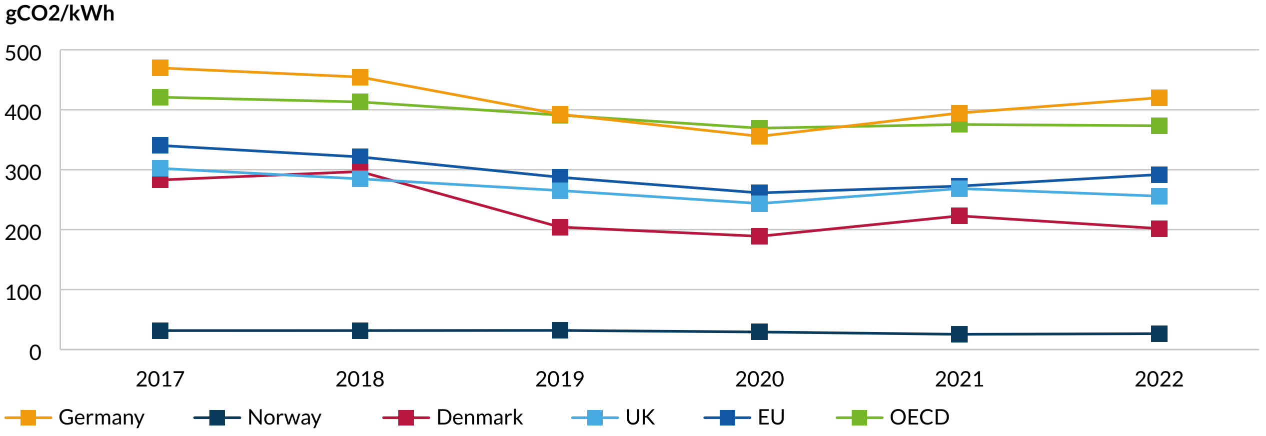
Figure 40 | Synthesis of the results – Electricity

		Germany	Norway	Denmark	United Kingdom
Targets	Fossil fuels phase out	🟧	🟩	🟩	🟧
	Renewable electricity	🟩	🟩	🟩	🟩
	Transmission network	🟧	🟧	🟩	🟧
	Distribution network	🟥	🟧	⬜	🟧
	Storage	🟧	🟧	🟧	🟧
Phase out	CO2 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	🟥	🟩	🟧	⬜
	Distribution network	🟧	⬜	⬜	⬜
	Storage	🟧	🟩	🟧	🟩
Regulation	Negative prices	🟥	🟧	🟥	🟥
	Subsidies coal & gas	🟥	🟩	🟥	🟥
	Time permission process	🟧	⬜	⬜	⬜
	Public support	🟩	⬜	🟩	⬜

🟩 sufficient 🟧 partially sufficient 🟥 insufficient ⬜ evaluation is not possible

Source: Authors' elaboration.

Figure 41 | Carbon intensity of electricity (2017–2022)



Source: EMBER (2023).

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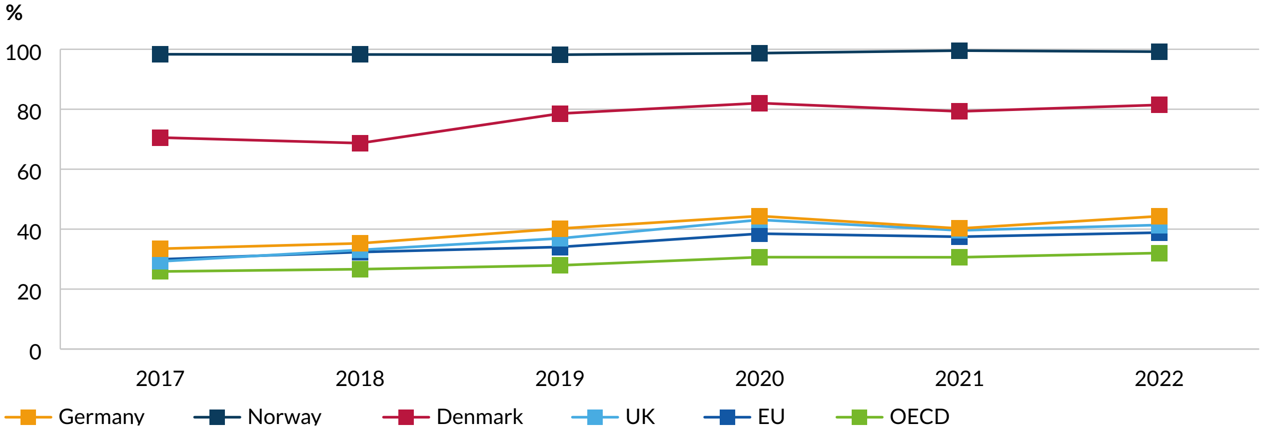
sity, 16 times lower than Germany's in 2022 (Figure 41). The challenge in the coming years lies in expanding the power system and integrating new flexibility to meet the growing demand driven by rapid electrification in sectors like transportation, heating, and partially, industry.

The four countries analyzed exhibit a higher share of renewable energy in electricity generation compared to the EU and OECD averages, with Norway and Denmark leading the pack (Figure 42). Denmark has excelled in deploying onshore and offshore wind power and phasing out coal and gas power generation. The UK is rapidly phasing out coal – down from 30% in 2000 to almost zero today – although gas remains significant (38% in 2022). Germany has concluded the phase-out of nuclear power but still has a high share of both coal (33%) and gas (16%) in 2022.

Overall, there is a need to shift from a sole focus on electricity generation to a more systemic approach, encompassing clear targets and strategies for infrastructure development and aligning electricity grids with future renewable energy deployment. All countries face varying degrees of insufficiency in their electricity grids, which are not yet fully ready to integrate rapidly increasing wind and solar generation, as reflected in curtailment and negative prices (Figure 43).

Figure 42 | Share of renewable energy in electricity generation



Source: EMBER (2023).

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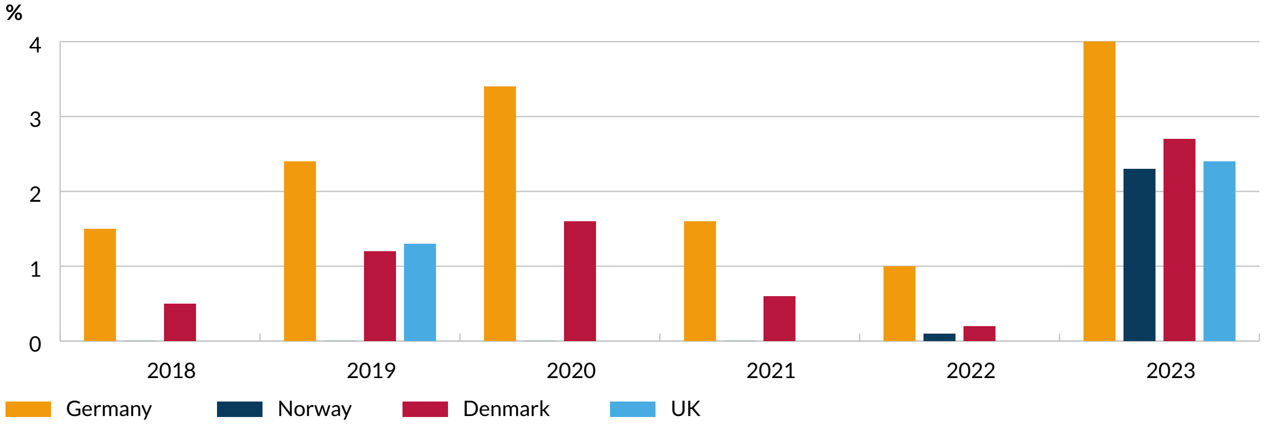
Clear targets and policy strategies are imperative for the expansion and upgrading of electricity grids, encompassing transmission, distribution, and storage. In this regard, the Danish TSO offers a good example of planning the expansion of transmission grids based on future (higher) targets for renewable energy deployment. Additionally, monitoring the share of energy storage relative to variable energy capacity (Figure 44) serves as a key indicator. The UK represents a good example of electricity storage, with 2.6 GW operational, 3.7 GW under construction, and 25.7 GW under development as of March 2024. The country is also advancing in new pumped hydro storage facilities and chemical storage, including H2 production (ENERDATA, 2024).

Moreover, while data on electricity generation and installed capacity are abundant, information on electricity grids is often scarce and inconsistent. Ensuring reliable, comparable, and open data is crucial for continually monitoring energy infrastructure development on the path to a zero-emissions future.

Figure 43 | Negative prices in wholesale electricity markets



Source: European Environment Agency (2023a).

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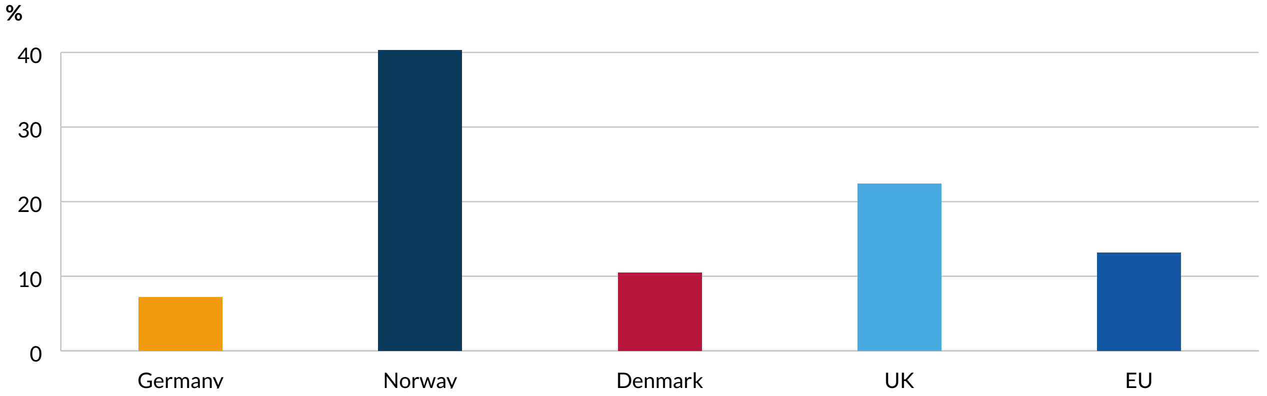
Figure 44 | Energy storage (operational and under construction in March 2024) as a percentage of variable renewable installed capacity



Source: ENERDATA (2024b).

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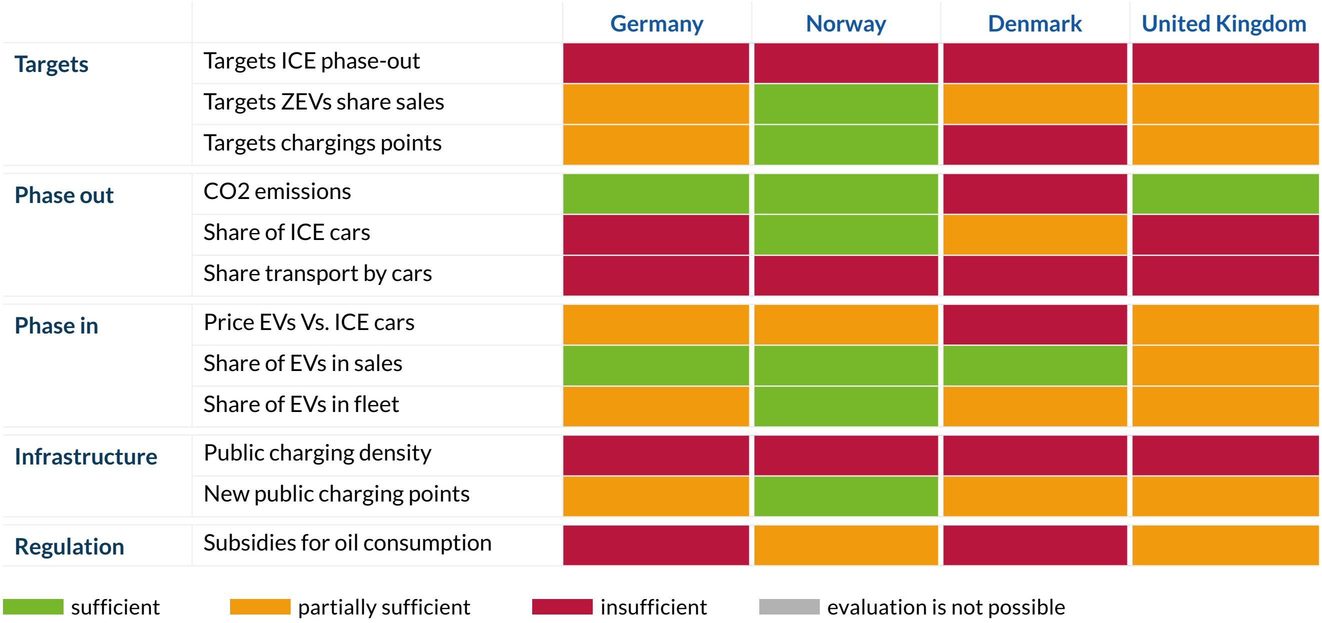
6.2 | Road transport

Norway stands out as the frontrunner in the transition to a zero-emission road transport sector, with seven indicators deemed sufficient and only five categorized as partially insufficient or insufficient. Notably, the Nordic nation is rapidly diminishing the share of ICE cars, resulting in a substantial reduction of related CO2 emissions (–22% from 2016 to 2021). If current trends persist, Norway is on course to achieve zero emissions before 2045. The country's notable trajectory positions it at the forefront globally, with EVs and plug-in hybrids projected to reach 100% by 2025.

In contrast, the other three countries – Denmark, Germany, and the UK – are encountering challenges in reducing the share of ICE cars within their total car fleets, as illustrated in Figure 46. The current rate of

Figure 45 | Synthesis of the results – Road transport



		Germany	Norway	Denmark	United Kingdom
Targets	Targets ICE phase-out	🟥	🟥	🟥	🟥
	Targets ZEVs share sales	🟧	🟩	🟧	🟧
	Targets chargings points	🟧	🟩	🟥	🟧
Phase out	CO2 emissions	🟩	🟩	🟥	🟩
	Share of ICE cars	🟥	🟩	🟧	🟥
	Share transport by cars	🟥	🟥	🟥	🟥
Phase in	Price EVs Vs. ICE cars	🟧	🟧	🟥	🟧
	Share of EVs in sales	🟩	🟩	🟩	🟧
	Share of EVs in fleet	🟧	🟩	🟧	🟧
Infrastructure	Public charging density	🟥	🟥	🟥	🟥
	New public charging points	🟧	🟩	🟧	🟧
Regulation	Subsidies for oil consumption	🟥	🟧	🟥	🟧

🟩 sufficient 🟧 partially sufficient 🟥 insufficient ⬜ evaluation is not possible

Source: Authors' elaboration.

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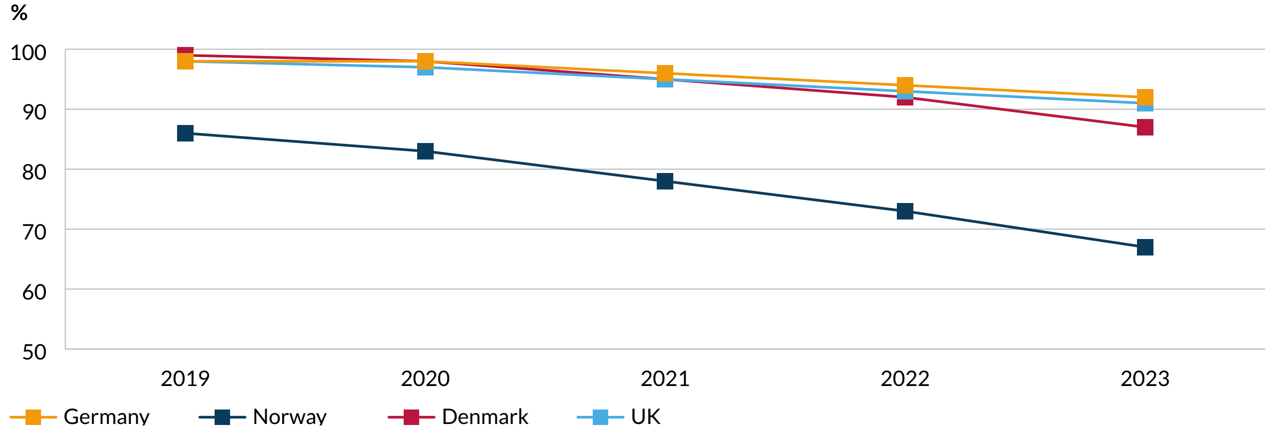
Figure 46 | Phase-out of ICE cars



Note: Share of internal combustion cars in total car stock.
Source: Statista (2024), Statistics Norway (2023), IEA (2023), UK Government (2024).

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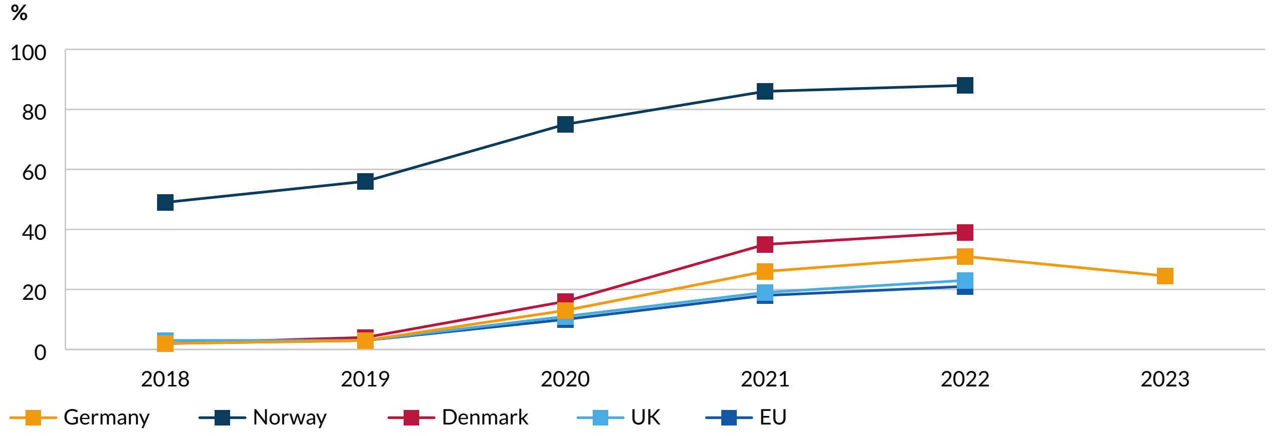
Figure 47 | Phase-in of electric and hybrid plug-in vehicles



Note: Share of EVs and hybrid plug-in vehicles in total car sales.
Source: IEA (2023c).

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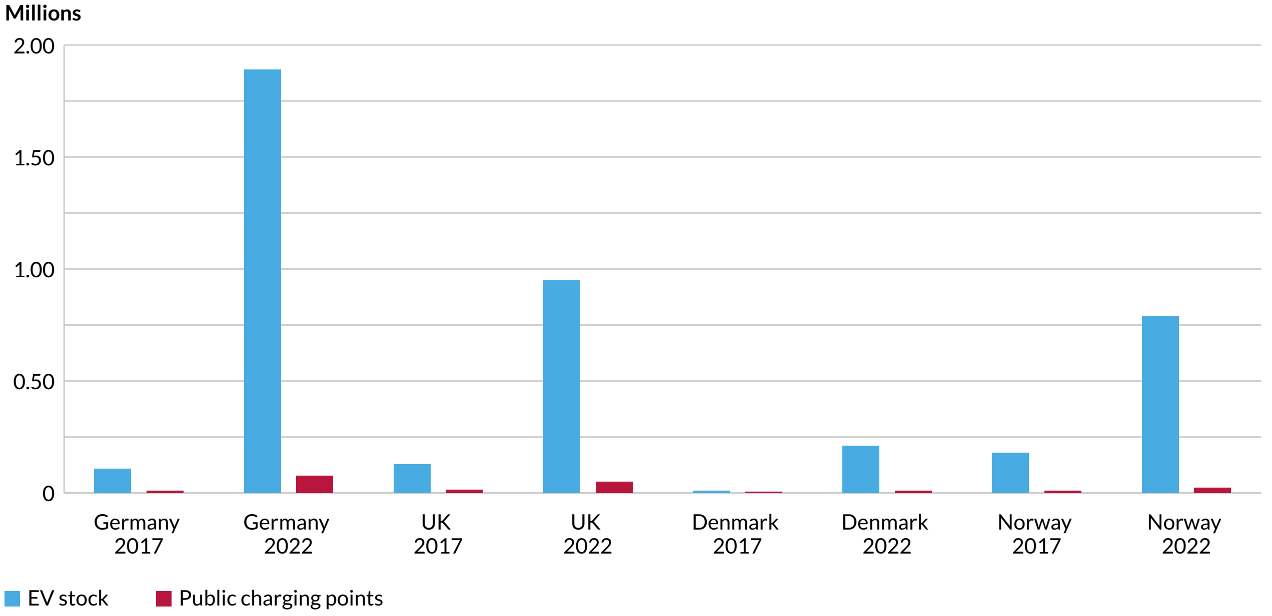
reduction is insufficient to attain zero emissions by 2045 in these countries. However, Denmark demonstrates a slightly faster pace in phasing out ICE cars compared to Germany and the UK. Notably, Denmark excels in EV sales, constituting 40% of total car sales in 2022 (Figure 47). In contrast, the UK and Germany are lagging behind, with the share of electric mobility in total sales not aligning with sectoral targets.

A common challenge faced by all these countries is the necessity to continually expand and upgrade the charging infrastructure (Figure 48) to support the growing adoption of electric vehicles. Furthermore, none of the investigated countries are effectively reducing their high dependence on cars for passenger transportation, a critical challenge exacerbated by the COVID-19 pandemic. The share of cars in passen-

Figure 48 | State of EVs charging infrastructure



Data source: IEA (2023c).

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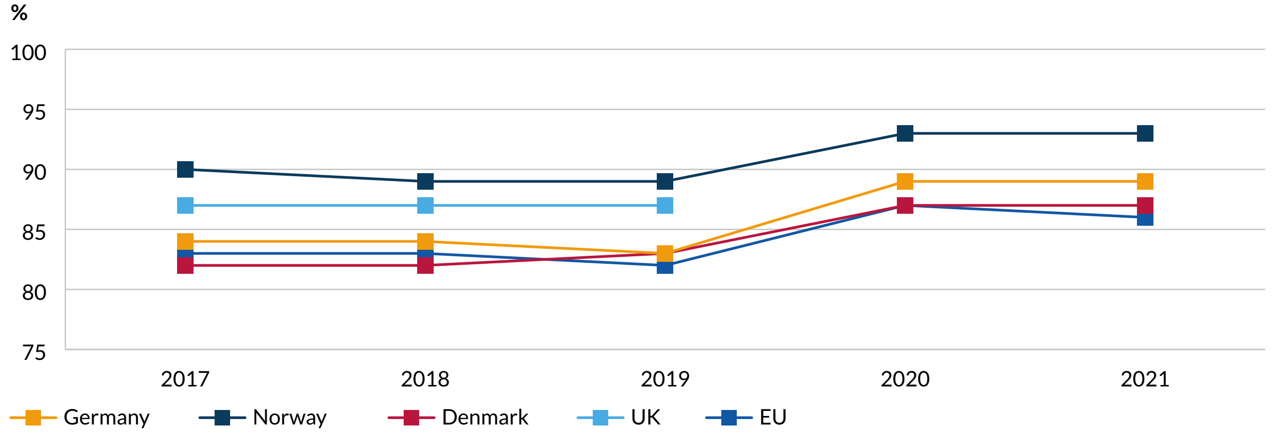
Figure 49 | Share of cars in total passenger transport



Source: Eurostat (2023b).

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ger transportation has continued to increase rather than decrease (Figure 49), underscoring the urgent need for the development of alternative transportation means and the implementation of further policy action.

Substantial subsidies benefiting oil consumption persist, highlighting the need to redirect funds toward climate-friendly alternatives.

Figure 50 | Synthesis of the results – Heating

		Germany	Norway	Denmark	United Kingdom
Targets	Fossil fuels phase out	🟥	🟩	🟩	🟧
	Heat pumps	🟩	🟩	🟩	🟩
	Zero emission heating	🟩	🟩	🟩	🟧
	Energy heating per m²	🟩	🟧	🟩	🟥
	Building renovation	🟩	🟥	🟩	🟥
	Building with energy storage	🟥	🟥	🟥	🟥
Phase out	CO2 emissions	🟥	🟩	🟧	🟥
	Oil and gas consumption	🟥	🟩	🟧	🟥
Phase in	Heat pumps cost Vs. FFs	🟥	🟩	🟩	🟥
	Heat pumps deployment	🟧	🟩	🟩	🟧
	Climate neutral heating	🟥	🟩	🟧	🟥
Infrastructure	Building energy intensity	🟩	🟩	🟩	🟥
	Building renovation	▨	▨	▨	▨
	Households with energy storage	▨	▨	▨	▨
Regulation	Building with smart meters	🟥	🟩	🟩	🟩
	Subsidies oil and gas heating	🟩	🟩	🟩	🟧

🟩 sufficient 🟧 partially sufficient 🟥 insufficient ▨ evaluation is not possible

Source: Authors' elaboration.

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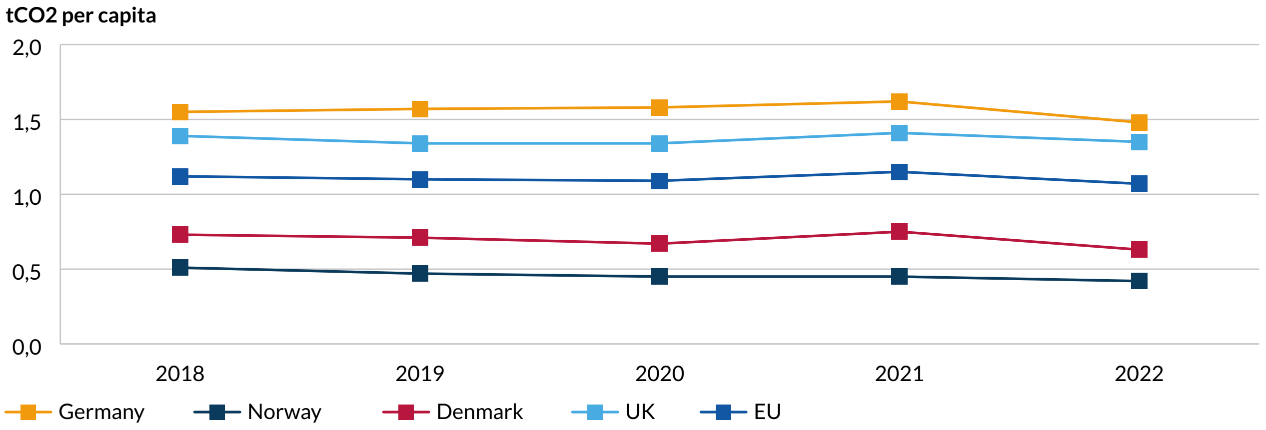
6.3 | Heating

Despite having one of the coldest climates in Europe and being a major producer of natural gas, Norway is leading the transition to zero-emission heating. Our assessment reveals that most metrics show sufficient progress, with only three rated as partially insufficient or insufficient. Norway has substantially lower emissions per capita than the other countries studied (Figure 51), and current CO2 emission reduction levels are compatible with a fully decarbonized heating system by 2045 or sooner. Norway established early ambitious goals, implementing a ban on the installation of fossil fuel-based heating systems in new buildings in 2016. Furthermore, as of January 1, 2020, new regulations prohibited the use of mineral oil for heating in both new and existing buildings. While natural gas is still permitted in existing buildings, its utilization is marginal. The cost of heat pumps is competitive with heat boilers, and the installation rate (Figure 52) is on track to achieve 100% penetration in the coming years. While roughly 57,620 heat pumps were sold in 2014, that number rose to 151,260 in 2023. In recent years, the popularity of heat pumps has increased as a more sustainable alternative to fossil-fuel-based heating systems. Residential energy intensity is decreasing, although it remains higher than that of Denmark (Figure 53), and 100% of homes are equipped with smart meters (Figure 54).

Overall, Denmark is also making strong headway in its transition to zero-emission heating. Our assessment reveals nine metrics as sufficient, three as partially insufficient, and only one as insufficient. Early-established policy targets have played a crucial role in driving the transition, with Denmark implementing measures to phase out oil and gas heating systems. Key initiatives include a ban on the installation of fossil oil and gas boilers in new buildings since 2013 and a general obligation for renewable heating in both new and existing buildings. More recently, Denmark has set ambitious targets for the share of zero-carbon heating, aiming for complete decarbonization of the heat supply for buildings by 2035. The deployment of heat pumps has accelerated in recent years, even if it is not yet fully on track, and costs have fallen. Denmark has the lowest energy intensity for heating of all the countries analyzed.

The heat transition in the UK and Germany is slower and faces several challenges. In both countries, CO2 emissions per capita are substantially higher than in the EU, energy intensity is higher, and the deployment of heat pumps has been too slow. Following the recent five-year trend, Germany is projected to have only 3 million heat pumps in operation by 2030. Recently, Germany has adopted more ambitious targets and new strategies that may accelerate its sectoral transition. Improvement in energy intensity in the UK has stagnated, which may constitute a major problem in the coming years.

Figure 51 | CO2 emissions from direct building energy use



Source: European Commission and Joint Research Centre (2024).

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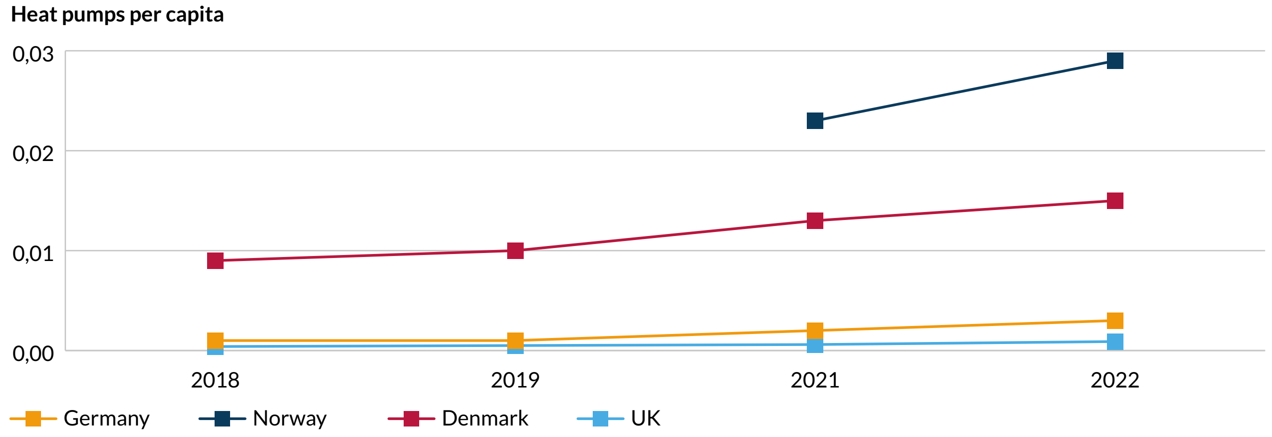
Figure 52 | Per capita sales of heat pumps



Source: EHPA (2023), Frauenhofer Institute (2020).

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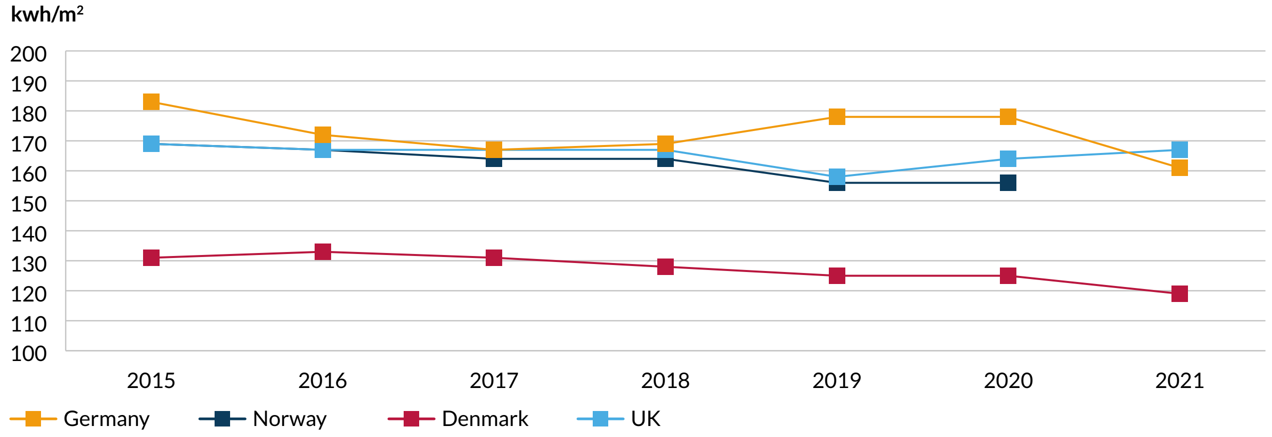
Figure 53 | Heating energy consumed per square meter



Source: IEA (2023d).

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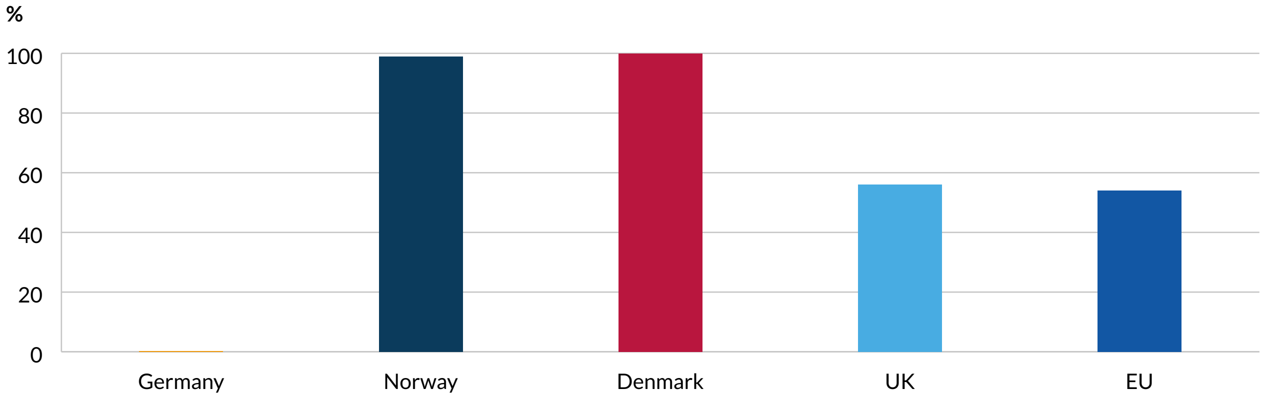
Figure 54 | Share of buildings with smart meters



Source: ACER/CEER (2022).

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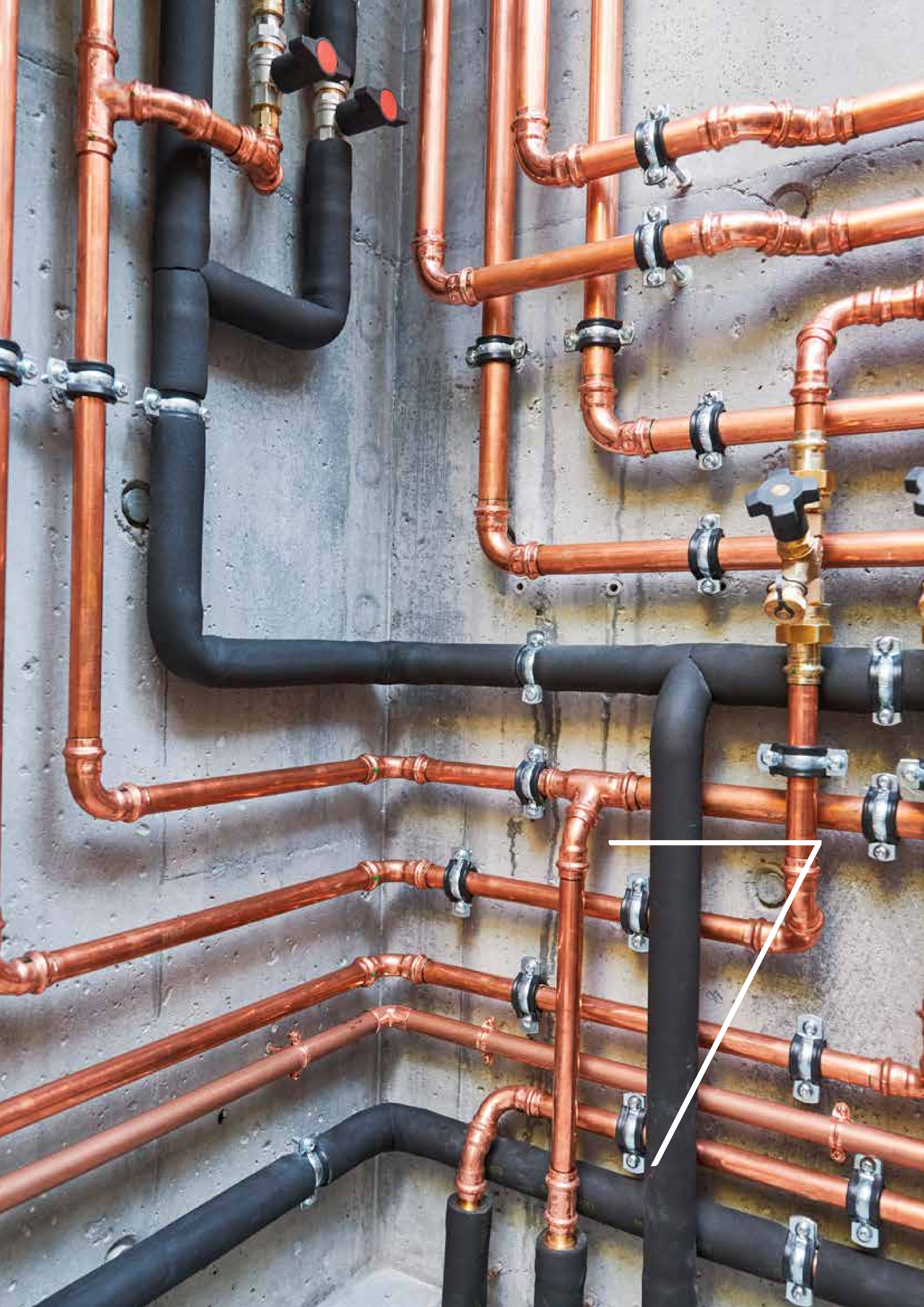

7

7 | A DEEPER DIVE INTO THE POLICY STRATEGIES OF TRANSITION LEADERS

Our analysis shows that Norway leads the transition to zero emissions across the three interrelated sectors we examined. Denmark is also progressing well in the electricity and heating sectors, though it faces challenges in the road transport sector. Conversely, the UK and Germany, despite progress in several indicators, appear to be relatively lagging. In this section, we review the main policy strategies implemented by leading countries which, in some cases, could prove helpful for Germany. Specifically, we focus on Norway's policies for road transport and heating, and Denmark's policies for heating. Similar to Germany, Denmark has faced the challenge of transitioning its fossil-fuel-based electricity system to one primarily reliant on intermittent renewable energy sources.

1 | Norway's road transport policy

Early policy targets

In 2012, Norway's parliament set an ambitious target for new passenger cars' CO2 emissions to be below 85 g CO2/km by 2020. This milestone was surpassed in 2017, with new passenger cars averaging 60 g CO2/km by 2019. The government aims to achieve 100% zero-emission car sales by 2025. Norway expects to reach its EV target by promoting a shift in consumer preferences toward EVs, without imposing an official ban on the sale of fossil fuel vehicles. The strategy focuses on reducing CO2 emissions while significantly enhancing energy efficiency through the adoption of EVs over conventional combustion engines.

Making EVs more attractive and affordable

Norway boasts the highest share of EVs globally, with 22% of the car fleet and 85% of car sales in 2021 comprising EVs. Differentiated taxation has been a pivotal policy to decrease the upfront cost of EVs, which has been a significant barrier to their deployment. Fossil fuel cars face multiple taxes, including registration tax, VAT on purchase, CO2 tax, and road use tax on gasoline and diesel. In contrast, zero-emission vehicles (including EVs) enjoy a range of incentives, including exemptions from VAT (25%) and registration tax (around EUR 10,000 on average), reduced toll road charges, ferry fees, and parking fees. The tax expenditure on EV incentives amounted to NOK 18.7 billion (EUR 1.9 billion) in 2021, significantly incentivizing EV adoption (IEA, 2022b).

Zero-emission vehicles also benefit from special e-number plates, enabling access to local incentives such as free parking and use of bus lanes. Additionally, ZEVs pay no more than half of conventional vehicle rates for parking, ferries, and toll roads, with local authorities determining rates up to the 50% level.

The national charging strategy

Most private EV owners can conveniently charge their vehicles at home, while commercial vehicles and city buses typically rely on depot charging. However, the proliferation of EVs would not have been feasible without publicly accessible charging stations along roadways (IEA, 2022b). The expansion of rapid charging services has mirrored the growth in EV adoption. As of September 2022, Norway has 5,041 publicly accessible rapid chargers (over 50 kW) for light vehicles, with 910 installed in 2022 alone. Notably, only around 700 of these rapid chargers have received public subsidies, with the majority being established by commercial entities. Vans can use the same charging infrastructure as passenger cars. Additionally, the first publicly accessible rapid charging station for heavy vehicles was inaugurated in Filipstad, Oslo, in October 2022, with financial support from the Oslo municipality.

Government support for EVs in Norway has been complemented by significant investments in charging infrastructure and grid design. An extensive network of fast-charging facilities is essential to facilitate the transition away from ICE vehicles, especially for longer passenger journeys and freight transport. Enova, a public enterprise promoting environmentally friendly energy production and consumption, has been instrumental in subsidizing the deployment of publicly accessible charging infrastructure for light vehicles. As EV numbers rise, so does the demand for rapid charging along the road network. Consequently, most charging stations have been established on market-driven terms without public subsidies, a trend expected to continue (Norwegian Ministry of Transport (2023).

The electricity grid plays a vital role in charging infrastructure deployment. An efficient system for grid connections and utilization is essential to accommodate the growing demand for charging services. The government aims to streamline the grid expansion process, reduce the time required for licensing applications, and enhance efficiency through increased digitalization. Furthermore, to address land use challenges associated with rapid charger deployment, national planning guidelines will be established to assist municipalities in allocating suitable areas for charging infrastructure (Norwegian Ministry of Transport, 2023).

The national strategy also prioritizes user-friendly charging services, including the development of a market portal for rapid charging of light vehicles, real-time availability information for publicly accessible charging stations, and standardization of charging facility designs to ensure universal accessibility (Norwegian Ministry of Transport, 2023).

Beyond electrification: supporting modal shifts

Norway's policy extends beyond electrification to support modal shifts and promote sustainable transport. Initiatives include exploring low emissions zones to create cleaner cities and setting a target of zero growth in passenger transport by car in large urban areas. Long-term urban growth agreements prioritize public transport, cycling, and walking alternatives, and measures such as road tolls and parking restrictions to curb car-based transport growth. State contributions finance large public transport projects, emphasizing coordinated efforts between the state and local authorities (IEA, 2022b). Indeed, national and local programs are essential to encourage modal shifts and ensure EV policies complement, rather than substitute, efforts to promote alternative transportation modes.

2 | Norway's heating policy

Electric-based heating solutions and heat pump integration

In Norway, electric heating is common in homes. Since 2016, regulations have prohibited the installation of heating systems powered by fossil fuels in new buildings. Starting from January 1, 2020, a rule was implemented that forbids the use of mineral oil for heating purposes in both new and existing structures. These regulatory actions have been instrumental in phasing out fuel oil for heating and cooling, prompting a transition to alternative heating solutions, such as heat pumps (the main technology for heating), biofuels, and direct electric heating systems. Although natural gas is still permitted in existing buildings, its usage is rare, and the installation of new natural gas heating systems is no longer allowed. The government-owned entity Enova promotes the adoption of local heating solutions powered by renewable energy sources, including woodchips, pellets, briquettes, air-to-water and water-to-water heat pumps, as well as solar thermal systems (IEA, 2022b).

Enova has introduced a set of incentives for heat pump installations. A bonus established in 2022 grants NOK 15,000 (approximately €1,500) for a combined system of a brine-to-water heat pump, an accumulator tank, and a water-based heating system. Since the building regulations do not offer incentives for heat pumps in new constructions, these subsidies are particularly noteworthy (EHPA, 2023).

Smart meter implementation

Norway has achieved a significant milestone by installing smart meters, also known as the Advanced Metering and Management System, in 98% of metering points across the country. This initiative encompasses around 2.9 million customers and caters to up to 99.5% of the nation's electricity demand. The government mandated in 2011 that all customers should be equipped with smart meters by 2019 without any specific support scheme for their deployment. These smart meters record energy consumption hourly and automatically transmit the data to the distribution system operator (DSO). They facilitate bidirectional communication, allowing customers to access time-of-use data on their energy consumption and pricing. While DSOs are not required to offer time-of-use information services directly, they must ensure that this information can be accessed by customers through third-party service providers or demand-side response tools, possibly via smartphone apps or in-home displays (IEA, 2022b).

District heating development

The DH sector in Norway delivered 5.9 TWh (0.5 Mtoe) to consumers in 2019, which represents approximately 8% of the total energy consumed for heating in buildings. The production of DH predominantly relies on waste (constituting about half of the supply) and biofuels (around 30%), with a minimal contribution from fossil gas and diesel at 4.3%. The service sector is the major consumer of DH, utilizing two-thirds of the production. The government anticipates a modest expansion in the DH sector in the forthcoming years and is currently exploring ways to enhance the synergies between DH and electricity production. The aim is to maximize the efficiency of existing infrastructures while fostering consumer flexibility within the power system and the DH network (IEA, 2022b).

Enova also supports enterprises aiming to develop new DH networks and drive innovation within the DH industry as part of the District Heating Programme. This support is conditional on the utilization of renewable energy sources, like biofuels, waste, and heat pumps. Additionally, cogeneration projects that are not eligible for electricity certificates can also receive financial assistance (IEA, 2022b).

3 | Denmark's heat decarbonization: district heating and expanding heat pump use

The production of district heat from renewable sources has been central to Denmark's green policy. In 2020, Denmark had the highest share of district heat in total final energy consumption among OECD countries, at 19%. District heat serves as the primary residential space heating source, catering to two-thirds of dwellings by 2021, solidifying Denmark's leadership in this area. The shift toward renewable energy is evident, with solid biomass comprising 51% of district heat generation in 2021, a substantial increase from 10% in 2011. Additionally, the utilization of waste heat has surged, constituting 9% of total heat production in 2021. Government initiatives are accelerating the transition, with plans unveiled in April 2022 aiming to convert up to 200,000 households from natural gas heating to district heating by 2028, accounting for half of the current natural gas user base. Concurrently, new district heat projects reliant on fossil fuels will be prohibited, reflecting the commitment to sustainable practices. While municipalities oversee heat planning and consumers are no longer obligated to connect to heat networks, they retain the freedom to opt for alternative heating technologies like heat pumps. With the ambitious goal of completely phasing out gas for heating by 2035, the government intends to equip non-district heating-covered dwellings with heat pumps (IEA, 2023a).

District heating's development

The development of district heating systems in Denmark has been driven by both top-down and bottom-up initiatives aimed at ensuring stable, accessible, and affordable heating for all. Initially, district heating aimed to enhance energy efficiency by utilizing surplus heat from thermal power plants. This evolved to encompass broader goals of providing reliable and cost-effective heating solutions across the nation, including in smaller communities. The global energy crisis of the 1970s further underscored the imperative to reduce energy import dependency and diversify energy sources. This prompted Denmark to embark on extensive, long-term planning initiatives for collective heat infrastructure nationwide. With increasing environmental awareness, efforts pivoted toward mitigating climate change, spurring ambitions for renewable energy adoption and sustainability (Johansen & Werner, 2022; Sovacool & Martiskainen, 2020).

Denmark led the Nordic region in adopting district heating and remains a pioneer in Europe. The Danish district heating sector is renowned for its technological advancements, innovative practices, robust research, and comprehensive heat infrastructure planning and policies within the global district heating community. Notable features include large-scale collective heat planning, mandatory connections, nonprofit principles, and comparatively higher average district heating prices. Denmark's expertise in district heating has also facilitated global exports of technologies and know-how.

While Denmark's district heating sector has successfully integrated substantial renewable energy sources, such as increasing the share of renewables in CHPs and reducing carbon emissions, challenges persist. These include rising biomass import reliance, evolving roles of CHP plants, shifts toward non-combustion heat sources, and competition from individual heat pumps in single-family homes (Johansen & Werner, 2022). Critics have also highlighted concerns about limited competition, with incumbents shielded by restricted third-party network access. Future advancements in "smart" thermal grids are anticipated to enhance sector integration as Denmark and other nations integrate more renewable energy resources into their energy systems.

In 2022, the Danish Utility Regulator imposed price caps on district heating and eliminated mandatory connections, promoting more efficient regulatory frameworks to stimulate investment. In March 2023, Danish legislation exempted geothermal heat projects from existing price regulations. Under this law, district heating companies and geothermal operators negotiate pricing through contracts that establish maximum consumer costs for geothermal heat. Geothermal energy is anticipated to satisfy 15–20% of Denmark's heating demand, supporting initiatives such as the large-scale geothermal plant in Aarhus (IEA, 2023a).

Support policies for zero-emission heating and smart systems

Denmark has implemented several concrete policy measures to support the deployment of heat pumps and district heating. These measures include subsidy schemes aimed at phasing out oil and gas boilers and boosting energy renovations. The government has established four key subsidy schemes to achieve these goals (IEA, 2023a):

- The building pool: Finances energy renovation and conversion from oil and gas boilers to heat pumps.
- The scrapping scheme: Provides subsidies for companies that supply heat pumps on subscription to households. By offering financial support for the installation and maintenance of heat pumps, the government aims to incentivize the adoption of this renewable heating technology.
- The disconnection scheme: Provides fee exemption for citizens converting from gas boilers to heat pumps or district heating.
- The district heating pool: Supports energy-efficient district heating and aims to lower consumer costs. This scheme promotes the use of renewable sources for district heating.

From 2018 to 2020, the government also implemented a subsidy scheme to promote the conversion to district heating and domestic heat pumps for households and companies. This includes support measures for household expenditures on the gas network (the disconnection scheme), a scrapping scheme that entails a subscription system for a heat pump for users who cannot bear the initial investment, and a building scheme that supports individual investments in heat pumps. Additionally, the enterprise scheme provides support for projects aimed at reducing energy consumption or CO2 emissions, while the district heating production scheme promotes the reduction of fossil fuels in district heat plants through support for investments in large heat pumps and solar heating systems.

The government has also advanced the implementation of smart electricity meters and smart charging of heat pumps and electric vehicles, allowing consumers and grid operators to control their consumption based on hourly electricity pricing. Furthermore, the government has initiated projects in the smart grids and digitalization space, such as building a digital twin of the electricity network and delivering a data integration solution using digital platforms to increase data visibility from smart meters and enable end-to-end monitoring (IEA, 2023a).

Denmark's recent plans and policy strategies for heating emphasize a rapid transition to renewable energy sources through district heating and electrification, building energy efficiency, and leveraging digitalization and smart grid technologies to optimize energy consumption and management.

4 | Denmark's electricity policy

Denmark has implemented a comprehensive suite of policy strategies and instruments to drive its energy transition, with a strong emphasis on renewable energy, grid infrastructure, energy storage, and digitalization. Overseeing these efforts is the Ministry of Climate, Energy and Utilities, which aims for climate neutrality by 2045 (IEA, 2023a).

Renewable energy policy

Denmark is globally recognized as a pioneer in renewable energy policy (Lipp, 2007). Starting with pilot projects in the 1970s in response to oil crises (Rüdiger, 2014), Denmark's initiatives have evolved to include ambitious projects like the energy islands in the Baltic and North Seas, which is potentially the world's largest renewable energy project (Østergaard et al., 2023).

Denmark's current targets are ambitious: by 2030, onshore wind and solar power generation are set to quadruple. Offshore wind capacity could potentially increase sevenfold to 18 gigawatts (GW) by 2030 and to 35 GW by 2050, up from today's 2.3 GW. Under the 2021 Power-to-X (PtX) Strategy, Denmark aims for 4–6 GW of electrolysis capacity by 2030. Regionally, Denmark supports deploying 20 GW in the Baltic Sea by 2030 and, together with eight European countries in the North Sea, has committed to a joint pledge of 120 GW of offshore wind capacity by 2030 and at least 300 GW by 2050 (IEA, 2023a).

Denmark continuously revises its energy policies to bolster renewable development, particularly in wind energy, where it has achieved substantial cost reductions and industry maturity. The government supports renewables through two main regimes: the "maximum price" sets a cap and offers a variable premium over market rates (capped at 58 øre/kWh for onshore wind parks), and a guaranteed premium that supplements market prices throughout the installation's lifespan (ENERDATA, 2024).

Special offshore wind parks benefit from a fixed feed-in tariff (FiT) determined through competitive tenders, ranging from 37.2 øre/kWh (Kriegers Flak park, €0.0499/kWh) to DKK 1.05/kWh (Anholt, €0.141/kWh). Conversely, a degressive FiT of 60/40 øre/kWh (€0.0805–0.0537/kWh) for large solar projects (≥ 500 kW) saw a surge in applications (4.5 GW) prompting the shift to tender-based support schemes in 2016. Solar PV plants under 500 kW can still benefit from the maximum price. Biogas-fired, biomass-fired, and hydropower plants also qualify for financial support. Until 2022, consumer electricity bills bore incentive costs through a Public Service Obligation (PSO) surcharge, with energy-intensive users receiving 85% compensation. Today, funding derives directly from the state budget (IEA, 2023a)(IEA, 2023a).

Denmark leads global offshore wind development efforts through a centralized one-stop-shop model: a single point of contact for permitting managed by the Danish Energy Agency (Danish Energy Agency, 2020). The maritime spatial plan represents a holistic approach to sea-based planning, balancing nature conservation, fisheries, and renewable energy interests. In 2023, there was broad political consensus to double renewable energy and energy island allocations within the maritime spatial plan, covering roughly 30% of sea territory. The government plays a pivotal role in identifying viable offshore wind zones, selecting sites, issuing permits, and allocating funds through competitive bids (IEA, 2023a).

As of 2023, a nationwide assessment identifies suitable areas for onshore wind turbines, solar PV, and power-to-x technologies. The government streamlines municipal planning with energy parks – combined wind, solar, and other technology sites – to expedite deployment. An interministerial team formed in 2023 aids municipalities in accelerating renewable energy deployment and supporting on-ground transitions (IEA, 2023a).

Coal phase-out

Despite a slight increase in 2021 compared to 2020, coal usage in electricity generation has steadily declined since 2006, with an 80% drop since 2005. By 2020, nearly all coal was used for generating electricity and heat. The complete phase-out of coal for heat and electricity is anticipated by 2028, contingent upon generator decisions. The government does not subsidize transitioning from coal to biomass or other fuels. Ørsted announced cessation of coal at its cogeneration plants effective January 1, 2023. Additionally, owners of plants in Odense (Fynsværket) and Aalborg (Nordjyllandsværket) plan to convert to alternative fuels (Fynsværket) or cease operations (Nordjyllandsværket by 2028).

Electricity grids and system integration

Denmark is poised to become a net exporter of electricity within eight years, necessitating adaptations in electricity grids to manage significant disparities in production and consumption across geography and time. Flexibility in consumption will be crucial for maintaining grid stability, and Denmark aims to lead in designing future market frameworks that support extensive integration of renewable energy, both domestically and regionally (IEA, 2023a).

ENERGINET, a state-owned company, has reinforced transmission lines and revamped grid management to accommodate the growing number of wind turbines. Recognizing the imperative of an integrated system plan, the government has included scenarios for future demand and flexibility requirements, incorporating technologies like hydrogen and thermal storage. Additionally, grid interconnection projects with neighboring countries have intensified in recent years (IEA, 2023a).

Denmark's hydrogen strategy, unveiled in 2022, targets 4 to 6 GW of electrolysis capacity by 2030 (ENERDATA, 2024a). The deployment of smart meters, completed by the end of 2020, facilitates hourly settlement of electricity consumption, laying the groundwork for future market offerings by aggregator companies (IEA, 2023a).

The PtX Agreement of 2022 supports the use of electricity from wind farms in power-to-x facilities, potentially aiding in the decarbonization of aviation and heavy transport. PtX technologies also aim to optimize grid usage by aligning renewable energy production and consumption within the same geographical areas for faster integration. Denmark has implemented geographically differentiated tariffs and permitted direct lines between generators and consumers, signaling reduced grid costs when electricity consumption is situated in surplus generation areas, or vice versa (Energinet, 2022).

Denmark's strategy for electricity transition is distinguished by robust policy leadership, iterative policy enhancements, and a commitment to integrating renewable energy into the grid while prioritizing inclusivity and meeting citizen needs.

8

8 | IMPLICATIONS FOR SECTORAL TRANSITIONS IN GERMANY

The case of Norway demonstrates that a rapid transition to zero emissions, primarily through electrification, is feasible. With its nearly decarbonized electricity generation, Norway is on course to achieve zero emissions in road transport and heating by or before 2035. While the country benefits from natural advantages in hydropower production and reservoirs, it also faces challenges due to its colder climate and abundant fossil-fuel resources, which could potentially increase reliance on existing technologies. Norway's early and ambitious targets for coal phase-out, fossil fuel-based heaters, and zero-emission vehicle sales have been instrumental in driving its transition.

In the road transport sector, Norway's experience highlights the potential for accelerating the phase-out of ICE cars through the rapid adoption of zero-emission vehicles. Sales of new ICE cars are approaching zero, and the existing fleet is continually decreasing. The Norwegian strategy includes three main pillars:

Reducing upfront costs of EVs: Several measures have been implemented to make EVs price-competitive with ICE cars, primarily through differentiated taxation (VAT, registration tax, CO2 tax, and road use tax on gasoline and diesel).

Expanding charging infrastructure: Supported by the public energy enterprise Enova, the government facilitates the deployment of charging infrastructure, with subsidies allocated primarily for chargers in remote areas.

Local incentives: Zero-emission vehicles benefit from special e-number plates, enabling access to local incentives such as free parking and use of bus lanes.

In the German electricity sector, there is a pressing need to prioritize the modernization of electricity grids and the development of distributed flexibility. Without substantial advancements in transmission and distribution grids and energy storage, the deployment of renewables and the phase-out of gas will be compromised. Additionally, fostering the growth of distributed flexibility, including flexible energy demand resources like storage, electric vehicles, heat pumps, and thermal storage, at the distribution level is crucial for achieving net zero. A comprehensive system-wide strategy, encompassing government targets, policy support, and market reforms, is necessary to facilitate significant growth in distributed flexibility and incentivize consumers to engage in demand-side response, such as smart charging of electric cars.

A heightened focus on the heating sector is urgently warranted. There is a critical need to expedite both the uptake of heat pumps and strategic decisions regarding district heating networks. Further policy support and incentives may be necessary to boost uptake rates of heat pumps. Additionally, early establishment of policy targets has been pivotal in driving the heat transition in Norway and Denmark, which implemented measures to phase out oil and gas heating systems as early as 2013.

9 | OUTLOOK AND LIMITATIONS

This report aims to develop an assessment framework for evaluating progress in sectoral transitions toward carbon neutrality, with a focus on systemic aspects. As depicted in Figure 2, we have identified five steps and critical analytical dimensions to assess the transformation of sectors toward climate neutrality, drawing from extensive literature on sustainability transitions.

While the empirical section of this report concentrates on evaluating electricity, road transport, and heating systems across four countries, the framework is applicable to other nations, particularly within OECD countries. Although many data sources used in this report cover all OECD or EU countries, additional national data sources may be required for specific variables.

Several limitations should be noted when interpreting the results. First, the study's scope does not encompass the assessment of specific policy instruments or strategies, despite outlining major policy measures in leading countries in the final policy chapter. Notably absent from the framework are subsidies for green technologies such as renewable energy technologies, charging infrastructure, or heat pumps, which typically influence technology deployment. The lack of robust and comparable datasets on technology incentives across countries, coupled with the analytical challenge of determining the necessity and sufficient volume of green subsidies, underscores the exclusion of these factors. In contrast, there is a broad consensus regarding the need to reduce fossil subsidies to zero as swiftly as possible from a decarbonization standpoint. Future research could explore the role of green subsidies and other policies in sectoral transitions across both leading and lagging countries.

Second, the evaluation of each variable across three states offers guidance for expert-driven assessment rather than presenting fixed parameters. Metrics should therefore be applied judiciously and in ways that consider the specifics of each case.

Third, some metrics lacked publicly available data, or the available data was insufficiently clear for evaluation. Additionally, certain data may only be accessible in national languages, and we encourage further exploration by other researchers into additional data sources.

Fourth, this evaluation framework assesses the current state and recent progress of variables over a defined 5-year period. This short timeframe is justified by the urgency to achieve sectoral transitions (approximately two decades, considering carbon neutrality by 2045) and the rapid technological advancements in energy sectors. Consequently, recent extraordinary events such as the COVID-19 pandemic or the energy crisis stemming from the Russian invasion of Ukraine have impacted variables like CO2 emissions or the adoption of new technologies. Thus, the results reflect actual occurrences rather than projections under “normal” circumstances. Applying this framework in the future will facilitate comparisons of technological, infrastructural, and regulatory dynamics during and post-pandemic, and we encourage subsequent studies to undertake such analyses.

Finally, the timing of sectoral decarbonization remains a subject of ongoing debate. While all sectors must decarbonize in the coming decades, there is no universally applicable timeline for achieving this goal in each sector. The suggested timeline (2035 for electricity and 2045 for road transport and heating) aligns with national plans to achieve net-zero emissions before 2050 but should not be viewed as the sole pathway to decarbonization.

These considerations provide a basis for potential improvements and further exploration in future studies.

LIST OF ABBREVIATIONS

CO2: carbon dioxide
DH: district heating
DSO: distribution system operator
EU: European Union
EVs: electric vehicles
ICE: internal combustion engine
CHP: combined heat and power
PV: photovoltaic
TSO: transmission system operator
UK: United Kingdom
USD: U.S. dollar
VAT: value added tax

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Address | Contact

Bertelsmann Stiftung
Carl-Bertelsmann-Straße 256
33311 Gütersloh
Telephone +49 5241 81-0
www.bertelsmann-stiftung.de

Dr. Christof Schiller
Senior Project Manager
Sustainable Social Market Economies
Telephone +49 30 275 788 138
christof.schiller@bertelsmann-stiftung.de

Dr. Thorsten Hellmann
Project Manager
Sustainable Social Market Economies
Telephone +49 5241 81-81236
thorsten.hellmann@bertelsmann-stiftung.de

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