THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Understanding policy effort for low-carbon energy transitions

Insights from coal power phase-out and wind power expansion

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Abstract

Globally and rapidly decarbonizing electricity generation is one of the most urgent climate change mitigation measures. There are frequent calls for governments to increase efforts for such decarbonization, but – what type, and what level, of policy effort is required across contexts and over time? This thesis conceptualizes and measures three elements of policy effort for low-carbon energy transitions, and traces their interactions: policy commitments, policy actions, and energy transitions outcomes in line with climate change mitigation targets. To this end, the thesis mobilizes empirical evidence on policy effort for two ongoing transitions processes: coal power phase-out, and wind power expansion. The insights on the geographical and temporal changes in policy effort enable this thesis to identify policy effort as a proxy for the strength and type of socio-political barriers to low-carbon technology change. More specifically, this thesis finds that policy effort does not necessarily decline as low-carbon technologies become economically competitive, but rather that new barriers tend to emerge as wind power grows, and coal power becomes destabilized. This thesis also finds that policy effort for coal power phase-out tends to increase in contexts with large and young power plant fleets, indicating comparatively high socio-political barriers. Extrapolating from these empirically observed regularities of policy-technology interactions, this thesis illustrates policy effort to overcome barriers to projected coal phase-out pathways, and targeted offshore wind growth. Overall, its findings highlight that sustained and adaptive policy sequences; as well as internationally concerted policy effort are likely required to enable energy transitions in line with climate change mitigation objectives.

Keywords: low-carbon energy transitions, policy effort, coal phase-out, wind power.

Appended publications

This thesis is based on the work contained in the following papers, referred to by their numbers in the text:

Paper 1 — Nacke, L., Cherp, A., Jewell, J. (2022). Phases of fossil fuel decline: Diagnostic framework for policy sequencing and feasible decline pathways. Oxford Open Energy, Volume 1, oiac002. DOI: 10.1093/ooenergy/oiac002.

J.J. and A.C. conceptualized the article. L.N. conducted the literature review and case studies. L.N. and J.J. wrote the original article. All authors revised the article. J.J. supervised the work.

Paper 2 — Vinichenko, V., Vetier, M., Jewell, J., Nacke, L., Cherp, A. (2023). Phasing out coal for 2 °C target requires worldwide replication of most ambitious national plans despite security and fairness concerns. Environmental Research Letters, Volume 18 (1), 014031. DOI: 10.1088/1748-9326/acadf6.

J.J. and A.C. conceptualized the article. M.V. and L.N. collected data on coal phase-out pledges. V.V. led data analysis and visualization. L.N. conducted data analysis on effects of the Russo-Ukrainian war on coal phase-out pledges. V.V. wrote the original article, all authors revised the article.

Paper 3 — Nacke, L., Vinichenko, V., Cherp, A., Jakhmola, A., Jewell, J. (2024). Compensating affected parties necessary for rapid coal phase-out but expensive if extended to major emitters. Nature Communications, Volume 15, 3742. DOI: 10.1038/s41467-024-47667-w.

J.J. & A.C. conceived the study. J.J., A.C. and L.N. developed the Methodology. L.N. led data collection and curation. L.N., V.V., and A.J. conducted formal analysis. L.N. and J.J. wrote the original draft with contributions from A.C. L.N. and J.J. revised the manuscript with contributions from A.C., V.V. and A.J. L.N., J.J., A.C., V.V. and A.J. contributed to visualisation. J.J. provided supervision and L.N. project administration. J.J. acquired funding.

Paper 4 — Nacke, L., Jewell, J., Cherp, A., Bhowmik, S. (2025). Policy effort for the deployment of mature technologies: The case of onshore wind power in Germany. *To be submitted for publication.*

J.J., A.C. and L.N. conceived the study. All authors developed the methodology. L.N. led data collection, curation, formal analysis, and visualisation with contributions from A.C. and J.J. L.N. wrote the original draft with contributions from A.C. and J.J.

Paper 5 — Kazlou, T., Nacke, L., Cherp, A., Pavlenko, A., Jewell, J. (2025). Closing the implementation gap: Probabilistic projection of expansion pathways for offshore wind in Europe under varying policy practices. *To be submitted for publication.*

T.K., J.J., and A.C. conceived the study. T.K. developed the methodology. T.K., L.N., and A.P. contributed to date collection and curation. T.K. led formal analysis and data visualisation with contributions from A.C., J.J. and L.N. T.K. wrote the original draft with contributions from L.N., A.C. and J.J.

Please note that in addition to presenting research from the five appended papers, this thesis presents few results that were additionally obtained through exploratory research, but are not included in the papers. These results are presented in two “Boxes” to separate them from the rest of the thesis.

Related outputs not included in this thesis

1 **Nacke, L.**, Jewell, J. (2022). Effects of Russia's war on European coal phase-out. Blog post and webinar. Available: https://coaltransitions.org/news/effects-of-russias-war-on-european-coal-phase-out/.

2 **Nacke, L.**, Jewell, J., Hermwille, L., Sovacool, B. (2022). Integrated research framework: Transitions in carbon intensive regions. CINTRAN Project Deliverable 1.1. Available: https://coaltransitions.org/publications/5424/.

3 Charalampidis, I., Vrontisi, Z., Fragkiadakis, D., **Nacke, L.**, and Jewell, J. A Regional Model-Based Assessment of the Socioeconomic Impacts of EU Climate Neutrality Pathways and the Effectiveness of the Just Transition Fund. Available at SSRN: https://ssrn.com/abstract=4891287 or http://dx.doi.org/10.2139/ssrn.4891287.

4 Hermwille, L., Brisbois, M.C., Hiteva, R., Yazar, M., **Nacke, L.**, Jewell, J., et al. Compounding injustices can jeopardize a just transition. Nature Energy. 2025;1–4. DOI: 10.1038/s41560-025-01785-x.

Table of Contents

Figures, tables and boxes

Figures

Tables

Boxes

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1 Introduction

2025 marks the ten-year anniversary of the Paris Agreement, a landmark deal to address climate change (1) by limiting global average temperature increase to "well below 2°C […] and pursuing efforts to limit [it] to 1.5°C above pre-industrial levels" (2). Decarbonizing the electricity sector is generally considered the fastest and cheapest way to achieve these targets, given the sector's substantial contributions to greenhouse gas emissions and the availability of cost-effective low-carbon technologies like solar and wind power, amidst rising electricity demand (3,4). To achieve this decarbonization, solar and wind power need to rapidly increase, and fossil fuel powered electricity – most urgently coal power as the globally biggest and most carbon-intensive electricity source – needs to rapidly decline (5,6) (especially given high uncertainties in likely carbon capture and storage deployment (7)).

So, where does the world stand ten years after signing the Paris Agreement? Are coal power phase-out and renewables growth in line with what is required to achieve climate change mitigation targets?

Progress on renewables deployment has been notable - 2023 and 2024 especially have seen record capacity additions, which are expected to continue over the coming years (8). In 2025, renewables are expected to provide more of global electricity demand than coal (8). As the deployment of renewables has grown, their costs have sunk, making them more attractive to companies seeking financial profits. Growing renewables deployment also creates new job opportunities (9,10). Optimists argue that these positive effects will sustain the acceleration of renewables deployment not only in the short-, but also the long-term, and enable climate change mitigation at a low cost (11,12,13).

Despite this progress, CO_2 emissions from electricity generation globally have plateaued rather than declined over the past 10 years, a trend which is expected to continue (8). What prevents emissions from declining, even though renewables growth is at an all-time high? The most straightforward answer is that *globally*, fossil fuel power generation has not yet declined (Figure 1). Most notably, phasing out coal power generation remains a major challenge globally.

At the national and regional level, there are however contexts where coal decline is already well underway: in advanced economies, coal power generation has been decreasing for almost two decades (14), and even in several growing economies, there are increasing cancellations of planned coal power plants (15). The experiences of countries where coal power is already declining may provide useful insights on drivers and barriers of coal decline for countries and regions where coal power is not yet declining – or is even expanding.

Coal power expansion has been especially pronounced in two countries that currently host the world's largest coal power plant fleets: China and India, where coal power additions accounted for roughly 97% of all new coal capacity in 2024 (16). In China, the number of coal projects beginning construction in 2024 was in fact at its highest since 2015 (17). This means that despite cases of regional coal decline, global trends are not yet in line with climate change mitigation targets. While the share of coal power in global electricity generation has declined from roughly 38% in 2015 to roughly 35% in 2024 (14), the total use of coal in 2025 is higher than it was in 2015, as total electricity demand increased over time (Figure 1).

Not surprisingly, there are frequent calls for governments to increase their efforts to meet the Paris Agreement targets: In a speech in February 2025, Simon Stiell, the UN Climate Change Executive Secretary, said that “we are already headed in the right direction. We just have to implement, and implement more and implement faster” (18). In its Sixth Assessment Report, the IPCC writes that a rapid “acceleration of mitigation efforts” will likely be required after 2030 for temperature targets to be achieved (19). However, while the head of the International Energy Agency has expressed his confidence that “governments have the tools” to accelerate energy transitions (20), climate and energy scholars do not agree on what those tools are, and what level of government intervention is required. In other words, scholars debate whether low-carbon energy transitions require a huge policy effort, or rather – an easy lift.

Optimists argue that the required transitions constitute a rather “easy lift” from the perspective of national governments. They highlight the driving force of increasing returns for renewables growth, technology learning (21), and economies of scale (22), which lead to declining technology cost – which in turn incentivizes renewables deployment, and increases their competitiveness with fossil fuels (11,23,24). These observed mechanisms are incorporated in energy models to project pathways for low-carbon energy transitions. Results from such models have been taken to show that while policy effort may be required at earlier stages of renewables deployment, their increasing economic competitiveness compared to fossil fuels enables continued diffusion even without further policy support (11,24,25).

Pessimists, on the other hand, argue that barriers to energy transitions are of a more systemic nature. They caution that ongoing transitions may induce negative feedback loops such as lowering electricity prices which may impede further investment in renewables (26,27); or rising opposition as transitions threaten fossil fuel industries and jobs; and as renewables interfere with existing landscapes and land uses (28,29,30,31). These scholars often conduct in-depth case studies of historical or ongoing energy transitions, observing highly granular and context-dependent mechanisms linking technological, societal and policy change. Findings from such disaggregated analysis for example show that negative effects of phasing out fossil fuels, such as industry closure, job losses and declining tax revenues are unequally distributed – meaning that even if renewables’ competitiveness may incentivize fossil fuel decline, backlashes, resistance and economic downturn may ensue among the most strongly affected actors and impede transitions (32,33,34,35).

The two views – optimists and pessimists – are at odds with each other regarding the main barriers to low-carbon transitions they identify; and regarding the level, and type, of effort they argue is likely required to overcome these barriers. Methodologically, it is hard to operationalize and quantify socio-political barriers to low-carbon energy transitions, which are often highlighted in qualitative and detailed case studies, and bridge these insights with quantitative projections from energy and climate models. It is however both policy- and scientifically relevant to resolve these divides: going beyond vague calls for “increasing policy effort” is important for policymakers and climate change mitigation advocates, to better understand what types of policies to implement and advocate for. Scientifically, better understanding the relationship between technology change and policy effort can inform not only an understanding of the evolution of policy-driven technology growth and decline trajectories, but may ultimately also help projecting energy transition pathways under different levels of policy effort.

1.1 Aim and research objectives

The research I present in this thesis contributes to resolving this disagreement, by advancing an understanding of interactions between policy effort and technology change across contexts and over time. To achieve this aim, this thesis fulfils three objectives:

1. Advance approaches of conceptualizing, measuring and quantifying policy effort for technology change.
2. Measure and map policy effort to the phases of two ongoing key processes in energy transitions: coal power phase-out and wind power expansion.
3. Derive insights on the level and type of policy effort for overcoming barriers to technology change in line with climate change mitigation targets.

In this thesis, I show how these objectives are addressed in the research outputs I have contributed to during my PhD: appended Papers 1-5. In these papers, we (me and my co-authors) empirically examine two currently ongoing key processes of technology change: coal power phase-out, and wind power expansion. These ongoing processes provide unique opportunities to better understand policy-driven growth and decline trajectories of technologies central to climate change mitigation (see Section 3.2 for a more detailed justification of the case selection). To synthesize and structure our findings on policy-technology interactions, I leverage and combine existing concepts of phases of technology change (36,37,38,39) and climate policy effort (40).

1.2 Main contributions

Conceptually, this enables me to advance an understanding of how policy effort evolves throughout phases of technology change. In this thesis, I advance emerging conceptualisations of policy effort by exploring feedbacks between its three elements: commitments, actions and outcomes. I also leverage our results to explicitly link the concept of policy effort to socio-political barriers that hinder technology change.

Methodologically, Papers 1 and 4 contribute to tracing the evolution of barriers throughout phases of technology change – using a set of diagnostic indicators for coal phase-out; and policy analysis for onshore wind expansion. Papers 2, 3 and 4 contribute to quantifying policy effort embedded in policy commitments (Papers 2 and 3) and policy actions (Papers 3 and 4). By abstracting from empirically observed levels of policy effort and connecting these observations to projected energy transitions outcomes, Papers 2, 3 and 5 explicitly trace the feedbacks between different elements of policy effort. Synthesizing the findings from our papers, I propose to use empirically measured policy effort as an indicator for socio-political barriers to technology change.

Empirically, our findings show that compensation for coal power phase-out (i.e. the level of policy effort embedded in policy actions) tends to be best predicted by avoided emissions (i.e. the level of policy effort embedded in coal phase-out targets). Our findings also challenge the assumption that policy effort declines with increasing technological maturity and competitiveness, by showing that policy effort is sustained over time and responds to increasingly diverse barriers. Finally, we show the scale of policy effort to overcome barriers to projected coal phase-out pathways and to offshore wind targets, which are both likely to require concerted efforts across countries.

Table 1 details the three types of contributions by the papers included in this thesis.

Table 1 Summary of contributions and relation to included papers.

Type of contribution	Description	Related paper(s)
Conceptual	Advancing an understanding of how policy effort evolves throughout the phases of technology change	Paper 1, Paper 4
	Explicitly linking policy effort to the level and type of socio-political barriers to technology change	Paper 2, Paper 3, Paper 4
	Exploring the feedbacks between three elements of policy effort: commitments, actions, and outcomes	Paper 3, Paper 4, Paper 5
Methodological	Tracing the evolution of barriers throughout phases of technology change using diagnostic indicators (for coal phase-out) and policy analysis (onshore wind growth)	Paper 1, Paper 4
	Explicitly measuring socio-political barriers by quantifying policy effort embedded in targets and compensation policies (for coal phase-out) and in the policy mix (for onshore wind growth).	Paper 2, Paper 3, Paper 4
	Connecting policy commitments and actions to projected policy outcomes	Paper 2, Paper 3, Paper 5
Empirical	Showing that the level of compensation for coal power phase-out tends to be proportional to avoided emissions (policy effort embedded in phase-out targets given the size and age of coal power plant fleets).	Paper 2, Paper 3
	Challenging views that policy effort declines with increasing technology maturity and competitiveness, because new barriers emerge with increasing technology deployment	Paper 4, Paper 5
	Showing the policy effort to overcome barriers to projected coal phase-out pathways and targeted offshore wind growth.	Paper 2, Paper 3, Paper 4, Paper 5

1.3 Structure of the thesis

Section 2 introduces the general research area and relevance of studying policy effort for energy transitions. Section 3 summarizes the overarching approach and main methods applied in this thesis, and Section 4 highlights major results. Methods (Section 3) and Results (Section 4) are divided into sub-sections about the two key-processes studied: coal power phase-out and wind power expansion. The Discussion and Conclusion (Section 5) synthesizes the contributions of the five appended papers, discusses limitations, and outlines how these can be addressed by further research.

2 Background

2.1 What are energy transitions, and why are they important?

2.1.1 The relevance of energy transitions for climate change mitigation and beyond

Human societies have converted 'fuel' – such as biomass, fossil fuels, sunshine, or wind – into useful energy for centuries, and at increasing amounts. From 1820 to 1920, global energy consumption increased roughly threefold – from 1920 to 2023, it increased tenfold (41). Increasing energy consumption has enabled societal advancements and economic growth, as well as trade, travel and communication globally. Most recently, energy has become more important to power the increasing use of artificial intelligence (42). Beyond making life more comfortable and exciting, access to energy helps to meet basic human needs by providing lighting, heating and cooling, or by powering hospitals. Still, not everyone has access to clean energy, and several countries have growing populations and growing economies (43), challenging aims to reduce global energy demand (44).

However, the increasing consumption of energy also has negative effects – energy generation is the sector with the highest CO_2 emissions, significantly contributing to global temperature change (45). This gives rise to a huge societal challenge: How to satisfy energy demand, while simultaneously mitigating climate change? The quick answer to this question is: by decarbonizing energy generation, the majority of which today is generated from burning fossil fuels (46). This means ramping up low-carbon electricity generation, which is a crucial component to decarbonizing energy and other hard-to-abate, energy-intensive sectors (47). However, these initial insights give rise to many more questions: How quickly does the use of fossil fuel-power need to decline, and low-carbon electricity generation grow, to meet climate change mitigation targets? What measures need to be taken to enable such transitions?

2.1.2 Projecting energy transitions in line with climate change mitigation pathways

A key analytical tool to understand what energy pathways are in line with climate change mitigation targets are complex integrated assessment models (IAMs) (48,49,50). Such models contain mathematical representations of mechanisms that operate in the real world, and extrapolate them to understand how the future may evolve given existing knowledge and model assumptions. Originally, IAMs were designed to answer "what if" questions, allowing scientists and decisionmakers to understand the likely trajectories of emissions, and their consequences for climatic change (51). For example, given the assumptions and mechanisms under which a given model operates, *what* will the temperature outcome be *if* existing trends of economic and technological development continue? Over time, the use of IAMs has expanded to also show mitigation strategies compatible with different warming levels (19,51) – including transitions from using unabated fossil fuel power to low-carbon electricity sources.

The pathways derived by such models typically indicate that the largest and cheapest mitigation potential lies in the rapid and global expansion of renewables power – specifically wind and solar power (19). Expanding low-carbon electricity generation is projected to not only satisfy increasing electricity demand due to economic and population growth, but also to electrify energy consumption in sectors like transport and industry, which are currently largely powered by fossil fuels. To date, coal power is the most widely used and most carbon intensive type of electricity. In ambitious climate change mitigation pathways, unabated coal power is phased out latest by mid-century, accompanied by a marked increase in low-carbon electricity generation (3,19). What is still debated is to what extent the realization of such pathways would require a departure from currently ongoing technology trends, and whether – and what type – of policy effort would be required to achieve them.

Some scholars argue that increasing rates of renewables growth globally indicate a global momentum (52) in their deployment. This momentum may be sustained over an extended period of time given increasing returns of technology learning, cost declines, and deployment rates (13). IAMs have been criticized for out-of-date assumptions regarding these cost dynamics, as well as out-of-date assumptions regarding levels of coal use – arguably causing these models to underestimate likely rates of renewables deployment and coal decline, and overestimate the policy effort required to achieve them (13,53). As renewables technologies achieve cost parity with fossil fuel-based technologies, they are expected to become more attractive to investors, and thus to be increasingly deployed even in contexts with low or no additional policy interventions such as carbon prices (11).

Other scholars argue that energy and climate models project faster renewables growth, and faster coal decline, than what may be expected under existing trends (54,55,56,57). These scholars argue for example that disaggregating coal phase-out pathways from global to national level reveals that historically unprecedented coal phase-out rates are required in major coal consuming countries such as China, India or South Africa – while China and India are the top countries building additional coal power (55,56). Even though cancellations of planned coal capacity additions across emerging economies indicate that roughly half of globally planned capacity may not be built (15), China alone added a record amount of coal capacity in 2024 (17). Similarly, for renewables growth, scholars caution that the fastest maximum growth rates ever achieved in individual countries are below what is projected by models in line with ambitious climate change mitigation targets (54), and that achieving such growth might thus require unprecedented efforts. Optimistic projections of renewables deployment based on cost reductions arguably disregard socio-political barriers such as scarcity of suitable land, grid integration challenges, or public acceptance (54,57,58). Energy and climate models have been criticized for their limited representation of socio-political mechanisms, often approximating policy interventions through globally enforced carbon prices and disregarding the complexity of and variance of different actors' interests in shaping energy transitions (59,60).

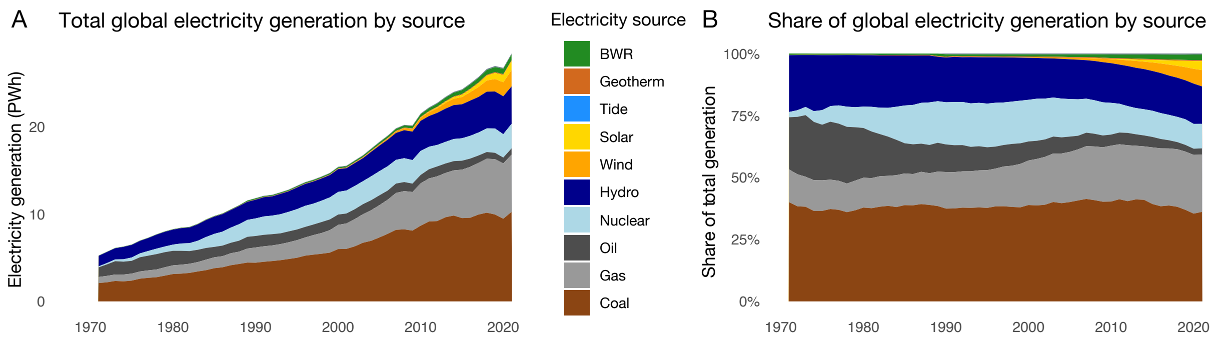
There is thus disagreement regarding whether, and under what level of effort, projected low-carbon energy transition pathways can be feasibly implemented in the "real world" (61) - or, in other words, whether they are "do-able under realistic assumptions" (62).

2.1.3 Historically observed patterns of energy transitions and technology change

To understand whether the projected transition of fossil fuel to low-carbon power generation is "do-able under realistic assumptions", scholars regularly compare the speed and scale of projected pathways to historically observed transitions (as indicated in the previous section), to understand whether similar changes have been achieved in the past, and under what conditions (55,56,63,64). This approach makes use of the fact that, while the transitions projected by climate and energy models present a significant change to the status quo of current electricity generation, energy transitions and other technological change have occurred historically. This section reviews historical evidence on energy transitions, and other technological change, and outlines how this evidence informs projections of low-carbon energy transitions.

In the early 1900s, coal and hydropower largely dominated global electricity generation (Figure 1). Throughout the first half of the 20th century, oil and natural gas power grew but following the oil crisis in the 1970s, electricity generation from oil declined, with generation from coal, gas and nuclear power increasing in absolute terms. Especially since the 2010s, renewables technologies like solar and wind power generation grew. Figure 1, Panel A, illustrates that, historically, transitions in terms of power generation sources have mainly been "additions" – i.e. that, rather than replacing one source of electricity, a new source has been added on to existing generation to satisfy overall increasing global electricity demand. Panel B shows that, over the past 50 years, the share of coal power generation has remained largely stable at around 35% of global electricity generation, with a slight decrease visible since the second half of the 2010s – indicating the size of the challenge in reducing its share to 0% over the next 30 years.

Figure 1 Total global electricity generation by source. Data from IEA (65). Own illustration.

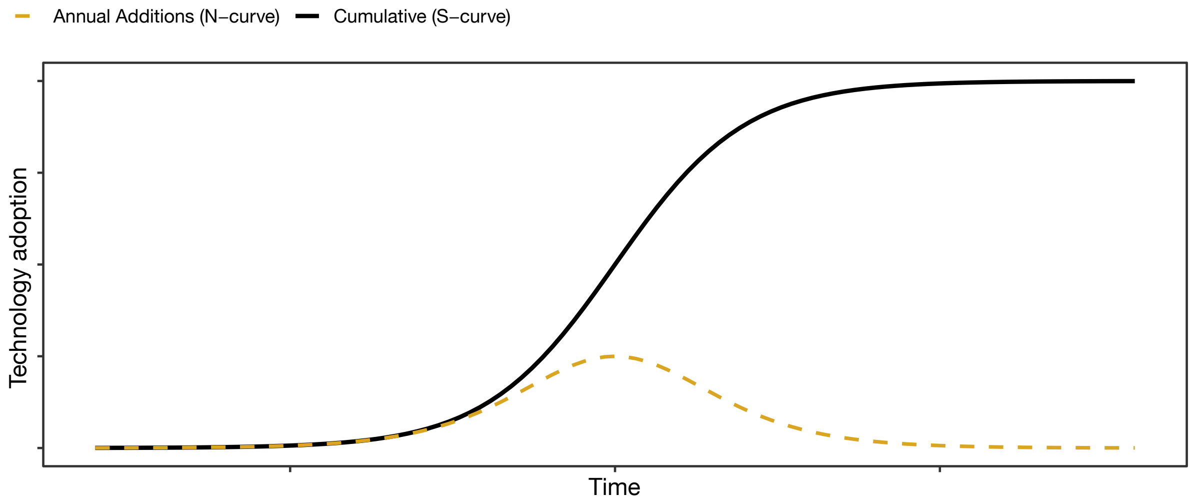


Changes in the use of fuels for electricity generation require technology change beyond simply replacing one fuel with another: To generate electricity from different fuels, different physical structures – or artefacts – are required, such as: different types of power plants to generate electricity from wind or solar power rather than from burning coal; transmission lines to transport electricity; or new cars that run on electricity rather than on oil. Knowledge and practices are required to build, operate and maintain these new artefacts (66). What do past transitions reveal about the conditions under which new technologies typically diffuse, and at what rates? And what insights may these historical observations entail for the rapid transitions required for climate change mitigation?

The diffusion of new technologies, i.e. their increased deployment over time, typically follows an S-shaped curve (Figure 2), where growth is slow at the beginning, then speeds up, and finally stabilizes and decelerates (54,67,68). This dynamic has been observed for the diffusion of many different societal innovations across history: in the middle ages, the spread of monasteries followed an S-shaped curve (69), the growth of the railway network in the UK throughout the 19th and 20th century can be visualized along the S-curve (68), and in the

1950s, S-shaped patterns described the adoption of a new type of corn by farmers in the United States (67). This macro-pattern – the S-curve – emerges as an aggregation of many "random, complex and largely unpredictable micro-factors" that together form this re-occurring shape (67).

Figure 2 Conceptual illustration of the typical S-curve of technology adoption. Own illustration.



Technology deployment along the S-curve can be delineated into four distinct phases (36): The first phase, when growth is overall slow, is called the "formative phase" (36,70,71,72). Experimentation around the new technology typically has not yet finished, so there may be several designs on the market. The costs of the technology in this phase are relatively high, and performance may still be spotty, meaning that there are only few adopters in the "niche" which the technology fills (71,73,74). It is generally agreed upon that policy support is important during this phase, especially if an innovation is needed to address grand societal challenges such as air pollution or climate change, rather than fulfill the needs of individual consumers (72,73). Such policy support may provide funding for experimentation to improve existing technology designs, as well as subsidies to encourage market actors to adopt the technology, even at high initial costs. Eventually, experimentation is likely to converge in one dominant design which may distinguish itself by its performance, lower cost, or by its appeal to consumer preferences (74,75). The formative phase is considered to end once a certain share of the market (typically between 0.1-2.5% (54,63,76,77)) is being occupied by the technology, which serves as an indicator that it has reached societal recognition and sufficiently high performance to "take-off".

Take-off ushers in the second phase of technological diffusion, at which growth progresses rapidly – the "acceleration" phase (36,54). This phase is characterized by increasing returns that drive adoption (36,72,78): As an invention becomes more broadly adopted, producers and industries gain increasing experience with the technology. Both the production of individual units, as well as the size of units, are typically scaled up, which leads to cost decline of the technology per unit (22,79). This increases adoption as the technology becomes cheaper, and in turn leads to gaining even more experience. This phenomenon is represented along "learning curves"(22,80), which can be steeper for some technologies than for others – meaning that the same increase in adoption of a technology may lead to a different rate of cost reductions.

However, declining technology cost may not be able to accelerate adoption indefinitely, given that many new technologies require broader, system-level changes. This can include changes in the regulatory environment, or of socio-cultural and physical infrastructures (64,66,69,81). Additionally, new challenges may emerge as technologies continue to diffuse. In the case of renewables, this has included for example public opposition, or land and resource scarcity (58,81,82). These barriers counteract the drivers of technology growth, inducing a third – stable – phase of technology growth, where growth persists, but does not accelerate anymore (36,54).

Ultimately, the market saturates and the fourth phase where growth stagnates is ushered in (this phase has also been called saturation, or "slow-down") (36,54,69). Growth ends because the market becomes saturated and there is no more demand for technology deployment, or due to hard constraints such as land scarcity.

On the "flipside" of the diffusion of emerging technologies, low-carbon energy transitions also require the decline of established technologies (39) – most rapidly, the phase-out of coal power generation (6). The rapid decline of coal power generation projected in line with climate change mitigation targets is unprecedented on a global scale [Figure 1A], and largely unprecedented on national level (55,56). However, individual countries have experience with coal decline, which provides insights for how and under what conditions decline typically unfolds.

One contributor to coal power decline is increased competition from alternative technologies, such as affordable renewables or gas power generation (74,83,84). Another driving factor is the depletion of domestic coal resources, the comparative affordability of coal imports (85,86,87), and changes in existing policy support to uncompetitive domestic coal industries (88,89). However, whether such decline is fast enough to be in line with climate change mitigation targets depends on the balance between drivers and barriers to coal phase-out. One barrier to phase-out is the remaining lifetime of operating coal power plants. Even if it is unlikely that new investments in coal power plants will be made in the future, closing coal power plants prematurely before they reach their "end-of-life" means that investors lose revenues (90,91), giving them an incentive operate coal power plants for as long as is profitable. Indeed, resistance from actors within the coal industry has often been highlighted as a barrier to phase-out (28,87,89) .

Finally, contextual factors can affect the speed of coal power phase-out. One such factor is system size – smaller energy systems with fewer coal power plants may be able to replace this capacity more quickly than larger systems with higher amounts of coal capacity (56). A second aspect is overall electricity demand: at stable, or declining demand, existing coal power plants can be closed down more easily than under rising electricity demand, which requires not only replacing but also adding additional capacity (56,92,93).

To summarize, historical observations of technology diffusion and decline provide insights that can help understand under what conditions a certain scale and speed of technology change tends to be feasible. However, the definition of feasibility also entails the term "do-able" – meaning, that actors are involved in realizing technology change (62). Agency of relevant actors may thus help overcome barriers and enable low-carbon energy transitions even under more challenging circumstances.

The research presented in this thesis specifically focuses on the agency of national governments in implementing policies to steer energy transitions. The following section explains this focus, and reviews prior literature on the relationship between policies and technology change.

2.2 What is the role of policies in energy transitions?

2.2.1 The relevance of national policies for energy transitions

While many different types of actors are involved in energy transitions, national governments arguably play an especially important role, since they are able to make binding decisions on societal level that steer energy transitions (94,95). Indeed, national governments are often called upon to implement policies that help innovative technologies surpass the formative phase, address barriers to the sustained acceleration of renewables, and induce the destabilization of locked-in incumbents (72,73,96,97,98,99).

Such policies are outcomes of complex policy-making processes in which different actors such as elected politicians, interest groups such as energy industries, workers unions or non-governmental organizations (NGOs), and supranational organizations such as the European Union (EU) interact (100,101,102,103). While these processes are not the primary focus of this thesis, a basic understanding of how different interests compete and negotiate policy outcomes is relevant to understand the evolution of policies, and their interaction with processes of technology change. The following section thus reviews various factors shaping energy policy and politics.

2.2.2 What factors shape energy policy and politics?

Energy policies are shaped both by the agency of relevant actors, as well as by the structural context in a given country that shapes their interactions (104). Structure may for example refer to the overarching "rules and resources" present in a given setting (rules largely refer to established regularities that shape social interactions, and resources to the "transformative capacity" in acting upon these rules, which varies across different actors) (105,106). Despite the persistent nature of "structure", the interests and capacities of actors allow them to interact with existing structures, which may re-shape structures over time (106). The remainder of this section reviews insights into how the interplay between structure and agency influences energy policies and politics, and in turn affects energy transitions.

One way in which state structures and institutions influence how energy transitions unfold is by affecting which actor groups have access to policy processes. For example, in countries where industry lobbies and workers unions have more direct access to decisionmakers, coal phase-out may progress more slowly or require stronger policy effort to appease these groups, than in systems where industry and governments interact less (107, 108).

However, the interests of the state can supersede individual interest groups. Domestic energy security for example is an important concern for national governments – i.e. the aim to secure the provision of energy to maintain critical social functions (109). On the one hand, energy security concerns can hinder coal phase-out in the case of abundant domestic coal resources. On the other hand, in case of a lack in domestic resources, security concerns can raise government interest in supporting domestic renewables power generation (89,92,110).

State goals entail not only securing, but also expanding electricity systems to provide energy access to all parts of the domestic population and industry, especially in contexts where populations and economies are growing (111).

Beyond state and incumbent interests, sufficiently strong public opinion can also affect national energy policy in the short- or the long-term – both as a driver, and as a barrier to rapid technology change. Sufficiently strong anti-fossil fuel norms and climate change concerns among the public can drive coal power phase-out and renewables expansion (112,113). Public opinion may however also hinder the growth of low-carbon technologies- one example is the effect of public safety concerns on nuclear power, especially after major accidents such as Tchernobyl in 1987, and in Fukushima in 2011 (114). In the German context, the latter incident reinforced an existing nuclear phase-out policy, despite a conservative government generally in favor of supporting nuclear power (115,116). Currently, onshore wind power faces public opposition in several countries, in part due to environmental concerns, or concerns of negative effects on those living closeby (117,118,119,120). Another example is voter backlash against technology phase-out; which may affect subsequent governments' environmental and climate policy. In the United States (US), for example, counties suffering from coal mining job losses showed a higher vote share for the Republican party more in support of the coal industry (30).

Whether states are able to pursue low-carbon policies despite backlash and incumbent resistance (assuming it's within their interest) depends in part on states' capacity to overcome socio-political barriers (115,121,122). There are different definitions of state capacity that translate into different measures (123). State capacity may relate to the presence (or absence) of corruption, whether states are able to implement and enforce regulations, the quality of public services, or states' capacities to manage conflicts, among others (123). Jewell *et al.* (122) for example found that countries with higher safeguards against corruption, lower levels of undue influence, and more transparent government operations (measured via the Functioning of Governance index) have a higher likelihood of phasing out coal. Similarly, Brutschin *et al.* (121) found that countries with higher ability to mobilize interest groups (measured via Sigman and Hansons' indicator) tend to prematurely retire coal power plants.

The extent to which different interests inform energy policy changes over time and depending on the national and global geo-political context. Energy security concerns gained prominence for example during the oil crises in the 1970s and 1980s (109), when oil prices rose in the context of political embargoes. This encouraged governments to support experimentation with alternative energy sources (116,124). As oil prices stabilized, energy security concerns became less prioritized (109). Recently, energy security concerns re-emerged as electricity prices rose following the Covid-19 pandemic and in the lead-up to the Russo-Ukrainian war (125,126,127).

2.2.3 Energy policy in the context of climate change mitigation

The previous section mainly discussed state interests such as energy security and economic growth. This section focuses on energy policy specifically in the context of climate change mitigation.

2.2.3.1 Political targets for energy transitions

In 2015, the 196 signatories to the Paris Agreement formalized the political goal to undertake efforts to limit global temperature change (2). This initial agreement was then followed by national and global targets to pursue efforts for climate change mitigation; such as supporting low-carbon energy transitions. For example, at the 23rd Conference of the Parties (COP23) in 2017, the Powering Past Coal Alliance (PPCA) was launched (128), with member countries pledging to phase out coal by 2030. At COP26, the Global Coal to Clean Power Pledge (GCCP) was made, signatories of which subscribe to the aim of coal phase-out for major economies in the 2030s, and globally in the 2040s (129). At COP28, more than 100 countries pledged to triple renewables deployment globally by 2030 (130).

Prior research has engaged with the question whether these energy transition targets are in line with the Paris climate targets. For example, the emission avoidance of coal phase-out targets made under the PPCA by 2018 was shown to fall short of climate change mitigation targets – among others because the members of the alliance covered less than 5% of globally active coal power capacity at the time (122). Countries *with* coal phase-out commitments tended to have already passed the peak in coal power generation, have lower shares of coal in their electricity supply, low to no electricity demand growth, relatively high GDP per capita, and low levels of corruption (122,131). Countries *without* coal phase-out commitments at the time included major coal consumers: China, India and South Africa, as well as the US, Germany, Japan, and Russia (55,122).

For renewables growth, recent targets set by individual countries (like Germany) and by the EU were shown to be in line with growth rates required under ambitious climate change mitigation scenarios (63). Globally, the pledge of tripling renewables deployment from COP28 is considered vital to keep 1.5°C-consistent pathways in reach (3).

While these ambitious targets give a sign of hope for climate change mitigation, all targets are not realized. Previous research indicates that more ambitious targets may be less likely to be achieved (132) which highlights the need to look beyond government commitments, and pay attention to the policy measures which are actually implemented.

2.2.3.2 Policy measures for energy transitions

One often-discussed type of measure in the context of low-carbon energy transitions are carbon pricing instruments such as carbon taxes or cap-and-trade schemes (133,134,135,136,137). Carbon pricing policies are often considered a “first-best” policy (138,139), i.e. they are considered the most economically efficient approach to achieving temperature targets. The underlying logic is that governments price the negative externalities of carbon emissions, such as air pollution or climate change – making carbon-intensive technologies less competitive and thus more prone to be phased out, with governments ‘profiting’ from the remaining carbon emissions rather than paying for abatement. From the perspective of scientists, carbon pricing schemes might be considered “analytically efficient” – they are relatively easily measurable and quantifiable. In energy and climate models, carbon pricing is often used as a proxy for the overall policy effort within a given pathway (60).

However, the effectiveness and social acceptance of carbon pricing schemes is debated. While some find that the introduction of carbon pricing often coincides with emission reductions (135), others find only relatively limited effects of carbon pricing on emission reductions (140). Yet others argue that despite potential short-term effects, carbon pricing only has limited effects on the longer term technological and systemic change required for climate change mitigation (133,141). One concern around carbon pricing relates to the distributional impacts of this policy – while it may be economically preferable on societal level, its effects can be unequally distributed across income groups. Depending on the national context and the respective policy design, carbon pricing may be either progressive – placing higher relative costs on higher income groups – or regressive – placing higher relative costs on lower income groups (137,142). While policy designs ensuring the progressiveness of carbon pricing schemes are possible, and revenue recycling options have shown to increase public acceptance of carbon pricing schemes (136), the absence of such designs may lead to backlash – which may ultimately lead to a weakening or repealing of carbon pricing policies, inhibiting their long-term effectiveness (143).

While carbon pricing is often highlighted as a policy option to steer low-carbon energy transitions, many scholars argue that ideally, combinations of several instruments within policy mixes are required (101,144,145,146). Policy mixes are typically conceptualized as combinations of multiple policy instruments implemented under an overarching policy objective (101,147), and assessed against their consistency, coherence, credibility and comprehensiveness toward achieving this objective (148). Policy mixes may contain multiple policy instrument types, such as regulatory policies, research and development (R&D) support, or voluntary schemes (149,150). For the overarching aim of low-carbon energy transitions, a policy mix may contain both "niche protection" policies to support emerging low-carbon technologies, as well as "creative destruction" policies to destabilize carbon-intensive technologies (96,98). Examples are combinations of a), financial incentives for low-carbon technologies with b) regulatory performance standards or fossil fuel subsidy withdrawal that constrain the competitiveness of carbon-intensive technologies. However, there remain significant uncertainties regarding the ideal configuration of policy mixes.

One uncertainty revolves around the trade-off between the effectiveness of policy mixes, versus the effort it takes to implement them. One controversy revolves around compensation policies for coal phase-out. Recent literature cautions that policies destabilizing existing industries induce unequally distributed negative effects: for example, workers within carbon-intensive industries lose their jobs, regions rich in fossil fuel assets lose large contributors to the regional economy, electricity consumers may suffer in case electricity prices rise, and fossil fuel industries lose revenues (151,152,153,154). This has led to calls for complementing phase-out policies with compensatory policies to ensure more "just" and more feasible transitions (154,155). Such expansive compensation policies have however also been criticized as becoming too expensive, and potentially ineffective in driving coal power phase-out (156,157).

Another uncertainty regarding the composition of policy mixes revolves around their temporal dynamics, and their interaction with technology growth over time. For example, one study counterintuitively found that policy mixes which maintain a similar balance of policy measures over time correlate negatively with renewables expansion (149). This indicates that the composition of policies in the policy mix needs to change over time as technology growth progresses – though it may be unclear how.

One emerging concept which can contribute to resolving these uncertainties is climate “policy effort”, measured in terms of countries’ commitments to climate change mitigation, the policy actions implemented to achieve these commitments, and the eventual outcomes in terms of emissions changes (40). Applying it to energy transitions, and tracing its elements over time, can help to better understand the temporal dynamics of policy-technology interactions, and how the level of effort embedded in policies corresponds to energy transitions outcomes (see Section 3.1).

2.2.4 Temporal dynamics and feedbacks between policy and technology change

One shortcoming in the current understanding of policy effort is that it conceptualizes policy effort as an exogenous driver of climate change mitigation, or technology change. However, socio-technical transitions literature has shown that policy and technology change are in fact interconnected by a series of positive and negative feedback loops, which shape their mutual interactions and temporal dynamics.

Positive feedbacks are mutually reinforcing increasing returns, where several developments positively influence each other (78,104,158). Section 2.1.3 already described the importance attributed to increasing returns in the technology literature (focusing mainly on technology learning and cost reductions). Policy literature shows that increasing returns can not only occur in the context of technology change, but also in the context of policy change (159): once a policy becomes introduced, it may for example shape expectations of future policies; it creates beneficiaries that are likely to support the continuation of the policy; and it can induce “learning”, meaning that amendments over time can further improve the policy at lower time and resource investment than it would take to design a completely new policy (159). In this way, existing policies influence politics (i.e. the processes by which new policies are negotiated) and by extension future policies. This mutually reinforcing process creates a positive feedback loop, which can lead to path dependency, as it becomes difficult to change an existing policy trajectory (159).

Feedbacks do not only affect technology and policy change in isolation, but also connect both processes: policy interventions affect conditions of technology change in different ways, for example by providing resources for R&D activities, supporting the formation of networks and coalitions around a certain technology, or reconfigure relevant aspects of the institutional structure within which technology change takes place (160). The subsequent technology change in turn “feeds back” into political processes, for example by inducing support (or objection) among different interest groups, or by creating increasing demands on state budgets (116,124,160,161). In other words, policymakers learn from and adapt to the prevalent issues to technology change at a given point in time, and subsequently adopt the policy mix (161).

Feedbacks across policy and technology change may be either positive, or negative. Positive feedbacks are those that mutually reinforce technology deployment and policy support. One example is, arguably, the process leading up to the Paris Agreement, as governments were encouraged by increasing deployment of low-carbon technologies, specifically renewables, to agree to ambitious targets for climate change mitigation (9). While this presents a desirable case of positive feedbacks from a climate change mitigation standpoint, a less desirable case is what Unruh (162) termed carbon lock-in. Despite the well-known negative environmental externalities of fossil fuel power generation, and the increasing competitiveness of low-carbon technologies, existing infrastructures have adapted to fossil fuel power generation, and workers unions and industry associations have formed powerful lobbies, politically supported for decades by subsidies and tax benefits (162,163,164). The potential for policymakers to upend such lock-ins through destabilization policies may be affected by strong resistance, and may thus require "buy-in" from the overall public – or slow, incremental change (97).

In the case of fossil fuel technologies, lock-ins have become increasingly entrenched over extended periods of time. However, if negative feedbacks emerge early-on in policy-technology interactions, they may prevent lock-in in the first place. This can happen if the process of adapting policy to feedbacks from technological growth is too slow, leading to poorly timed policy interventions (165), or if policymakers lack the capacity to adequately respond to the feedbacks from technology change (161). One example is policy support for solar power growth in China, where initially accelerating growth led to challenges (for example grid integration), which could not be immediately resolved by policymakers, who then introduced restrictive policies to slow down solar power growth (166).

From a climate change mitigation perspective, what is then important is to break up the positive feedbacks entrenching carbon-intensive technologies, and prevent negative feedbacks from hindering renewables expansion. One proposed strategy is to sequence policies over time, by introducing less stringent policies initially – such as a low carbon price only focused on few sectors, to avoid backlash – while also introducing policies that support the build-up of renewables interest groups (139,167). This should then enable an increasing stringency of low-carbon policies over time. However, some have cautioned that the policy sequencing framework focuses primarily on the positive feedback effects that relax stringency barriers, while neglecting feedback effects that can strengthen barriers– for example, rising consumer electricity prices due to subsidizing renewables may induce resistance from electricity consumers, rather than only strengthen interest groups (168).

2.3 Puzzle, research objectives and research questions: Understanding policy effort for energy transitions

To summarize, scholars focusing on energy policy generally argue that a combination of multiple policies is required for low-carbon transitions (96,144,146). However, the ideal configuration of such policy mixes remains unclear: while some call for compensation of negatively impacted actors of energy transitions (154), others argue that such extensive policies may become excessively expensive, calling rather for destabilization of incumbents (96,156). Additionally, while it has been proposed that policy sequences enable the removal of socio-political barriers over time (167), it is unclear how exactly these barriers evolve over time and what this implies for the temporal dynamics of policy mixes (149,168).

Simultaneously, optimists among energy modelers argue that increasing returns of technology growth likely enable renewables to replace fossil fuel-based power generation under relatively low climate policy effort (11,13,25,53). Attention is especially called to enabling the growth of renewables in the short term, with less and less policy effort likely required in the long term (13).

There is a lack of integration between the highly contextualized, granular evidence on policies, and highly aggregated, stylized energy modelling. Energy and climate models have been criticized for their focus on techno-economic rather than socio-political mechanisms, underrepresenting the complex role policy and politics play in technology growth (169): model assumptions may miss socio-political barriers to technology change, such as resistance to energy transitions (55,60,170), or other socio-political barriers to renewables deployment (52,57,58) – challenges which likely require sustained policy effort even as renewables costs decline (81).

To address these disagreements, the research I present in this thesis aims to advance the understanding of interactions between policy effort and technology change, and contribute to bridging evidence on socio-political barriers, policy effort, and macro-patterns of technology change. To this end, this thesis pursues three objectives:

1. Advance approaches of conceptualizing, measuring and quantifying policy effort for technology change.
2. Measure and map policy effort to the phases of two ongoing key processes in energy transitions: coal power phase-out, and wind power expansion.
3. Derive insights on the level and type of policy effort for overcoming barriers to technology change in line with climate change mitigation targets.

For the first objective, I draw on emerging conceptualizations of climate policy effort as policy commitments, targets, and outcomes (40), based on which I describe how we measure and map policy effort in the five appended papers in connection to low-carbon technology change (Section 3).

For the second and third objective, we measure and map policy effort for to two ongoing key processes of low-carbon technology change: coal power phase-out, and wind power expansion. This entails answering two research questions:

> Mapping the *type of policy effort* to transitions processes: What policy sequences are associated with progressing phases of coal power decline and wind power growth?
>
> Mapping the *level of policy effort* to transition processes: What level of policy effort has been associated with coal power decline and wind power growth?

For the third objective, we connect our empirical observations of policy-technology interactions to projected energy transitions outcomes. This entails answering a third research question:

> Abstracting from empirical observations: What insights do these ongoing processes entail for projected energy transition outcomes in line with climate change mitigation targets?

3 Approach and Methods

This section reviews the overarching framework and provides a summary of the methods we apply in the individual papers. Detailed methods descriptions can be found in the articles.

3.1 Analytical framework

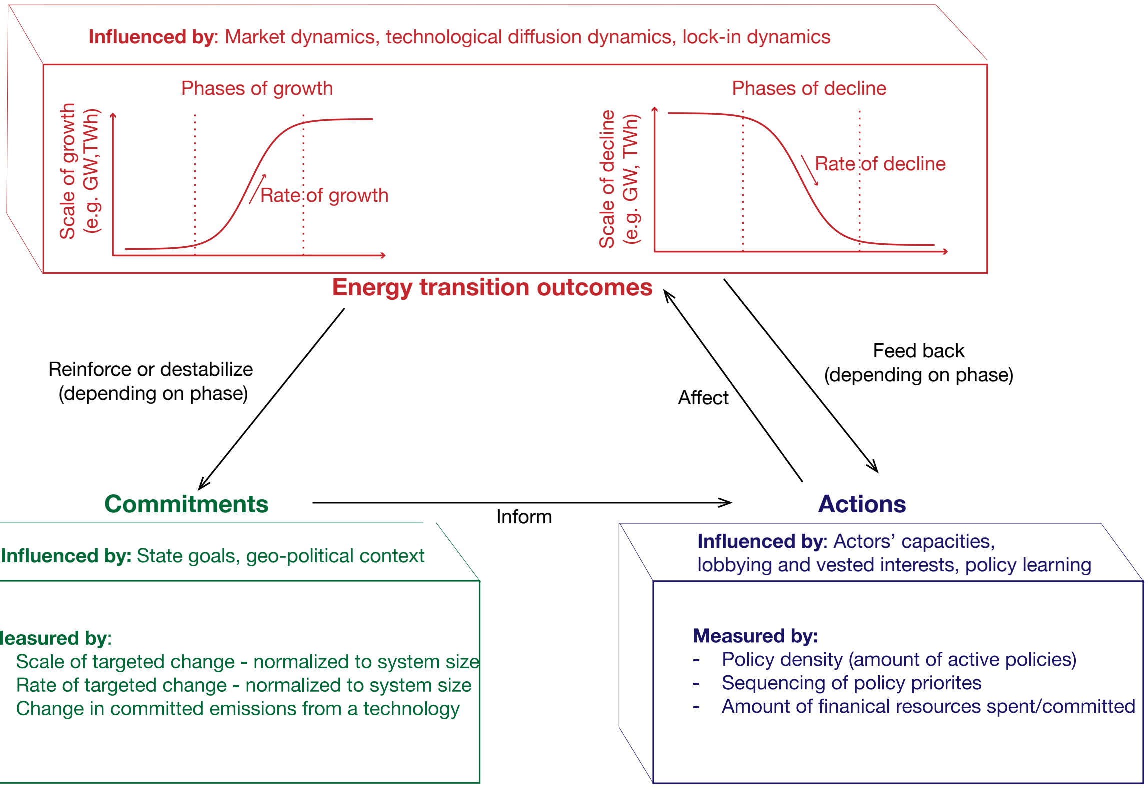
To synthesize and structure our findings on policy-technology interactions, I draw on emerging conceptualizations of climate policy effort (40), and connect it to an understanding of the macro-phases of technology change (Figure 3).

Lieberman (40) identifies three elements to policy effort: “policy commitments”, “policy actions”, and “policy outcomes”. Commitments refer to policy targets, which in the context of this thesis means targets for renewables deployment, or fossil fuel phase-out. Policy actions refer to specific measures implemented to achieve these commitments. For the case of energy transitions, this may relate to the strength of individual policy measures, as well as to mixes or sequences of multiple policies. Policy outcomes refer to “observed changes” (40) – in the context of energy transitions, this refers most directly to observed changes in renewables deployment or fossil fuel decline, but may ultimately also refer to observed changes in emissions as a result of these energy transitions. Figure 3 illustrates the major approaches to measuring the three elements of policy effort adopted in this thesis (see Sections 3.3 and 3.4 for a detailed description).

This existing approach to climate policy effort assumes a linear relationship between these elements, with policy outcomes as the result of policy actions to achieve policy commitments (40). In this thesis, I advance this conceptualization by linking it with insights on policy-technology feedbacks, i.e. that technology change potentially induced by initial policies “feeds back” and affects subsequent policy actions and commitments (Figure 3) (160,161). In addition to policy-technology interactions, energy transitions outcomes are also influenced by factors such as geopolitical changes, market dynamics (e.g. electricity prices and technology costs), or natural resource constraints.

To structure the study of policy-technology interactions over time, I draw on the concept of phases of growth and decline, throughout which the speed, drivers and barriers of technology change shift (36,39,54,171). This makes it possible to more systematically trace and compare the temporal dynamics of technology change, policy effort, and contextual developments. It also adds an important dimension for the comparison of energy transitions across national contexts, where the same technologies may be in different phases of growth or decline.

Figure 3 Analytical framework: Interactions between policy commitments, actions and outcomes for energy transitions. Own illustration.



This framework provides the basis to answer the three research questions outlined in Section 2.3:

(1) Mapping the *type of policy effort* to transitions processes to better understand the evolution of policy sequences throughout the phases of technology change.
(2) Quantifying the *level of policy effort* associated with technology change, embedded in policy commitments and policy actions.
(3) Abstracting from empirical observations, and connecting them with projected energy transitions outcomes in line with climate change mitigation targets.

3.2 Case selection

The five papers included in this thesis assess two key processes for the decarbonization of electricity systems: coal power phase-out, and wind power expansion.

Coal power phase-out is one of the most urgent energy transition components, with pathways in line with global climate targets projecting unabated coal power generation to be phased out globally by mid-century (3,19). Abated coal power generation, i.e. equipped with carbon capture and storage (CCS) technologies, is projected for extended periods of time under few pathways, but it is highly unlikely that sufficient CCS-capacities will be available, and cost efficient, in time (7). This reinforces the challenge of rapidly phasing out coal, which is still increasing globally in absolute terms, set to plateau only as of 2027 (172).

However, coal trends are not uniform across countries: Only few countries have already completed coal phase-out, while many others have commitments to phase out coal

(173,174). Other countries still increase their use of coal – China, for example, added a record number of coal power plants in 2024 (15,17). This makes coal phase-out an ideal case to assess socio-political barriers to decline at different phases of the transition, and across contexts.

To study temporal patterns of renewables expansion, onshore wind power is an interesting case. Among variable renewables, it is a relatively mature technology with take-off (i.e., the end of the formative phase) in European frontrunner countries almost 30 years in the past (63,175). Paper 4 focuses especially on onshore wind deployment in Germany, which is a frontrunner in Europe with the highest wind deployment per square meter (175). Onshore wind power is projected to continue to grow rapidly under climate change mitigation pathways, and Germany recently set targets for deployment roughly in line with these pathways (63). This makes it an ideal case to observe how policy effort has evolved over an extended time period, and recently in the context of targets for acceleration of growth.

Offshore wind power, in contrast, is globally still at an early phase of expansion, with deployment progressing in few frontrunner countries (176,177). Ambitious commitments for further offshore wind deployment have emerged in recent years, with the EU targeting 86-89 GW by 2030 and 355-366 GW by 2050 of cumulative offshore wind deployment across its eligible member states (i.e. those with sea basins) (178). This makes offshore wind an extremely interesting case to trace the emergence of socio-political barriers, and level of policy effort, during early phases of growth: What type of policies do frontrunners display that aim to maintain accelerating growth at early phases of deployment? What insights do these entail for latecomer countries only beginning to develop offshore wind capacity?

3.3 Methods to measure and map policy effort for coal power phase-out

3.3.1 RQ1 Mapping the type of policy effort: Framework for a policy sequence throughout phases of coal power phase-out (Paper 1)

To be able to map types of policies to phases of coal phase-out, Paper 1 first introduces a diagnostic approach to identify the phases of coal power decline, and the main barrier to decline in each phase, as a basis for a policy sequence for coal power decline.

We draw on Elinor Ostrom's (179) approach to identify combinations of key variables that describe mechanisms affecting continuity and change across interconnected systems. Here, we focus on three different, but co-evolving systems: [1] The technological system which contains the relevant knowledge, practices and artefacts that enable coal production and power generation – under climate change mitigation pathways, this system is to be phased out. [2] The industrial system which contains the companies owning and operating coal power plants, and coal mines, as well as the workers employed in these companies. [3] The regional system where these artefacts, practices, companies and workers are primarily located. Based on a review of multi-disciplinary literature, including socio-technical transitions studies, business and management literature, and regional geography and just transitions literature, combinations of variables that indicate decline, or continuation, in each system over time are identified and enable the diagnosis of the phase of decline a given country or region is in.

Based on the diagnostic variables characterizing each of these systems over time, we identify the evolution of major barriers across the phases of decline. These inform a proposed policy sequence which addresses the relevant barrier in each phase, enabling industrial and regional systems to decouple from technological decline. To test the applicability of this framework, three illustrative examples of countries in each phase of decline are assessed, including what types of policies are in place.

3.3.2 RQ2: Measuring the level of policy effort embedded in policy commitments: *Targets* for coal power decline (Paper 2)

While only few countries so far have completely phased out coal power, many countries have committed to doing so. In Paper 2, we collected data on all coal phase-out commitments of national governments from publicly available government websites and legal databases. Since major geopolitical events may affect these commitments; we also conducted an assessment of which of these pledges may be at risk of being withdrawn due to the energy crisis in 2022 by collecting additional information on changes to pledges between 2022 and 2023.

We measure the policy effort embedded in coal phase-out commitments through the following metrics:

(1) The coal power decline rate, calculated as the share of coal in power generation in the year of adopting the pledge divided by the number of years between the pledge and the phase-out date.
(2) The "avoided emissions" (122) embedded in each pledge, which measures by how much each respective pledge reduces emissions relative to a reference retirement case where all coal power plants operate at the average load factor until the end of the average national historical lifetime.

3.3.3 RQ2: Measuring the level of policy effort embedded in policy actions: Compensation for coal phase-out (Paper 3)

Paper 3 focuses on a specific policy action: financial compensation for negatively affected actors of coal phase-out. We examine all countries with coal phase-out commitments for the presence or absence of compensation policies. We then review policy documents to retrieve the amount, beneficiaries, and origin of compensation. The origin of compensation is mainly differentiated between "domestic" and "international" compensation – identifying whether national governments commit funding to domestic coal phase-out, which may require relatively high levels of domestic capacity to stem this effort, or whether governments receive foreign support in phasing out coal power.

We conduct a multivariate linear regression analysis to identify whether the existence and amount of compensation is associated with more ambitious phase-out, i.e. higher policy effort. We use the two previously defined variables for policy effort (see Section 3.3.2) as the main dependent variables. The regression analysis also controls for other relevant characteristics of the coal sector (such as the amount of workers, or domestic coal mining) and state capacity (such as the size of the national economy, or government effectiveness).

3.3.4 RQ3: Abstracting from empirical observations: Compensation in line with projected coal phase-out pathways for China and India (Paper 3)

Based on empirical observations of the amount of financial compensation, and results from the multivariate regression, Paper 3 develops a counterfactual "what if"- scenario, in which China and India – the two countries with the largest coal power plant fleets globally- phase out coal power in line with 1.5°C- and 2°C- IPCC AR6 climate change mitigation pathways, and implement compensation schemes in line with empirical observations for other countries. We calculate avoided emissions for China and India in line with climate change mitigation pathways, and calculate compensation based on the interquartile range of empirically observed compensation per ton avoided CO_2 emissions, and based on the best-performing linear regression models. Estimated compensation is then compared to existing financial flows, such as historically received aid, fossil fuel subsidies, and annual COP climate finance pledges.

This "what-if"-exercise is not meant as a prescriptive policy proposal, calculating absolutely required levels of financial compensation. Instead, it presents an approach to visualize socio-political barriers to coal phase-out based on empirically observed policy effort.

3.4 Methods to measure and map policy effort for wind power expansion

3.4.1 RQ1: Mapping the type of policy effort over time: Policy sequence throughout phases of onshore wind growth (Paper 4)

Paper 4 delineates onshore wind growth in Germany into four "macro"-phases of technology growth (formative, acceleration, stable growth, and stagnation phase), and "micro"-pulses during the stable growth phase, where technology growth de- and re-accelerates over shorter periods of time (36,175).

To delineate the end of the formative phase, we identify the take-off point for onshore wind power, following previous literature (54,180) at the point where a technology reaches 1% of final market share. We define the increasing rates of annual capacity additions after the take-off point as the acceleration phase. We define the end of the acceleration phase as the second year in a row in which the amount of capacity additions declines.

According to the standard S-curve theory, such slow-down in capacity additions may signal stagnation – however, we build on recent insights which interpret brief periods of slow-down followed by re-accelerating growth as "growth pulses" (175). The end of the acceleration phase indicates the starting point of the first growth pulse, and the pulse ends in the last year in which growth re-accelerates. A renewed slow-down then signals the beginning of the second growth pulse (or it may signal prolonged stagnation of growth in case there is no re-acceleration).

The types of policies deployed over the past 50 years are then mapped to these observed growth pulses, shedding light on what types of policies were most prevalent in different phases of technology growth. To this end, all policies are classified by their overarching policy priorities.

3.4.2 RQ2: Measuring the level of policy effort embedded in policy commitments: Targets for onshore wind growth (Paper 4)

To measure policy effort embedded in commitments for onshore wind power, Paper 4 traces legally binding targets for renewables and onshore wind in Germany since the first iteration of the renewables law came into force in 2000. Following the approach of Vetier *et al.* (175), these targets are normalized by total electricity supply, and by total onshore wind power potential (181).

3.4.3 RQ2: Measuring the level of policy effort embedded in policy actions: Policy density and financial support for onshore wind growth (Paper 4)

To assess policy effort embedded in policy actions for onshore wind power expansion, Paper 4 uses two measures: first, policy density and second, financial resource mobilization.

The measure of "policy density" quantifies the amount of onshore wind-relevant policies active in a given year (182), and has been used in prior literature as an indicator of policy effort (183) or policy ambition (184). In our case, it is a useful measure because it enables the aggregation of policies of various types – such as regulatory, economic and information policies – as well as policies of various policy areas, such as R&D support, environmental protection regulations, electricity market regulations, among others. The downside of measuring policy effort via policy density may be that it does not account for the strength, or stringency, of individual policy measures.

Paper 4 thus complements this measure with assessing the amount of financial support over time as an additional indicator of the level of policy effort. For onshore wind power in Germany, this mainly includes public research funding (traceable since the 1980s), as well as feed-in remuneration (since the 1990s). Data on public research funding is extracted from two sources: from the IEA (185), and from the EnArgus database (186) published by the German government with data available at project level. For the latter, all funding explicitly targeted at onshore wind power is identified and individual projects are classified by the same policy priorities as for the onshore wind policy sequence (Box 2).

3.4.5 RQ3: Abstracting from empirical observations of policy effort: Governance models and probabilistic projections for offshore wind power (Paper 5)

Offshore wind power growth is at a much earlier stage than onshore wind: at the time of writing, only six European countries have more than 1GW offshore wind capacity installed, and only one country (the UK) more than 10GW (176,187). However, individual countries and the EU have ambitious (though non-binding) commitments for offshore wind (178). Instead of mapping policy effort across phases of offshore wind growth, given its early stage of diffusion, Paper 5 compares policy actions implemented to support offshore wind across countries, and projects deployment under current policy actions to compare it to policy commitments. To this end, we capture offshore wind targets across 23 relevant EU countries (those with access to a seabed), plus the UK and Norway. We then conduct a review of the current offshore wind governance regimes across these countries, capturing information regarding seabed ownership and management, type of financial support, and permitting processes. We identify three types of governance regimes across all countries.

We then probabilistically project offshore wind deployment across the European Union, the UK, and Norway by 2030 and 2050, and compare these projections to offshore wind targets. The starting point for these projections are Maritime Spatial Plans, which specify the allocation of maritime area for building offshore wind power, and thus inform the capacity potential in a given country. To estimate the speed with which this capacity potential is likely to be realized, Paper 5 models deployment under each of the three government regime types, based on variables such as the auction frequency and size (i.e., the amount of capacity to be auctioned and how often), and project-level data on the typical speed of completion, and failure rates, of offshore wind projects.

To capture uncertainties in the distribution of all of these variables, Paper 5 captures a range of values for each variable based on the empirical data. A Monte-Carlo simulation (N = 10,000) is conducted for every country to derive probability distributions for offshore wind deployment based on these uncertainties. In each run, values are randomly drawn from the probability distributions for the individual variables, resulting in an overall probability distribution on country-level for offshore wind deployment by 2030 and 2050 respectively.

Paper 5 then projects offshore wind deployment levels under several scenarios with changes in offshore wind policies and compares these outcomes to national and EU-level commitments for offshore wind growth.

4 Results

4.1 Policy effort for coal power phase-out

4.1.1 RQ1: Policy sequence mapped to phases of coal decline

In Paper 1, we identify three phases of decline that the technological system of coal power generation, the industrial system of coal power companies and workers, and the regional system of coal-rich regions, undergo – each with different barriers requiring a sequence of different policies to sustain decline (Figure 4).

The first phase is characterized by technological "lock-in", wherein the coal power technology is widely used, and tightly coupled with mature industrial and stable regional systems. An illustrative example of such lock-in is South Africa, where coal power generation provided about 80% of electricity in 2022, with plans for retrofitting old and adding new coal power plants (188). The industry is dominated by state-owned utility Eskom, which owns 45GW out of the country's roughly 47GW coal power (189), and manages electricity generation, transmission and distribution (190). While coal power and coal mining are also tightly coupled with regional economies, providing high shares of employment in individual regions (191,192), regional movements have begun emerging that support a "just transition" away from coal power (193). To maintain destabilization and decline, policy actions further destabilizing the status quo are likely required. In the case of South Africa, plans for such policies at the time of writing included an unbundling of Eskom to break up its monopoly over the different parts of the electricity supply chain (188). A Just Energy Transition Partnership (JETP) Agreement had also been formed in 2021, in which a consortium of Global North countries pledged financial support to implement policy measures moving away from coal power, and supporting alternative forms of employment (194).

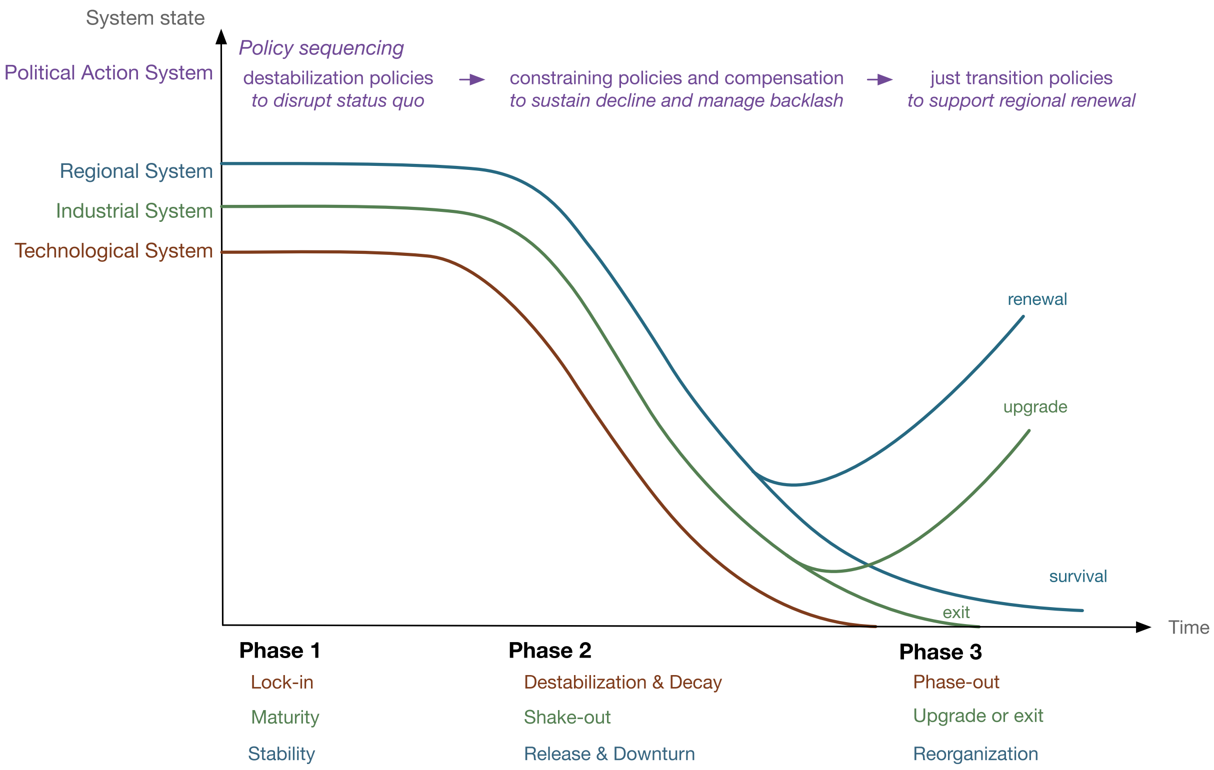
In cases where policy actions, or other contextual developments, sufficiently destabilize coal lock-in, the second phase of decline is ushered in. This phase is characterized by declining coal power generation and capacity, likely accompanied by closure of companies in the coal industry and economic downturn in coal-dependent regions. An example of a country in the second phase of decline is the US, where the availability of affordable and domestically produced natural gas; and more recently also renewables generation; have impaired the economic competitiveness of coal power (83). Additionally, electricity demand is stagnating, encouraging the closure rather than retrofitting or replacement of aging coal power plants (83,195). Consequently, the number of companies in the coal power sector is declining, and with them, tax revenues in coal-dependent regions (196,197). Policies aiming to address these challenges have included support for technological innovation as well as regional economic development, but public resistance to coal decline has remained strong and was utilized by Donald Trump especially in his first election campaign (196). In 2024, the Biden administration had introduced rules further constraining the generation of coal power and supporting negatively affected regions, another hallmark of the second phase of decline (see Box 1). However, these policies have since been revoked in an executive order by current President Donald Trump (198).

In cases where coal decline is sustained, it ultimately enters the third phase: phase-out of coal power generation. This phase is typically characterized by a complete withdrawal of the industry (with companies either relocating to other countries, or going bankrupt), and persistently low employment rates and outmigration from former coal regions, limiting potential for economic recovery and indicating a prolonged "survival mode". However, industries and regions may also manage to decouple from decline and reorient towards new technologies or revenue streams. While few countries, and only very recently, have surpassed this final stage of coal power phase-out, a historical example of coal mining phase-out occurred in the Netherlands in the 1970s. Coal mining decline was kicked off by the discovery of the Groningen gas field, which allowed for affordable and domestic production of power from natural gas. The mining phase-out was politically agreed upon (85,86), and accompanied by policies supporting the reorientation of coal companies towards other industries, as well as the retraining of workers (86). In retrospect, these measures are considered partly successful, with one former coal company having successfully reoriented while others closed (85). Regional economic development was hampered by the ensuing financial crisis, which hindered the growth of new industries in former coal regions.

The above examples of countries in the three different phases of coal phase-out illustrate the push-and-pull of drivers and barriers of decline throughout its different phases – while in the first phase, the main barrier to decline is the lock-in of the technological system, first signs of destabilization may emerge. As destabilization becomes more prevalent, a critical challenge is to sustain decline despite backlash.

The following chapter takes a closer look at levels of policy effort required for sustaining destabilization while managing backlash.

Figure 4 Phases and policy sequence of fossil fuel decline. Source: Figure 2 in Paper 1.



4.1.2 RQ2: Level of policy effort for coal power decline

This section first describes policy effort embedded in coal phase-out commitments, and then focuses on the effort embedded in compensation policies as one type of "policy action" to achieve these commitments.

4.1.2.1 Coal phase-out commitments

By 2022, 43 countries across the globe had "policy commitments" to phase out coal power with a specific end-year, covering 17% of the global coal power plant fleet. The number of countries with phase-out pledges has increased over time – by 2018, 30 countries had committed 4.4% of global coal power to phase-out (122). By 2018, countries with relatively low shares of coal in their electricity generation and with relatively high "functioning of government" (FoG) tended to pledge coal phase-out. The latter indicator reflects government capacity in the sense of governments' independence from undue influence, their transparency, and absence of political corruption (199). In Paper 2, we find that by 2022, coal phase-out pledges diffused to countries with more challenging contexts, meaning overall higher shares of coal power in electricity generation and lower functioning of government.

Around 2022, concerns also arose regarding the implementation of existing coal phase-out commitments, as the energy crises following the Covid-19 pandemic and in the lead-up to the Russo-Ukrainian war led governments to increasingly prioritize energy security concerns – which entailed increasing targets for domestic build-out of renewables power, but also sparked concerns regarding the increasing use of coal power rather than natural gas (200,201,202). However, we find that the five European countries with the largest amount of coal power indeed recommitted to their original phase-out targets, while five countries with smaller amounts of coal power amended their original phase-out targets. Overall, European coal phase-out commitments remained intact, notwithstanding potential short-term increase in coal power generation.

In Paper 2, we further find that the rate of coal decline implied in the coal phase-out commitments of large European and OECD countries (calculated as a share of national electricity supply) are indeed comparable to coal phase-out rates projected in line with most climate change mitigation pathways for these regions, including those consistent with a 1.5°C-target. For the rest of Asia, and especially India and China – the two countries with the largest coal power plant fleets globally – projected coal phase-out rates in line with climate change mitigation targets are beyond what has been historically committed, or ever achieved, in large countries.

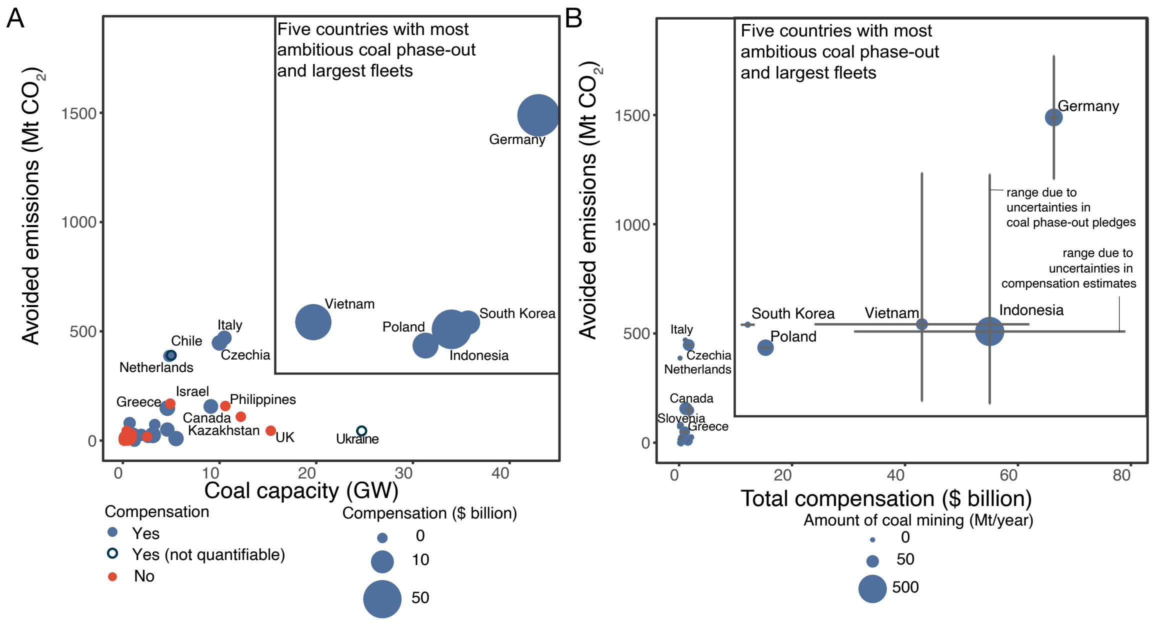
Paper 2 also assesses avoided emissions embedded in phase-out commitments – a measure which captures the age of the retired coal power plants. From a climate change mitigation perspective, phasing out younger coal power plant fleets is desirable, because it means lower emissions compared to the "business as usual" without the coal phase-out policy, in which power plants would have continued operation until they are closed down at their end-of-life. The central estimate for total avoided emissions under coal phase-out commitments by 2023 is 5.8Gt avoided CO_2. The central estimate for avoided emissions from coal phase-out for China and India under 1.5°C-consistent IPCC AR6 pathways amounts to roughly 15 times as much – 86 Gt avoided CO_2 emissions compared to the baseline scenario with no phase-out policy.

These findings indicate that while coal phase-out commitments have diffused over time to more challenging contexts and cover a larger share of the global coal power plant fleet, the level of effort embedded in these commitments is not yet in line with what is required under climate change mitigation pathways on a global level.

4.1.2.2 Compensation policies for coal phase-out

One type of “policy action” typically associated with ambitious coal phase-out commitments is financial compensation to negatively affected actors: more than half of all countries with coal phase-out commitments also have associated compensation schemes (Figure 5A). Financial compensation entails transfers of public funding from governments to, for example, coal companies for lost revenues; coal workers for support during unemployment or for retraining; coal regions for support with infrastructure improvements or to attract alternative businesses (see Figure 7 for a detailed analysis of the distribution across these different purposes).

Figure 5 Countries with coal phase-out commitments by avoided emissions, coal capacity, and compensation amounts. Source: Adapted from Figure 1 in Paper 3.

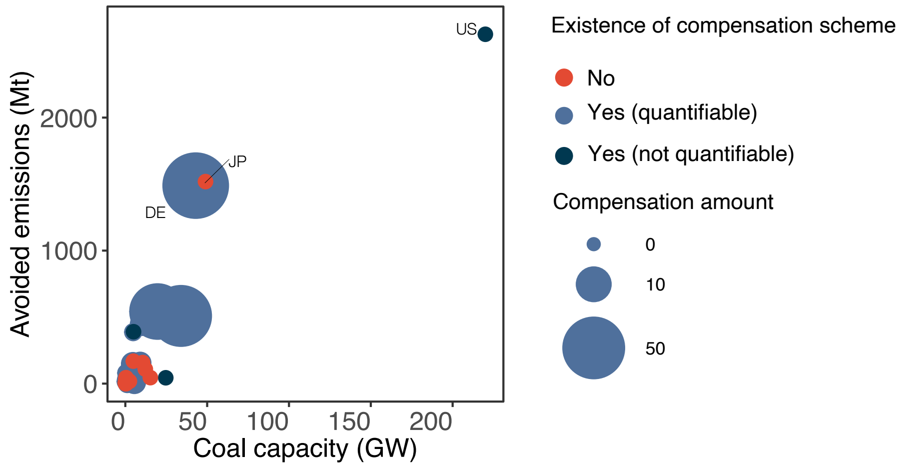


Countries with compensation policies typically have more challenging contexts for implementing coal phase-out (Table 2, Figure 5A): they tend to have domestic coal mining, which means that phasing out coal power generation also affects the coal mining industry and workforce. Additionally, they tend to have larger and younger coal power plant fleets. Phasing out younger coal power plants means larger losses for coal power plant owners and investors – also called “stranded assets” (91). It also means job losses earlier than anticipated for workers employed in these plants (170).

Box 1 Exploratory analysis of coal phase-out commitments in Japan and the US.

At the time of publishing Papers 2 and 3, several countries that would have been expected to have coal phase-out commitments based on their contextual characteristics (including the relatively low share of coal power in the electricity mix, and high institutional capacities) did not have such commitments. These include the US and Japan. However, in 2024, both countries participated in a G7-pledge to phase out coal power by 2035 (203).

Figure 6 Countries with coal phase-out commitments by avoided emissions and coal capacity, including US and Japan. Adapted from Figure 1 in Paper 3.



In the case of Japan, realizing this commitment would mean roughly 1.5 Gt avoided CO_2 emissions – comparable in scale to avoided emissions of the German coal phase-out. No compensation policy has been put in place to support the implementation of the commitment, and Japan has recently been criticized for failing to include the phase-out target into its seventh Strategic Energy Plan (SEP) (204), indicating that its realization is highly uncertain.

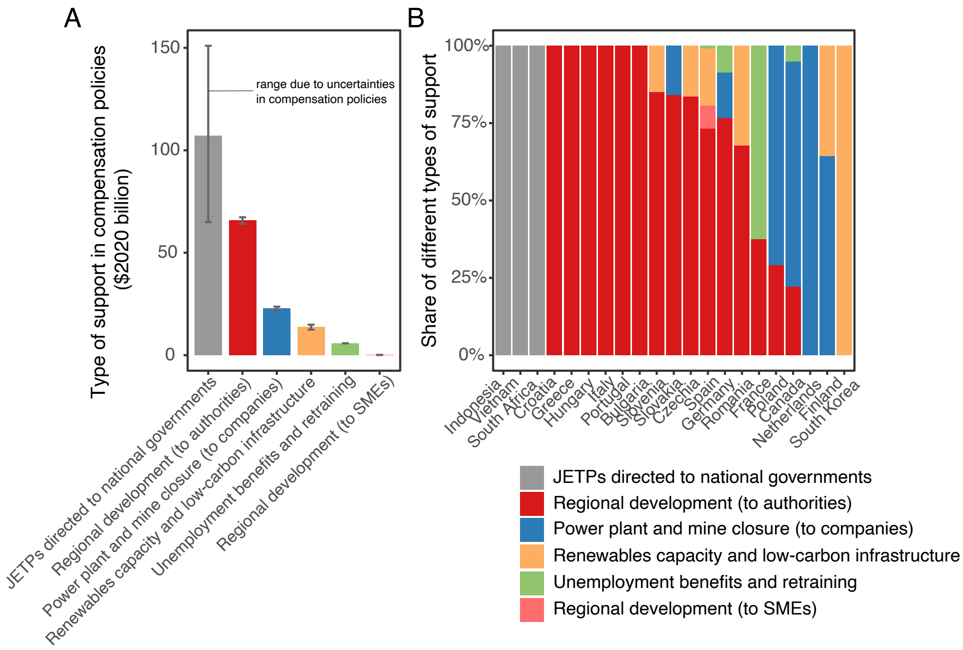
Following the US commitment, the Biden administration implemented national legislation de facto phasing out unabated coal power (205). Avoided emissions of realizing this phase-out commitment would be 2.6 Gt CO_2 – almost double avoided emissions estimates of the German phase-out commitment. Financial support for coal regions was also planned in the Inflation Reduction Act, with funding of $750 billion explicitly aimed at coal regions, and additional funds likely available to coal regions as well (206). However, in 2025, the Trump administration revoked the coal phase-out legislation (207) and attempted to freeze funding under the Inflation Reduction Act (at the time of writing, the latter measure had been blocked by a US court) (208).

To summarize, while both cases show signs of destabilization, socio-political barriers to coal power decline persist (83,163,196).

Having examined the contexts in which compensation policies are typically implemented, the natural follow-up question is, who are the recipients of compensation? Does compensation go to workers, power plant owners, or other recipients?

Detailed allocations by recipients were not available for all types of compensation flows at the time of writing. Specifically, the details of implementing Just Energy Transition Partnerships (JETPs), under which Indonesia and Vietnam receive support for coal phase-out from a consortium of Global North countries, were still under negotiation. Overall, the JEPTs make up the largest amount of all compensation (Figure 7). The second largest amount supports regional development in coal-intensive regions. A large share of this is attributable to Germany, which has famously promised 40 billion Euros for the development of its coal regions (209). Another relatively large share of compensation to coal regions comes from the EU's Just Transition Fund (EU JTF) (see Hermwille *et al* (210) for a detailed account of how JTF is allocated across beneficiaries). A lower overall amount of funding goes to companies for power plant and mine closure to support renewables capacity and low-carbon infrastructure, and to workers for unemployment benefits and retraining.

Figure 7 Type of support in compensation policies. Total amounts with uncertainty ranges (Panel A) and share of different types of support for the central estimate by country (Panel B). Source: Adapted from Figure 2 in Paper 3.



4.1.2.3 Relationship between coal phase-out commitments and amount of compensation

Regarding the relationship between levels of policy effort embedded in (1) policy commitments and (2) policy actions for coal power phase-out, one may expect a proportional relationship: Given that the socio-political barriers are likely higher in the case of commitments to phase out relatively large and young coal power plant fleets (indicated by relatively high avoided emissions), these may require stronger policy actions, such as higher financial compensation. Indeed, countries with avoided emissions above 500 Mt CO_2 and above 20GW installed coal capacity pay compensation above $10 billion, while countries with lower avoided emissions and smaller fleets pay up to $1 billion.

This hypothesized relationship is further confirmed by a multivariate regression analysis which tests the relationship between the amount of financial compensation and the amount of avoided emissions of the phase-out, while controlling for other relevant variables such as the amount of coal workers, or national GDP (see Paper 3 for all variables). Different combinations of these control variables are tested across a total of 820 models. Overall, avoided emissions is the most consistent and strongest predictor of compensation – present at a significance level of < 0.1% in the 50 best-performing models (ranked by Akaike

Information Criterion (AIC)). We thus find that the policy effort embedded in policy commitments, and policy actions, for coal phase-out are roughly proportional.

Given that avoided emissions likely indicate higher barriers to phase-out (due to foregone investments and job losses), the estimate of compensation per unit of avoided emissions may serve as a proxy for policy effort required to overcome socio-political barriers for ambitious, policy-driven coal phase-out – which our empirical observations suggest lies at $27-45 per ton of avoided CO_2 emissions. For most cases, this "cost" of compensation per ton avoided emissions ($/t$CO_2$) is well within the range of the carbon price under the European Union Emission Trading Scheme (EU ETS) over the last five years. For few countries, compensation is below the carbon price. These tend to have no active coal mining (e.g. Italy, France and the Netherlands) or a particularly small coal fleet (e.g. Slovenia). Hungary is a clear outlier with compensation far above the range of carbon prices – while its total compensation is comparable to Finland and Portugal, its coal phase-out affects one coal plant which has already been in operation for more than 50 years and a small coal mining industry, and thus the avoided emissions are very low.

The finding that coal phase-out compensation tends to correlate with avoided emissions of phase-out indicates that policy effort required to phase out especially young and large power plant fleets is typically relatively high, providing a quantitative indication of the socio-political barriers to phase-out based on empirical observations. However, not all policy effort needs to be borne by national governments. Indeed, roughly half of all flows under current compensation schemes originates from international sources (56% central estimate; uncertainty range 43%-64%), meaning that donor countries or the EU pledge to support recipient countries in coal phase-out. The other half of compensation is domestically-funded (44%; uncertainty range 35-58%). "Access to international funding" is one of the control variables positively correlated with amounts of compensation, and four out of the five countries with the most ambitious phase-out receive international funding in support of their coal phase-out: Poland and Germany receive support from the EU's Just Transition Fund, and Vietnam and Indonesia via their respective JETPs.

4.1.3 RQ3: Abstracting from empirical observations: Insights for level of policy effort to overcome socio-political barriers to coal power phase-out

The world's major coal consumers are China and India, with the two largest coal power plant fleets globally, and no commitments for coal phase-out at the time of writing. Coal phase-out pathways in line with what is required for 1.5°C- and 2°C-temperature outcomes project faster decline of coal in these countries than ever achieved historically and pledged by any other country (55), whereas we find that for EU and OECD countries, coal phase-out rates projected in climate change mitigation pathways are largely in line with historical decline rates. This indicates that the policy effort implied in these pathways is higher for China and India, than for EU and OECD countries. Additionally, China and India tend to have younger coal power plants than other countries, and both have domestic mining industries (Table 2). Our findings from section 4.1.2.3 indicate that these factors make it more likely for countries to have compensation schemes associated with coal phase-out.

Table 2 Comparison of countries with coal phase-out commitments with and without compensation schemes, and China and India. Adapted from Table 3 in Nacke (211).

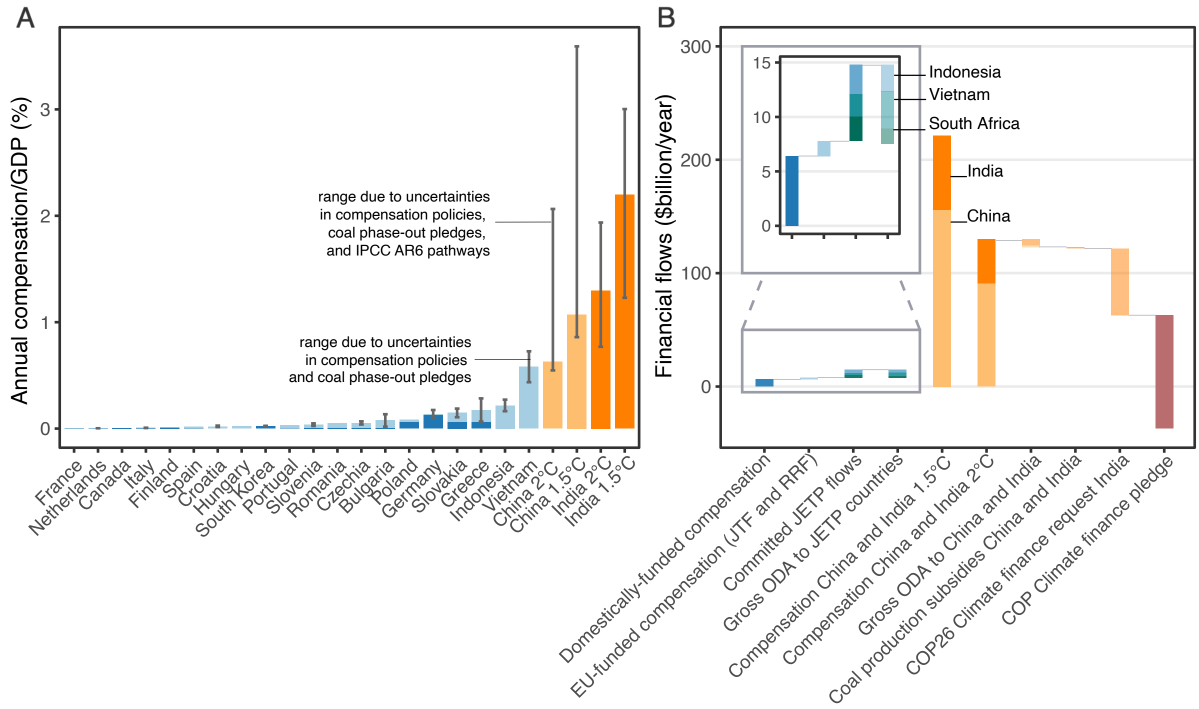
	Nr of countries (no coal mining)	GW of operating coal plants	Avoided emissions (Gt CO_2)	Pledged compensation ($billion)
Countries with coal phase-out commitments. Avoided emissions based on commitments.				
Phase-out pledges & compensation schemes	23 (3)	258	5.8 (4.7-7.7)	186 (118-253)
Phase-out pledges, no compensation schemes	20 (11)	51	0.7	-
Two countries with the largest coal fleets globally. No coal phase-out commitments. Avoided emissions based on 1.5°C-consistent climate change mitigation pathways.				
China	domestic mining	1150	60 (42-69)	-
India	domestic mining	240	26 (21-30)	-

To approximate the policy effort to overcome socio-political barriers to projected coal phase-out pathways in China and India, the best-performing regression models (section 4.1.2.3) are used to estimate what amount of compensation would be aligned with coal phase-out in China and India in line with these pathways, if they would pledge compensation at similar rates to current coal phase-out countries.

We find that compensation in China and India would be 17 times higher than all compensation empirically observed, and outstrip pledged international climate finance. Total compensation would be highest in China, given especially the size and young age of its coal power plant fleet. Compared to national GDP, however, India bears an especially large burden with compensation for coal phase-out in line with 1.5°C-consistent pathways making up 2.3% of its GDP (central estimate) (Figure 8). These results do not prescribe a precise policy approach, as policy implementation is always context-dependent. Rather, they visualize the strength of socio-political barriers to coal phase-out in monetary terms, and provide an approach to bridge empirically observed policy observations with quantitative climate change mitigation models.

An overarching insight from empirically observed coal phase-out compensation schemes is that policy effort embedded in commitments (i.e., the ambitiousness of coal phase-out commitments) tend to require stronger policy effort in terms of policy actions. While this may sound intuitive at first, this thesis is able to show that policy effort does not necessarily only increase with the speed of phase-out, but with the level of socio-political barriers to this phase-out which tend to be higher for phasing out younger coal power plants.

Figure 8 Empirically observed and extrapolated compensation to China and India. Empirical compensation is blue shaded and extrapolated to China and India is orange shaded. Annual flows as share of GDP (Panel A) an total annual flows (Panel B). Source: Figure 4 in Paper 3.



4.1.3 Summary: Phases, policy effort, and barriers to coal power decline

We have identified three phases of national-level coal power decline, across which the major barriers and corresponding policy priorities vary. In the second phase, once decline has begun, there is a risk of backlash and resistance, requiring policies to manage backlash while sustaining decline.

One approach to achieve this are compensatory policies to mitigate negative effects of coal power phase-out. We assess the level of policy effort embedded in such compensation schemes by measuring the amount of compensation and find it to be generally proportional to avoided emissions of coal phase-out commitments. These national-level findings can help better understand the feasibility and fairness implications of coal power phase-out in line with global climate change mitigation targets.

4.2 Policy effort for wind power expansion

4.2.1 RQ1: Policy sequence mapped to phases of wind power growth

To replace fossil-fueled power generation, technologies for low-carbon power generation need to expand. This section focuses on the empirical case of onshore wind power in Germany, analyzing how policy priorities have evolved throughout the phases of onshore wind growth.

Paper 4 delineates three macro-phases of onshore wind growth in Germany: first, we identify take-off in 1998, delineating the shift from the *formative phase* (technologies face relatively high costs, and deployment is irregular) to the *acceleration phase* (where increasing adoption and declining technology cost mutually reinforce each other). Following the acceleration phase (1999-2004), onshore wind enters a phase of overall stable growth (2004-present). The stable growth phase aggregates from short-term pulses, where growth decelerates and then re-accelerates: After 2004, capacity additions declined and then re-accelerated (“*Slow-down and first pulse*”), followed by another crash in 2017 and recent signs of a re-acceleration which political targets aim to continue (“*Crash and targeted pulse*”) (see Figure 9). The fourth phase, prolonged stagnation without re-acceleration, has not yet been observed in Germany. The remainder of this section examines how policy priorities have evolved along the macro-phases, and micro-pulses, of German onshore wind growth.

German government interest in supporting the diffusion of renewables technologies emerged in the 1970s and 1980s in the context of the oil crisis and increased electricity prices (115). Research and Development (R&D) funding became increasingly available for renewables overall and onshore wind power specifically, benefitting the development of the technology itself, and the formation of a domestic onshore wind industry (212,213). Over time, onshore wind industries grew both in Germany and adjacent European countries, like Denmark (115). Simultaneously, public resistance to nuclear power as another promising and low-carbon source of electricity increased, making onshore wind power politically preferable (115,116). Few parliamentarians began pushing for a feed-in tariff to support the uptake of the technology (116,124). The feed-in tariff became introduced in 1991, primarily targeted at small-scale hydropower. Yet, it surprisingly led to the take-off and acceleration of onshore wind power deployment, marking the end of its *formative phase*.

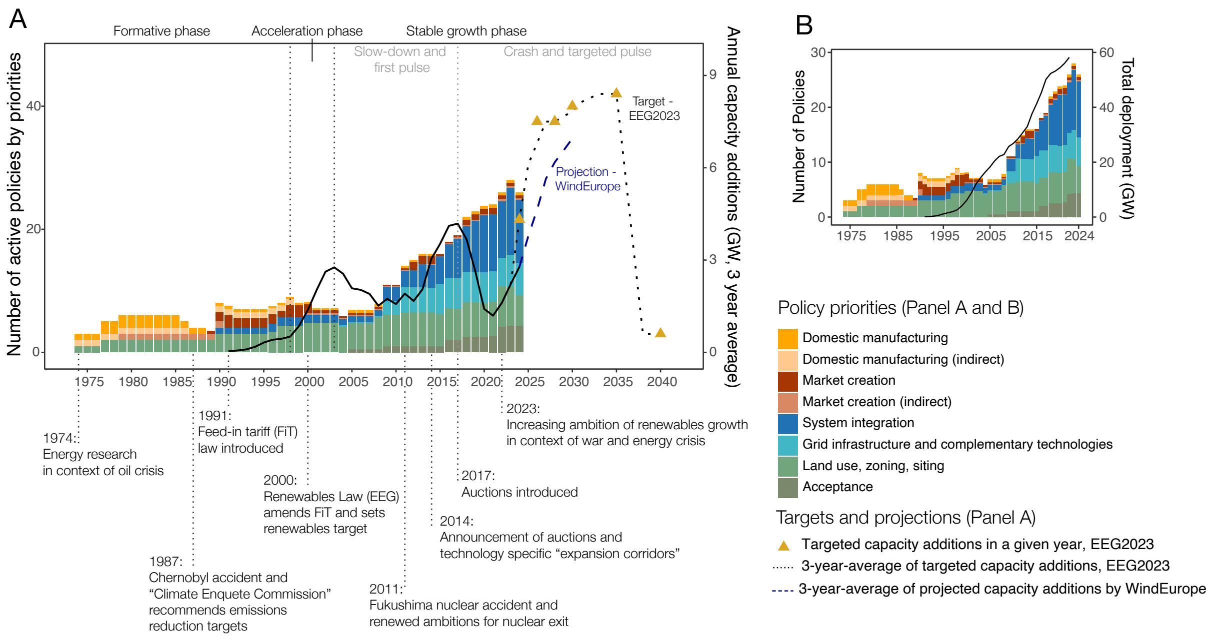
We find an *acceleration* of German onshore wind expansion from 1999-2004. In this phase, policies were mainly focused on “market creation”: the FiT law from 1991 was replaced with the Renewables Law (German: Erneuerbare-Energien-Gesetz, abbreviation: EEG). The EEG maintained but re-designed the FiT: the new law set legally binding remuneration levels per kWh of generated electricity, and introduced a “correction factor” based on wind potential at different sites, to encourage a more geographically distributed deployment.

Around 2004, acceleration of growth stopped and onshore wind entered the *stable growth phase*: growth initially began slowing down, stabilized around 2008, followed by a pulse of re-accelerating growth. Around the time of stabilization, additional policies were introduced, especially focused on the integration of onshore wind into the electricity grid; as well as into existing electricity markets (Figure 9) – indicating the emergence of non-cost related barriers to deployment. Another challenge for onshore wind was rising cost of policy support (103,116) (see also Section 4.2.2.2). Costs were born by both household and industry consumers via the renewables levy, leading the government to widen exceptions for energy-intensive industries (in turn increasing the burden on household consumers) (103,116). Following this amendment, the European Commission threatened a legal case against the FiT-system under EU competition law (103). This sped up the arguably already ongoing transition to turn the FiT-system into an auction scheme, under which developers compete against each other in bidding processes where only the lowest bids for feed-in remuneration are awarded state support.

For onshore wind, the introduction of this auction scheme was announced in 2014 – three years before it came into place. This may have led to a “rush” of installations as developers aimed to ensure support under the previously administratively set FiT-levels. This rush exacerbated problems of grid instability and curtailment and led to further restrictive policies to slow down deployment, introduced in 2017, at the same time as the auction system came into place. The policy change in 2017 coincided with a crash in onshore wind deployment (Figure 9).

Onshore wind growth fell far below the "corridors" for capacity additions envisioned in the EEG. The auction system was maintained, but revised to address undersubscription (214). Since 2021, there has been a renewed uptick in onshore wind capacity additions – whether the resulting pulse will be in line with recent ambitious targets for onshore wind deployment, made in the context of the Russo-Ukrainian war and climate change mitigation concerns, remains to be seen. New policies as well as revisions to existing policies were introduced to support re-acceleration; for example to improve social acceptance of increased renewables deployment; increase support levels for onshore wind under the auction scheme; speed up permitting of onshore wind plants and ensure availability of land for onshore wind deployment.

Figure 9 Phases and policy mix for onshore wind power growth in Germany. Mapped to annual capacity additions, targets and projections (Panel A) and cumulative deployment (Panel B). Source: Figure 2 in Paper 4.



4.2.2 RQ2: Level of policy effort for onshore wind power growth

4.2.2.1 Level of policy effort embedded in commitments: Targets for onshore wind

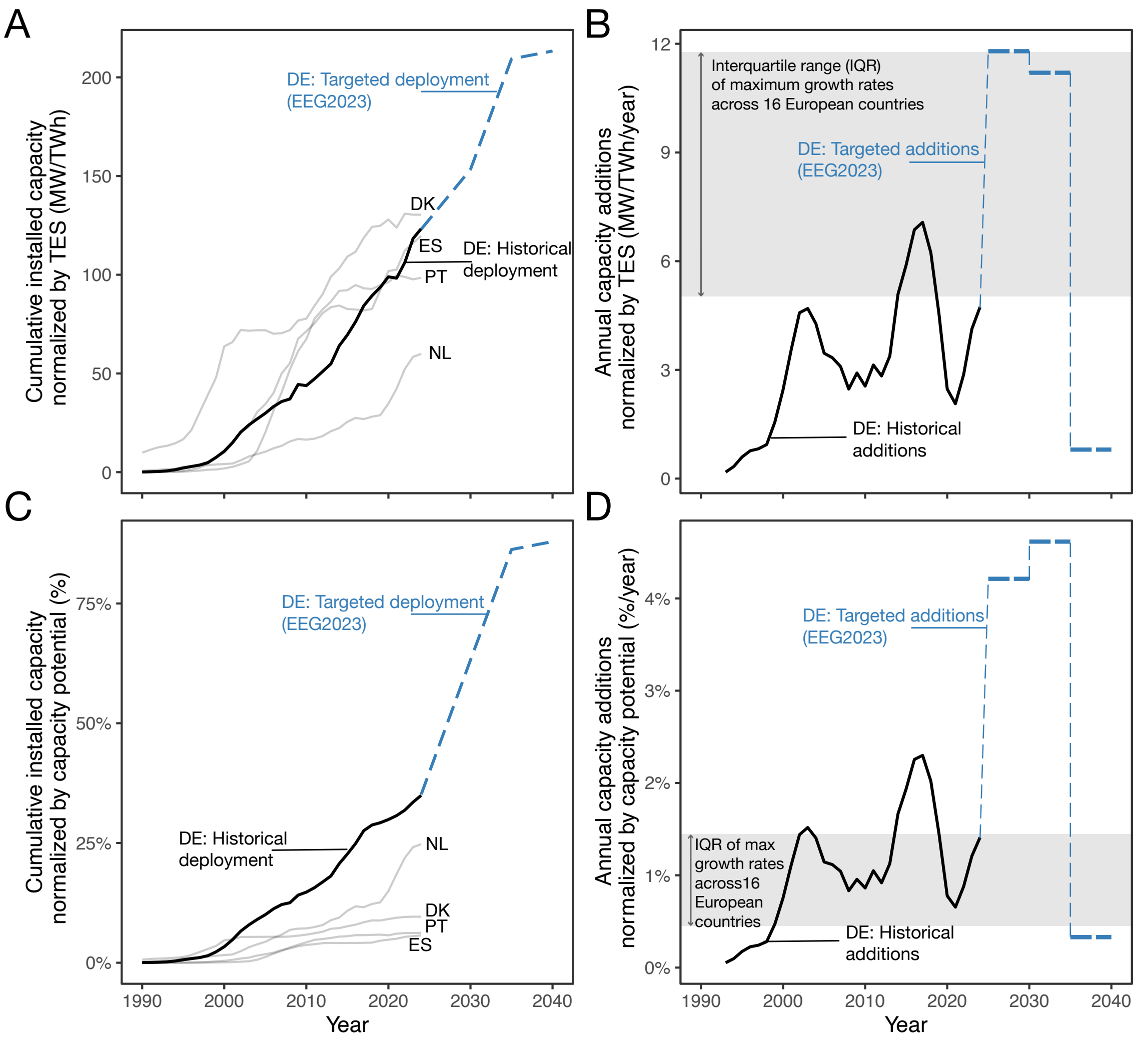
Paper 4 captures the evolution of binding onshore wind targets within the EEG. In early iterations of the EEG, targets were set for renewables deployment overall, rather than differentiated by technologies. For example, the first iteration of the EEG from 2000 contained the target to "double renewables share in total energy by 2010". The following iterations shifted to targeting a certain renewables share in electricity (rather than energy). The time horizon for these targets gradually expanded, first to 2020 (EEG2004 and EEG2009), and later to 2050 (EEG2012).

A technology-specific target for onshore wind power was for the first time introduced in EEG2014, targeting annual capacity additions of 2.5 GW per year in addition to repowering. This targeted ambition slightly declined in the following EEG-iterations, with EEG2017 amending corridors to 2.8-2.9 GW per year, but including repowering. EEG2021 set targets in terms of total capacity to be achieved over time – net of repowering – in line with 1GW-2.5GW annual capacity additions. Only EEG2023 targeted a significant increase in onshore wind capacity expansion of up to 8.4 GW capacity additions per year, toward a total of 115 GW by 2030, and 140 GW by 2040 (compared to a target of 71 GW by 2030 under EEG2021).

Overall, targets for renewables deployment became more technology-specific and expansive over time – however, the ambition embedded in onshore wind power targets in terms of the speed of expansion has remained roughly stable up until the energy crisis in 2022.

Figure 10 compares the most recent German onshore wind targets to other European onshore wind frontrunners, as a share of onshore wind power in the total electricity supply, and in terms of the share of onshore wind potential. In terms of onshore wind as a share of total electricity supply (Panels A and B), Germany's historical deployment and targets are relatively in line with other European frontrunners. In terms of onshore wind as a share of its total national potential, Germany's targets aim at expanding onshore wind above 75% of the country's wind potential, meaning that deployment needs to expand beyond easily accessible and highly optimal sites – likely requiring support in terms of policy actions to enable such expansive exploration. Germany's targets are beyond what other European frontrunners have achieved in the past.

Figure 10 Historical and targeted onshore wind deployment in Germany compared to other European frontrunners. Deployment normalized to the size of the electricity system (Panels A and B), and to total onshore wind potential (Panels C and D). Source: Figure 1 in Paper 4.



4.2.2.2 Policy effort embedded in policy actions: Policy density and financial support for onshore wind

To measure the level of policy effort embedded in policy actions for onshore wind growth, Paper 4 assesses: (1) the evolution of annual policy density, i.e., the number of active policies in a given year, and (2) the level of financial support.

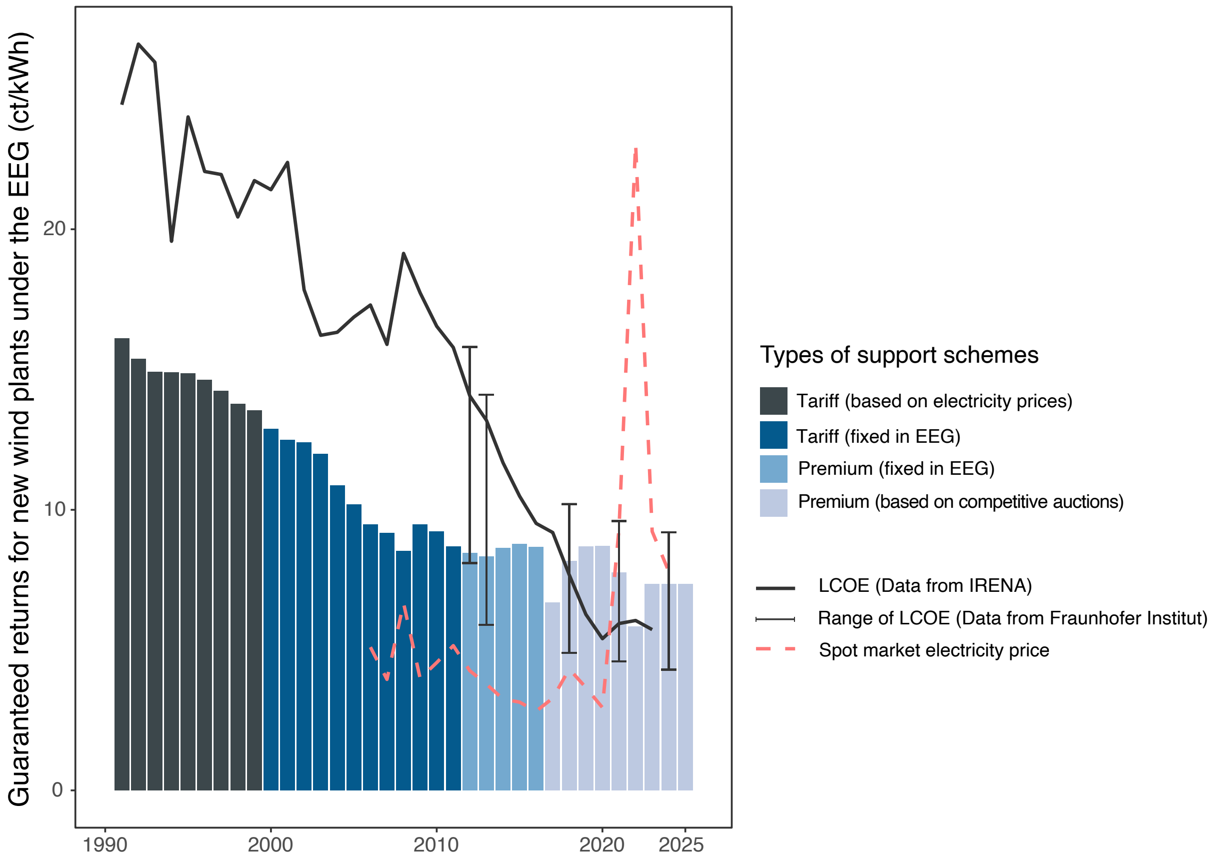
To measure policy density, policy data from Section 4.2.1 is aggregated across policy priorities to capture the total amount of onshore wind-relevant policies active in a given year. Policy density increases over time, and especially following the first slow-down of onshore wind growth (Figure 9). The findings in Section 4.2.1 on policy priorities can help explain this phenomenon – as technology growth progresses, additional barriers arise including integration of technologies into existing systems and infrastructures, public opposition, etc. The overall increase of policy density may stem from the fact that some challenges remain relevant throughout the entire technology lifecycle, rather than becoming completely resolved. For example, the issue of land use and zoning regulations remains relevant throughout the different phases of growth, because early on, completely new rules need to be established to enable placement of a new technology . Over time, as the size of the technology and the amount of installations increase, rules may need to be revised or amended to ensure permanent and sufficient land availability. Somewhat surprisingly, and even despite declining technology cost, profitability seems to remain a relevant challenge throughout the different stages of growth, given that support for market access in terms of FiTs (or premiums) remained active over 40 years. An alternative explanation may be policy path dependency, making it harder to withdraw support as beneficiaries may protest.

The remainder of this section contains a detailed analysis of financial support for onshore wind deployment. In our analysis of feed-in remuneration, we consider two major perspectives: the perspective of *onshore wind power operators*, and the perspective of the *state*. Our main findings are that guaranteed levels of remuneration to *onshore wind power operators* have remained relatively stable since around 2009, and increased relative to levelized cost of electricity generation (LCOE) since the introduction of the auction system. Totally annually paid support by the *state* has steadily grown, and only begun declining with increasing electricity prices in recent years; meaning that market prices cover guaranteed remuneration to operating onshore wind plants.

For *onshore wind power operators*, what mainly matters is the remuneration level guaranteed to them by law – this is the revenue they can expect for the first twenty years of operation. What may, additionally, matter is the type of remuneration scheme – under the original FiT (active from 1991-2012), operators received remuneration directly from the state without interacting on the market. Under the feed-in premium (FiP), operators need to sell their electricity on the market and receive the difference between the market price and the guaranteed remuneration level from the state. Under the auction scheme, the premium system is maintained – however, not all operators are automatically guaranteed state support. They need to acquire relevant permits to realise an onshore wind project, and can then participate in auctions – however, if they are not awarded the bid, they will have to sell electricity on the market, without state support. This introduces an additional level of risk for operators compared to the previous schemes (215).

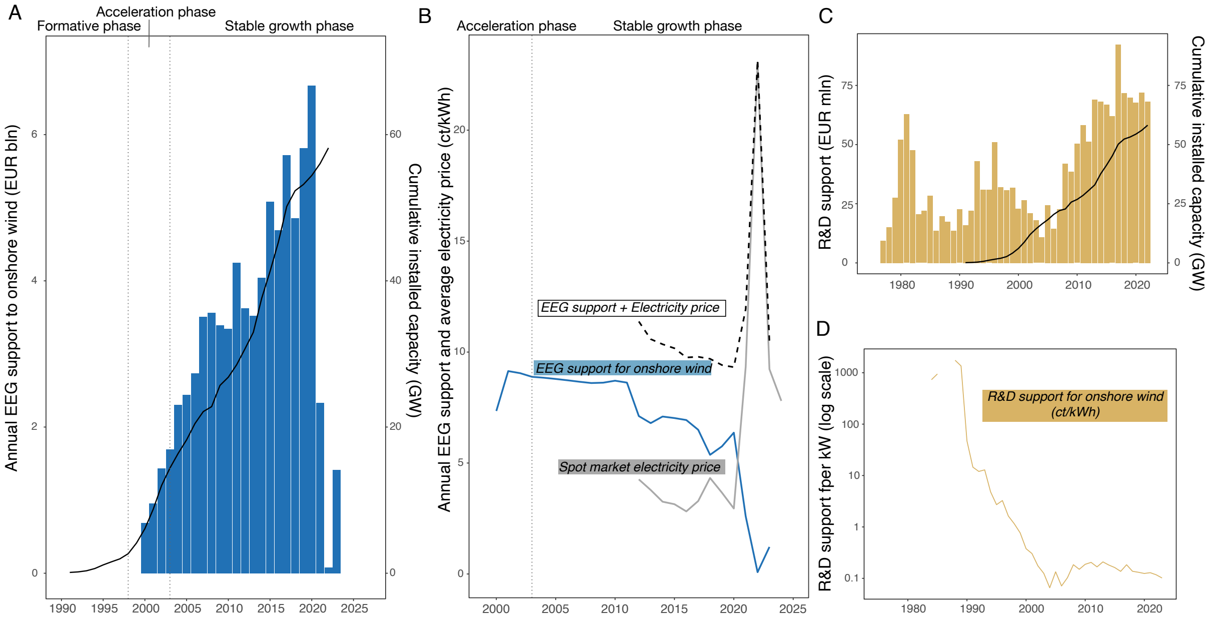
Figure 11 shows the evolution of guaranteed remuneration, as well as the type of remuneration scheme, over time, and compares them to LCOE estimates and spot market electricity prices. A first observation is that guaranteed levels of feed-in remuneration declined more strongly between 1991 and 2007, and only very slightly since 2007 – this coincides with the first stabilization of onshore wind growth after the slow-down between 2004 and 2008. A second observation is that guaranteed remuneration levels tended to be below LCOE, which is surprising given that this would mean that costs of production are higher than prices of wind power. However, it is possible that average LCOE estimates from IRENA are slightly higher than in reality, a hypothesis which is supported by the fact that the lower ends of ranges of LCOE estimates from Fraunhofer Institute (available only for individual years) coincide with promised levels of remuneration. The relationship between LCOE and remuneration levels has changed since the introduction of the auction system, with average auction results above LCOE estimates. One explanation may be the increased risk to investors under the auction scheme (explained in the previous paragraph). The last component to Figure 11 is the spot market electricity price, which is a proxy for the revenue wind power operators can expect from the market. The electricity price has historically been below legally guaranteed remuneration indicating that the government provided policy support in addition to market revenues. However, in the context of the recent electricity crisis sport market prices have spiked, indicating a market environment where onshore wind may be profitable without government support. How long this environment lasts remains to be seen. Additionally, the burden of paying these electricity prices falls on the consumers and may then require government support to electricity consumers.

Figure 11 Levels of remuneration guaranteed to onshore wind plants that begin operation in a given year, compared to LCOE and electricity prices. Colours indicate the type of support scheme. Source: Figure 3 in Paper 4.



Next, Paper 4 examines feed-in remuneration from the perspective of the *state.* What mainly matters from this perspective is the amount to be paid to active onshore wind operators in each given year. Figure 12 (panel A) shows that, until 2021, *total* feed-in support for onshore wind power increased with each year, likely due to increasing onshore wind electricity generation. Panel B shows that support *relative* to onshore wind electricity generation has remained surprisingly stable since the EEG first came into force in 2000. It began declining around 2012, with the switch to the feed-in premium. In 2022 and 2023, both total and relative feed-in dropped due to a surge in electricity prices, meaning that developers received returns from market prices in line with (and above) the feed-in premium. Whether this indicates a long-term decline in required policy effort for onshore wind power will depend on further developments of electricity prices, as well as the evolution of non-price related barriers.

Figure 12 Annually paid financial support to onshore wind power in Germany. Source: Figure 4 in Paper 4.



Additionally to feed-in remuneration, the German government also provides R&D support for onshore wind power. Surprisingly, the *total* amount of R&D support has stayed relatively constant over time, and potentially even seen a slight increase. This is surprising because, as technology deployment progresses, fewer challenges in technology performance may be expected that require R&D effort to address (see Box 2 for an exploratory analysis of R&D funding priorities over time). Relative to deployment, R&D funding has declined by roughly three orders of magnitude (Figure 12, Panel D).

Box 2 R&D funding analysis- data triangulation and classification by scope and priorities

The finding that total R&D funding for onshore wind power remained stable over the past 50 years was quite surprising. This is why I conducted exploratory analysis of project-level R&D funding, classifying individual projects by the same policy priorities as in Section 4.2.1 – to better understand what barriers to onshore wind growth R&D funding is earmarked to over time.

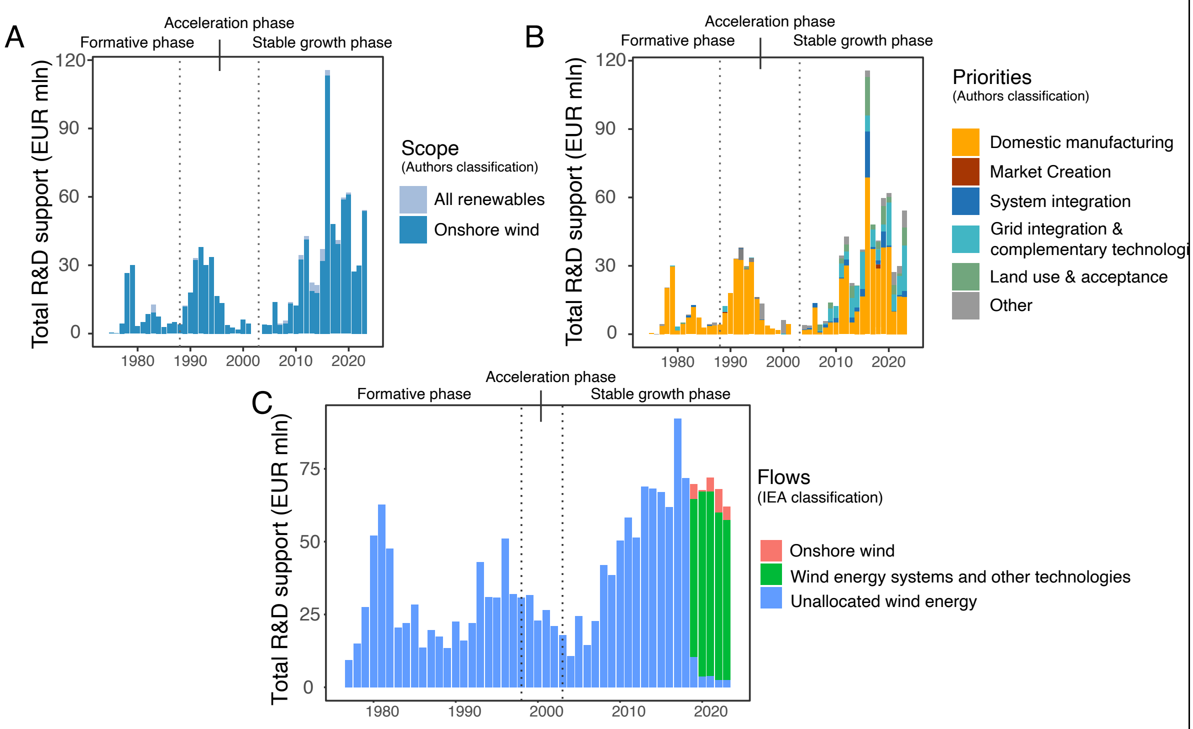
Up-to-date, project-level R&D data can be retrieved from the EnArgus-database (186). It includes information regarding the amount of funding, as well as the titles of individual research projects, and in some cases more detailed descriptions of the project aim. The database contains almost 3000 individual projects that contain references to "Windenergie" (German for: wind power). The analysis conducted here is based on a web-scraping algorithm extracting all projects containing the term "Windenergie" from the website, followed by a manual selection of only those projects de facto relevant to onshore wind power.

To triangulate this data, R&D funding data retrieved from EnArgus (Figure 13, panels A and B) is compared to R&D funding data from the more commonly used IEA database (185) (which is also used in Paper 4). For IEA data, all funding where the "Flow" column explicitly refers to offshore wind power is excluded (this classification only starts from 2018). Both databases show largely similar results between EnArgus and IEA data.

I classify funding data from EnArgus in two ways: First, by scope – where "onshore wind power" denotes all funding that could be allocated explicitly to onshore wind power. "All renewables" denotes funding that is generally allocated to renewables power generation, meaning it may potentially be relevant for onshore wind power. Second, by priorities, using the same categories that were also used to classify policies in the onshore wind policy mix. The categories for acceptance and land use related projects were so small that they were subsumed under one category to keep them visible.

A large share of annual funding is allocated to domestic industries, which is intuitive given that a lot of R&D activities are conducted by – and benefit – domestic industries that engineer onshore wind power plants. Roughly since the 2010s, other priorities have become increasingly important, with increasing amounts of funding focused on grid integration and complementary technologies such as storage. Some projects were also focused on facilitating system integration, for example focusing on electricity market dynamics. Land use and acceptance-related projects investigate for example questions of how onshore wind impacts local biodiversity and protected species. In 2018, few projects were also focused on market creation – this was to learn more about the implementation of auctions for onshore wind power, since onshore wind capacity additions plummeted after the initial auction set-up. Overall, these findings somewhat mirror the evolution of priorities observed in Section 4.2.1, with especially system and market integration barriers becoming more relevant after the initial slow-down of onshore wind power in the early 2000s.

Figure 13 German Research and Development funding for onshore wind power. Data from EnArgus database (Panels A and B), classified by scope (Panel A) and type of funding priority (Panel B). Data from IEA (Panel C), IEA classification by type of flow.



4.2.3 RQ3: Abstracting from empirical observations: Insights for policy effort to achieve policy commitments for offshore wind

As a single case study, Paper 4 illustrates the evolution of policy effort for a mature technology throughout phases of growth in an individual country. However, climate change mitigation also requires policy effort for emerging technologies at earlier stages of deployment – such as offshore wind power. At the time of writing, only six European countries have more than 1GW offshore wind power installed: France (1.5GW), Belgium (2.3GW), Denmark (2.5GW), Netherlands (4.5GW), Germany (8.3GW), and the UK (14.8GW). In 17 other European countries, there are commitments to develop offshore wind power at varying stages of implementation. In some countries, small-scale offshore wind projects are already installed (e.g. Portugal, Finland) or under construction (e.g. Poland), while in other countries policy actions for offshore wind projects are still under development (e.g. Sweden). What speed of deployment may be expected under current policy effort, and what type of effort may be required to achieve targeted deployment for offshore wind power?

To contribute to answering this question, Paper 5 utilizes empirical observations of governance regimes across 23 European countries as the basis for probabilistic projections for offshore wind power deployment. We thus explore the interaction between three elements to policy effort: We estimate likely deployment (the 'outcome') under current governance regimes (i.e. policy actions), and compare these with national and EU-level policy commitments. We then test several scenarios where policy actions are adjusted, finding that a rapid diffusion of the best policy practices may enable an achievement of targeted deployment by 2050.

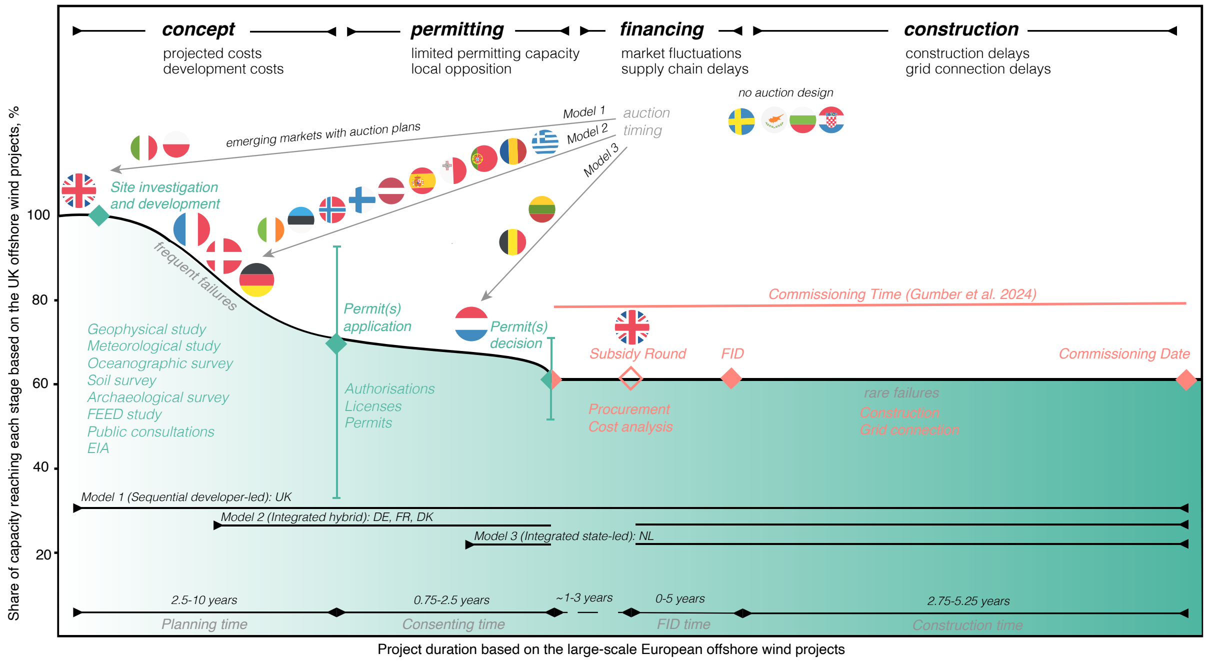
4.2.3.2 Policy actions for offshore wind deployment classified by regime types

In the six countries with more advanced offshore wind deployment, governance regimes changed over time and with the growth of offshore wind deployment. Since 2005, an increasing amount of countries has introduced auctions for offshore wind deployment (177). Before, developers could submit applications for preferred sites to the relevant public authorities in a given country (a so-called "open-door" planning system) (216). Open-door systems can be problematic because there are limited areas for offshore wind deployment, meaning that several developers may be preparing plans and conduct assessments to deploy offshore wind at the same site, and face sunk investments as only one developer will receive the permits to in fact install and operate a power plant (216). Additionally, competing land uses such as fishery or military uses may prevent offshore wind deployment unbeknownst to the developer. By the mid-2010s, countries with more mature offshore wind deployment had all shifted to a streamlined centralized approach, where the government pre-selects offshore sites, and then holds auctions in which developers compete for the further development of these sights (177,217).

Paper 5 classifies the types of policy actions implemented by countries with advanced offshore wind deployment into three regime types (Figure 14): The first- "sequential developer-led" – governance regime describes current practices in the UK, where project development starts once seabed rights are allocated to a developer under a site leasing process, and a subsidy is allocated on a competitive basis only after necessary permits are granted. The second- "integrated hybrid" – regime type is based on governance regimes in France, Denmark and Germany, where auctions for leasing of land and financial support (or concessions) are combined. The third – "integrated state-led" – regime type is based on current practices in the Netherlands, where the state conducts extensive pre-investigation and permitting of sites, such that the developer can take a final investment decision (FID) and begin project construction immediately after winning the integrated auction for seabed leasing and financial support. Belgium has more recently implemented an integrated state-led model as well.

By 2025, there were established or planned auction schemes in 17 other European countries with potential for offshore wind power deployment. These newer schemes tend to assimilate the more established governance regimes in frontrunner countries, and can thus be classified by the three regime types outlined above. In four countries with potential for offshore wind deployment (Sweden, Cyprus, Bulgaria, Croatia), no such policy actions (i.e. centralized governance and auction schemes) are in place at the time of writing. However, in all of these countries, there have been at least discussions of introducing a centralized governance regime for offshore wind (218,219,220).

Figure 14 Illustration of project development stages under three governance regimes across 23 European countries. Source: Figure 1 in Paper 5.



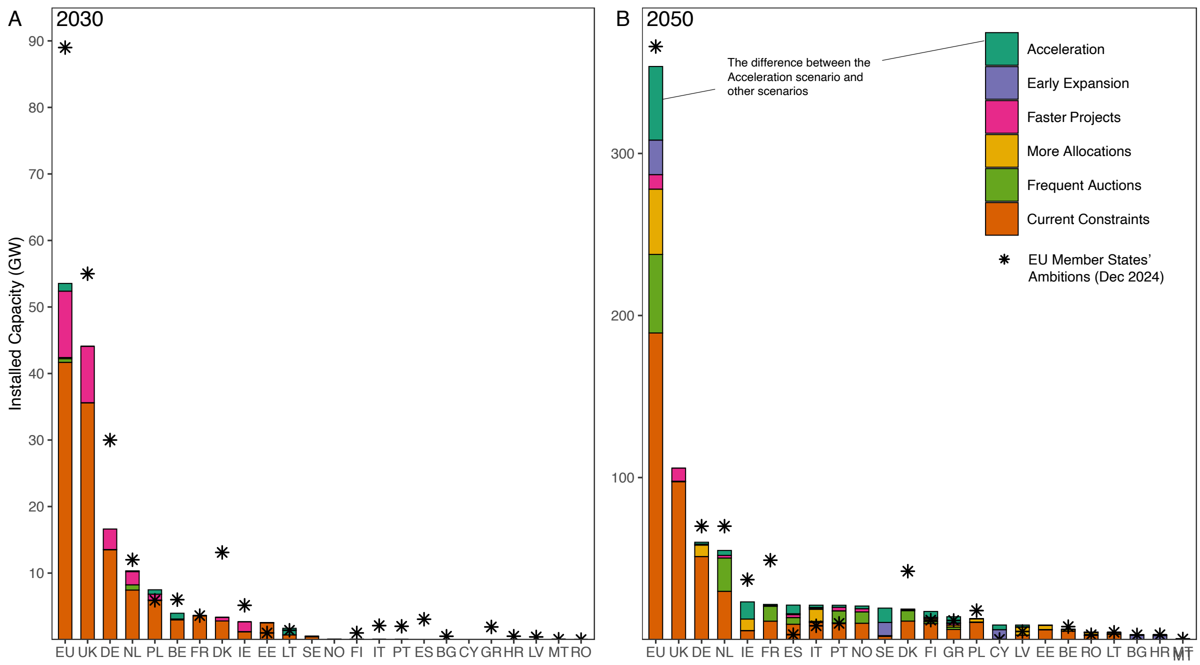
4.2.3.3 Probabilistic projections for offshore wind deployment under current and best-practice policy actions compared to policy commitments

To estimate the probabilities for the scale and speed of offshore wind deployment across the 23 European countries, we combine the classification of countries by governance regimes with project-level data on current trends in offshore wind deployment (221). The highest levels of deployment under current policy practices in an individual country is forecasted for the UK – with a median estimate of 97 GW capacity by 2050, followed by Germany – median estimate of 51 GW by 2050, and the Netherlands – median estimate of 30 GW by 2050. These estimates suggest that the UK is likely to reach and surpass its current offshore wind ambition (set to 43-50 GW by 2030), but that deployment under current policy practices in Germany and the Netherlands likely falls short of their 2050 offshore wind targets (70 GW each). On EU level, a median deployment of 42 GW (IQR 40-44) by 2030 and 189 GW (IQR 180-199) is projected by 2050, resulting in an implementation gap of 46 GW (by 2030) and 177 GW (by 2050) compared to EU commitments.

This indicates that additional policy actions are likely required. In five policy-specific scenarios, Paper 5 tests different amendments to current policy actions and estimates the extent to which they add up to the required levels of policy outcomes. The first, "More Allocations", scenario tests the effect of expanding the amount of seabed allocation for projects. The second "Early Expansion" scenario foresees a speeding up of policy implementation with countries introducing auctions earlier than planned. The third, "Frequent Auctions", scenario tests the effect of increasing auction frequency and size. The fourth, "Faster Projects" scenario tests the effect of speeding up project development from auctions to operation. Finally, the "Acceleration" scenario combines all of these four amendments.

By 2030, there is little effect of these policy-specific scenarios, given that almost all deployment by then depends on the realization of offshore wind projects that are currently already in development – meaning that only limited deployment effects can be achieved by speeding up development of existing projects (Figure 15A). By 2050, projected deployment only under the final "Acceleration" scenario reaches 354 GW (median estimate, IQR 343-370), largely in line with the EU commitment of 366 GW (Figure 15B). The cumulative impact of implementing all policy measures is greater than the sum of implementing individual policy measures at a time, due to the mutually reinforcing effect of several policies – for example, expanding area allocations and simultaneously auctioning these areas more frequently.

Figure 15 Probabilistic projections for offshore wind deployment across European countries compared to commitments. Bars show projections for offshore wind deployment by 2030 (Panel A) and 2050 (Panel B), compared to offshore wind targets from EU member states. Source: Figure 4 in Paper 5.



4.2.4 Summary: Phases, policy effort, and barriers to wind expansion

Overall, our findings suggest that sustained policy effort is likely required despite technology cost decline to prevent deceleration of growth as new socio-political barriers emerge over time. In the case of onshore wind power, the policy sequence began with R&D and demonstration support as well as few zoning regulations in early phases of deployment. Over time, and especially to re-accelerate growth after stagnation, additional policy instruments related to system integration and grid expansion as well as social acceptance become increasingly important, with tendentially increasing policy effort in terms of both policy density and strength of financial support. Recent changes may indicate a more favorable market environment to onshore wind in Germany.

Our probabilistic projections for offshore wind are based on current practices across EU countries, as well as four specific policy adjustments. However, our findings from onshore wind power indicate that with increasing deployment, new barriers may emerge that may well require further policy effort.

5 Discussion and conclusions

5.1 Main contributions

In this thesis, I present approaches to measure policy effort for energy transitions, and map it to two ongoing transitions processes: coal power phase-out and wind power expansion. The findings indicate that policy effort does not necessarily decline as low-carbon technologies become more economically competitive, but rather that socio-political barriers shift throughout phases of coal decline and onshore wind growth, requiring sustained policy effort and adaptive policy sequences. While it is already well understood that national contexts affect the growth and decline of energy technologies, this thesis also highlights the temporal dynamics of policy-technology interactions.

5.1.1 Conceptual contributions

The research I present in this thesis contributes to an improved understanding of policy effort, by tracing its evolution throughout phases of technology change, and connecting it explicitly to socio-political barriers to technology change.

I draw on emerging conceptualizations of climate policy effort in terms of policy commitments, targets and outcomes, and contribute to advancing it by examining feedbacks between its three elements (Figure 3). Policy commitments, such as renewables or coal phase-out targets, are likely to inform the policy actions implemented to achieve these commitments – such as compensation schemes, feed-in tariff levels, or the frequency with which renewables auctions are held (among others). Policy actions in turn are likely to affect coal phase-out and renewables trajectories, i.e. the intended policy outcomes – however, these outcomes may be accompanied by emerging challenges such as increasing policy cost, societal backlash, or system integration concerns, which may lead policymakers to either revise their policy commitments, and/or policy actions.

To trace these feedbacks over time, our papers connect the concept of policy effort with existing understandings of phases of technology change – in Paper 1, for coal power phase-out, and in Paper 4, for onshore wind growth. These contributions provide a conceptual foundation to better understand how policy effort tends to evolve as technologies grow or decline, thus making it possible to address ongoing debates around the level of policy effort and the policy sequences likely required for low-carbon technology change and to mitigate climate change.

Additionally, I propose to explicitly link the type and strength of policy effort to the type and strength of socio-political barriers to technology change – based on insights from Papers 2 and 3 on coal power phase-out, and Papers 4 and 5 on wind power expansion. This means that measuring policy effort may serve as a proxy for the strength of socio-political barriers to technology change, which are harder to operationalize and quantify than well-understood techno-economic mechanisms such as technology cost and learning rates. Ultimately, such ways of quantitatively approximating socio-political barriers may inform the consideration of these barriers in the projection of pathways for renewables growth and fossil decline in line with climate change mitigation targets – a connection which is explored in Paper 3 for coal power phase-out, and Paper 5 for wind power growth.

5.1.2 Methodological contributions

To trace the evolution of barriers throughout phases of technology growth and decline we develop a diagnostic framework for coal power phase-out based on indicators of decline across several interconnected systems and connects it to a policy sequence for coal power decline. This diagnostic approach makes it possible to account for different stages and policy problems across contexts. For onshore wind power, we use policy analysis of a frontrunner country with a long history of onshore wind deployment, identifying the major policy priorities as an indicator of the barriers addressed by policymakers over time. When using the insights from this approach for other countries, one needs to consider the stage of wind deployment, as well as other relevant contextual differences (such as wind potential, public opinion on wind power, or governments' capacities to support technology growth).

We also quantify policy effort embedded in policy commitments, and policy actions, as an indicator of the type and the strength of socio-political barriers to technology change. To quantify policy effort embedded in commitments, we assess avoided emissions of coal phase-out targets, capturing the age and size of national coal power plant fleets; the rate of decline normalized by the electricity system size, capturing the role of coal in the national electricity system; or wind targets normalized by the total national wind potential. To quantify policy effort embedded in policy actions, we measure policy density (showing how many and what type of policies governments deploy); as well as levels of financial resource mobilization (for example coal phase-out compensation and feed-in support for onshore wind power). Combining various measures of policy effort makes it possible to explore the connection between effort embedded in commitments versus actions. It also makes it possible to balance the advantages and disadvantages of different measures. For example, policy density does not illustrate the strength of individual policy actions, while a pure focus on the level of financial resource mobilization may miss non-economic components of the policy mix.

We also propose avenues for connecting empirically observed policy effort with projected climate policy outcomes – such as climate change mitigation pathways. First, we extrapolate the empirically observed relationship between compensation amounts (policy effort embedded in policy actions) and avoided emissions (policy effort embedded in commitments) to projected coal phase-out in climate change mitigation pathways to understand what level of policy effort may be required for these pathways. Second, we extrapolate from observed policy regimes and failure rates for offshore wind power to probabilistically project pathways for deployment, and test several policy scenarios for increased offshore wind deployment.

5.1.3 Empirical contributions

Based on diagnostic indicators for barriers to coal power phase-out, we propose a policy sequence combining policies to sustain decline and manage backlash. Empirically, we indeed find that roughly half of all countries with commitments to phasing out coal power have compensation schemes to address negative effects and backlash to coal phase-out – and that the amount of compensation tends to be proportional to avoided emissions. This finding sheds light on the global distribution of socio-political barriers to phase-out coal. By comparing empirically observed to extrapolated compensation for coal phase-out of major emitters in line with climate change mitigation targets, we highlight the discrepancy in required effort across countries, in particular the high effort required for emerging economies to overcome barriers, which raises feasibility and fairness concerns of rapid global coal power phase-out.

In addition to national contexts, the phase of technology change may also impact the type and level of policy effort required. However, despite the popular assumption that decreasing technology cost alleviates the need for policy effort over time, we find that levels of policy effort – both in terms of the amount of policies and the amount of financial support – overall tends to increase rather than decrease with progressing phases of technological growth. More recently, increasing energy prices, and thus higher returns for electricity producers, have meant that less public resources are required to incentivize onshore wind growth. On the one hand, this may indicate a gradual shift to an environment where market-conditions push renewables deployment (25). On the other hand, empirical evidence indicates that an increasing amount of non-economic policies may be required to address emerging barriers to accelerated onshore wind deployment. Additionally, increasing electricity prices shift the burden of "financing" deployment to consumers, which may ultimately reinforce acceptance issues and require further policy interventions.

For the case of offshore wind power, we find that while current policy effort is not yet in line with commitments for offshore wind deployment, adopting best policy practices across EU countries may enable the achievement of commitments (including additional auctions, additional seabed allocations, and earlier market entry for newcomer countries). Drawing on the insights from the onshore wind policy mix in Germany, one should however also expect feedbacks from increased offshore wind deployment that may require additional, or adjusted, policy effort.

Overall, the research presented in this thesis shows that policy effort for technology change is not a new phenomenon, but that it has persisted over extended periods of time – from coal mining phase-out in the Netherlands in the 1960s and-70s to compensation schemes for coal phase-out implemented around the globe in the 2020s. From renewables support in Germany under the oil crisis in the 70s and 80s, to governance schemes for offshore wind deployment spreading across European countries since the 2010s. We leverage the empirical window these past efforts provide to better understand the role of policy effort in enabling energy transitions. While the future contains uncertainties, such empirical evidence can inform more and less likely ranges of uncertainties, and make it possible to better understand which futures may lie ahead and under what conditions they may be reachable.

5.2 Limitations and potential for further research

When interpreting and learning from the analysis and results presented in this thesis, several limitations need to be considered.

First, we study currently evolving processes and ongoing transitions, which means that the availability of empirical evidence changes over time. One example is the evolution of coal phase-out commitments during the course of my PhD – after data collection and analysis for Paper 2 was completed, the US and Japan – two countries with relatively large coal fleets – made coal phase-out commitments (though the US' has since been withdrawn). Similarly, the coal phase-out and compensation policies this thesis focuses on are currently in the process of being implemented, meaning that it is not possible to assess whether these policies will ultimately be implemented completely and successfully, or not. This limitation is partly addressed by assessing the evolution of coal phase-out commitments over time, and across countries, also under changing geo-political developments (Paper 2) to understand trends in policy diffusion and their underlying mechanisms. However, assessing the evolution of coal phase-out policies throughout their implementation phase, and as coal phase-out progresses in more countries, remains critical to further deepen the understanding of the evolution of the fossil fuel decline process in the context of climate change mitigation.

Second, this thesis contains multiple articles that consider individual transition processes in isolation – Papers 1, 2 and 3 are focused on coal power while Papers 4 and 5 are focused on onshore and offshore wind power, respectively. However, low-carbon energy transitions must involve the simultaneous transitions of multiple energy technologies, including phase-out or decline of the combustion of various fossil fuels, potentially supported by carbon removal technologies; as well as the increased use of variable renewables on- and offshore, likely supported by new energy storage technologies. While the works in this thesis consider the systemic impacts of individual transitions processes, we do not explicitly focus on trade-offs and synergies across technologies. For example, is there a trade-off between policy effort for one type of renewables technology compared to another? Is there a trade-off between policy effort for renewables growth and coal phase-out, or does one encourage the other? Does overall policy effort for energy transitions remain roughly stable, as it moves from technology-specific policies early-on to system-related policies such as grid expansion or electricity market reform? And finally, to what extent is there policy learning across technologies – could policy effort for newly emerging technologies be informed by policy effort for more mature technologies, and is such learning likely to be successful or hinder growth, given different technological characteristics?

A third limitation is that in the papers currently included in this thesis, there is a trade-off between examining policy effort for technology change over a longer timeframe and over several phases (Papers 1 and 4), and examining policy effort for technology change across a larger amount of countries (Papers 3 and 5) – but at one moment in time. Paper 2 partly addresses this limitation by comparing the diffusion of coal phase-out commitments across countries at two points in time. One additional avenue for research may be to examine the evolution of policy sequences over a prolonged period of time in multiple countries, to compare policy sequences or onshore wind, or for coal phase-out, across contexts.

A fourth limitation is that we do not quantify the stringency or directionality of all identified policies – though we quantify the strength of financial support by assessing how much funding has been committed in support of a certain energy transition target. Quantifying the stringency and directionality of a broad range of policies and over time is challenging because it is difficult aggregate the stringency of different policies, it is challenging to identify an appropriate baseline, and it may be difficult to disentangle publicly stated policy objectives from “real” policy objectives. Future research may aim to address these questions to better assess the extent to which policy acts as a driver, versus a barrier, of deployment over time.

5.3 Conclusion

“Climate politics is inseparable from all of our other politics” – this statement by Jane Flegal (Former Senior Director for Industrial Emissions at the White House Office of Domestic Climate Policy) on a recent podcast episode (222) really rung true with me. After five years of research on policy effort for low-carbon energy transitions, one major take-away has been that both climate and energy policy are inextricably linked with many areas beyond climate change mitigation. For achieving global climate change mitigation targets, this may be cause for both hope, as well as for concern.

Low-carbon energy technologies have become increasingly economically competitive, they provide opportunities to generate a profit, to increase employment, and to contribute to satisfying growing electricity demand. However, with increasing renewables growth, these technologies also threaten established fossil fuel businesses and jobs, they require changes to established infrastructures and the policy support they receive may gain increasing attention with their growing deployment. And finally, in an age of arguably increasing polarization, it may just be enough of a reason to counteract renewables deployment because one’s opponent supports it (222).

The cause for hope, to me, is that it both economically and politically does not seem to make sense to *completely* abandon support for low-carbon technologies – because they are important for societies and economies beyond climate change mitigation. The cause for concern is that climate change mitigation requires renewables diffusion and coal power phase-out at a certain rate (rapid) and scale (global).

Some optimists believe this can be achieved thanks to market mechanisms driving the adoption of mature renewables, and the phase-out of fossil fuels. However, by tracing feedbacks between policy commitments, actions and outcomes for coal phase-out and wind expansion, this thesis empirically shows that socio-political barriers to energy transitions matter over time, and across contexts – even as renewables technologies mature and become competitive.

My aim with this thesis is to advance an understanding of socio-political barriers, and policy effort, for technology change, and to contribute to methods of observing and quantifying these elements. I am confident that policy support for low-carbon technologies will not ever completely disappear even in a more polarized and volatile world, simply because these technologies are beneficial for societies and economies beyond climate change mitigation. From a climate change mitigation perspective, however, it is all the more important to better understand how policy effort interacts with low-carbon technology change, and what policy actions may be most relevant in the coming phases of technology change to enable energy transitions in line with climate change mitigation targets.

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