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Advancing methodologies for assessing feasibility and realism in energy transitions

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Advancing methodologies for assessing feasibility and realism in energy transitions

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Abstract

The global transition away from carbon-intensive fuels such as coal towards low-carbon energy technologies like wind and solar power is critical for mitigating climate change. Despite agreement on its desirability, persistent uncertainties surround the practical speed at which this transition can occur. Integrated Assessment Models (IAMs) and energy systems models have significantly advanced our comprehension of how this shift might progress. However, it has been challenging to integrate crucial yet difficult-to-quantify socio-political factors into these models. This limitation has hindered our ability to evaluate the feasibility of the scenarios and pathways generated by these models in real-world contexts.

This licentiate contributes to addressing this gap and develops methods to quantitatively capture the effects of societal and political factors in shaping the growth of solar PV and onshore wind power, and the decline of coal.

Paper 1 develops a new modelling approach for projecting the global growth of solar PV and onshore wind using national-level data. The proposed hybrid model accounts for the dynamic interplay between economic, socio-technical, and political factors shaping technology growth at distinct phases of technology diffusion. We use these projections to create empirically-grounded feasibility zones for the future growth of these technologies until 2040. We find that their most likely range of deployment is in-line with 2°C warming, but substantially lower than scenarios consistent with the Paris agreement. Achieving deployment required to meet the 1.5°C target and the Global Pledge on Renewables would require solar PV and onshore wind in the whole world to scale as fast as in a few leading countries with exceptionally favorable circumstances.

Paper 2 develops an approach to empirically estimate the cost of overcoming socio-political opposition to the phase-out of coal power by collecting data on national schemes to compensate actors negatively affected by the transition. We analyse the relationship between the ambition of coal phase-out pledges and compensation schemes and find that globally, compensation amounts to over USD 200 billion (uncertainty 163-258), of which about half is provided internationally. Extending similar transfers to India and China to phase out coal in line with the Paris temperature targets could make compensation flows larger than all current international climate financing.

Together, they build on emerging work on feasibility spaces for the future deployment of different climate mitigation options, and advance methodologies for quantifying the level of policy effort required to accelerate the energy transition.

Keywords: Energy transitions, climate change mitigation, technology diffusion, solar PV, wind energy, coal phase-out, compensation, feasibility

List of Publications

This thesis is based on the following publications:

Paper 1
A. Jakhmola, J. Jewell, V. Vinichenko, A. Cherp, “Future growth of wind and solar power projected by historical national experience”. *Under review.*

Paper 2
L. Nacke, V. Vinichenko, A. Cherp, A. Jakhmola, J. Jewell, “Compensating affected parties necessary for rapid coal phase-out but expensive if extended to major emitters”. *Nature Communications* (2024), In press.

Contributions

Paper 1
Conceptualization: A.C., J.J., V.V.; Methodology: A.C., J.J., V.V., A.J.; Data curation: A.J., V.V.; Formal analysis and visualisation: A.J., V.V.; Writing - original draft: A.J., A.C., J.J., V.V.; Writing review and editing: A.J., J.J., A.C.; Supervision and funding acquisition: J.J.

Paper 2
Conceptualization: J.J., A.C.; Methodology: J.J., A.C. and L.N.; Data collection and curation: L.N.; Formal Analysis: L.N., V.V., A.J.; Writing original draft: L.N., J.J., A.C.; Writing review and editing: L.N., J.J., A.C., V.V. and A.J.; Visualization: L.N., J.J., A.C., V.V., A.J.; Project administration: L.N.; Supervision and funding acquisition: J.J.

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– Avi

Acronyms

IAM:	Integrated Assessment Model
IPCC:	Intergovernmental Panel on Climate Change
AR6:	Sixth Assessment Report
UNFCCC:	United Nations Framework Convention on Climate Change
COP:	Conference of Parties (of the UNFCCC)
IIASA:	International Institute for Applied Systems Analysis
IEA:	International Energy Agency
SSP:	Shared Socio-economic Pathway
PPCA:	Powering Past Coal Alliance
PV:	Photovoltaic
USD:	United States Dollar

Contents

CHAPTER 1

Introduction

The global energy system is on the cusp of a transition from carbon-intensive sources like coal and oil, to low-carbon technologies like wind turbines and solar photovoltaics (PV). This transformation in the state of the energy system [1] is pivotal to global efforts to mitigate climate change [2]. However, despite a broad consensus on the desirability of, and necessity for this transition, there are large uncertainties over how fast it can realistically unfold.

These uncertainties stem from the sheer complexity of modern energy systems which are composed of, and driven by myriad technical, economic, social and political factors [3]. Advances in computing over the last five decades have helped facilitate the emergence of sophisticated energy system, and Integrated Assessment Models (IAMs) which have been used to simulate the long-term evolution of such systems. While the focus of energy system models is quite specific, the more expansive IAMs have facilitated exploration of the interdependence between energy, and other socio-economic and geo-physical systems. Over time, efforts to improve the representation of different socio-economic and technical parameters in models have only added to their complexity and enhanced their influence [4]. They have grown to play an increasingly important role in shaping energy and climate policy – from informing national plans and targets, to supporting the negotiation of international treaties like the Kyoto Protocol and the Paris Agreement [4–6].

However, the models' rising influence has also brought more scrutiny and their (in)ability to adequately account for critical, but more intangible social and political factors has been repeatedly called into question [7–9]. Despite persistent efforts to improve 'model realism', modellers have found it challenging to marry the quantitative logic of the models with messier, hard-to-quantify socio-political factors. For example, while models have substantially improved their representation of how increasing deployment drives reductions in technology costs, they have struggled to quantify and integrate societal factors like public opposition to siting new renewable energy projects, or resistance to the closure of coal mines and power plants in coal-dependent regions.

This inability to adequately account for socio-political factors has ramifications for the real-world feasibility of the scenarios these models help us construct and explore [9]. Though they are able to generate thousands of pathways for the future, they fail to indicate which of them are more likely to be realised under a given set of socio-political circumstances [10, 11]. This complicates the process of translating model outcomes into actionable policy advice; though models can tell us what is technically possible, or economically beneficial, they fail to tell us what is realistically doable.

There is an emerging strand of literature which attempts to address this question of feasibility by bridging the gap between the quantitative, 'techno-economic' models [3] and empirical knowledge from other disciplines in the social sciences [9, 12]. This Licentiate builds on this body of knowledge. By analysing socio-political mechanisms which influence energy transitions, it advances methods for assessing the feasibility of future pathways for the rise of renewables such as onshore wind and solar PV, and the decline of incumbent energy sources like coal.

The prospects for onshore wind and solar PV have undergone a dramatic shift over the last two decades. With a rapid rise in deployment and steeply declining costs, they find themselves at the forefront of the transition to a future low-carbon energy system. They are progressively out-competing incumbent energy sources like coal not only on climate-friendliness, but also on cost. These developments have made them increasingly attractive to IAMs and energy system models, where their ability to generate cheap, low-carbon electricity often drives their rapid, large-scale uptake in many scenarios [13–

17]. However, the trajectories of new technologies are shaped not only by drivers such as declining costs – which are well-represented in models – but also barriers like public opposition, conflicting land uses, and political inertia [18]. Identifying, isolating, and accounting for the cumulative effects of these constantly evolving mechanisms has proven methodologically challenging. What would the pace and cost of a transition led by wind and solar PV look like if models could incorporate these elusive mechanisms?

This question also applies to the future of carbon-intensive energy sources like coal. On the one hand, models demonstrate that the emergence of low-carbon alternatives makes the rapid phase-out of coal techno-economically plausible [19]. On the other hand, recent empirical analyses suggest that existing policies and commitments are insufficient to phase-out coal fast enough to meet the 1.5°C target [20–22]. It is widely recognised that the phase-out of coal power faces considerable socio-political opposition from actors set to be negatively affected by it. These include not only companies involved in coal mining and power generation, but also workers and regional economies dependent on the coal sector [23]. While this opposition is well-documented, its impact on the pace of coal phase-out is underrepresented in modelling analyses where typically, the use of coal declines rapidly in the face of increasingly cost-competitive low-carbon alternatives and/or stringent climate policies. What happens to these projections when we also begin to account for socio-political barriers?

This Licentiate contributes to resolving these questions.

Contributions of this Licentiate

The Licentiate begins by outlining the intellectual history of IAMs and energy system models and charts the emergence of quantitative modelling as a means to understand and address global challenges. I trace the development and rising prominence of models from the 1970s to the present and explore their evolution in the face of increasingly complex questions about the future of coupled socio-economic and natural systems (Section 2.1).

In unpacking the types of causal mechanisms models have been able to integrate so far (Section 2.2), I also highlight that efforts to improve their representation of socio-political factors have found little success (Section 2.3). I relate this challenge to the broader problem of assessing the real-world feasibility of different climate and energy pathways (Section 2.4). Building on emerging literature trying to merge multi-disciplinary perspectives on energy transitions (Section 2.5), this Licentiate contributes towards efforts to bridge the gap between quantitative modelling and empirical research in the social sciences.

Conceptually, it advances the state of the art on using empirical evidence that captures the role of socio-political barriers in shaping the energy transition to design feasibility spaces for future technology growth and decline. It also develops an approach for quantifying the level of policy effort required to accelerate transitions.

Methodologically, its contributions are twofold. Paper 1 develops an approach to project empirically-grounded feasibility zones for the global growth of onshore wind and solar PV. It introduces a new, hybrid model which uses empirical, national-level data that capture the aggregate outcome of the dynamically evolving mechanisms shaping technology growth. Meanwhile, Paper 2 develops an approach to empirically estimate the monetary cost of overcoming socio-political barriers to coal phase-out.

Empirically, it projects feasibility zones for the global growth of onshore wind and solar PV until 2040, and benchmarks their growth in contemporary scenarios and pathways. In doing so, it also quantifies the level of policy effort required to accelerate growth to be in-line with what is required for the climate targets (Paper 1). It also builds a comprehensive database of compensation schemes, their costs, beneficiaries, and funding sources, links them to the acceleration of coal phase-out through political commitments, and estimates the cost of extending such schemes to major coal users like China and India (Paper 2).

CHAPTER 2

State of the art

2.1 Climate-energy-economy and energy system models

The production and consumption of energy has been pivotal in propelling the rise of modern industrial society over the past two centuries [24]. Given its central role in driving socio-economic change, the extraction, transformation, and utilization of energy sources have received much academic attention. Starting with classical economists in the 19th century [25], these investigations branched into specific sub-disciplines such as energy and natural resource economics. Much of this literature assumes that the allocation of energy (and other scarce) resources proceeds through equilibria characterised by an 'optimal' balance between demand and supply. This balance is achieved through transactions between rational, self-interested agents in a perfect market, or through decisions made by a perfectly efficient and omniscient social planner. This 'neoclassical' view has been used to explain not just the stability of the energy system at a given point in time, but also its transformation in response to resource scarcity, changing demand, technological innovation and other socio-economic developments [26].

The emergence of concerns over environmental degradation, energy security and nuclear proliferation in the 1970s created the need for new analytical approaches to study such complex global challenges. Aided by ongoing advances in computing, this demand helped launch a new age of quantitative models for studying critical socio-economic and natural systems. It began with the *Limits to Growth* report [27] on the impacts of human activities on the natural environment. The report pioneered one of the first global models simulating the long-term, co-evolving future of society and the environment. Shortly after, the world was hit by the 1973-74 oil crisis, which sparked urgent discussions on society's overt reliance on scarce fossil fuels. *What was the most efficient way to allocate the use of these finite resources over time, given the heavy inter-dependence between economic development and energy use?* As we saw earlier, this was exactly the type of question economists had been striving to answer.

In 1973, Nordhaus [28] leveraged neoclassical economics' formal, quantitative perspective to develop one of the first ever energy-economy models. The development and use of such models exploded in the aftermath of the oil crisis through initiatives like the Energy Modelling Forum in the US, and the Energy Project at the International Institute for Applied Systems Analysis (IIASA) in Austria [4]. The latter helped inform *Energy in A Finite World* [29], a landmark report outlining different scenarios for the development of future global energy demand and how it could be met.

Meanwhile, escalating concerns about human-induced climate change prompted the development of Integrated Assessment Models (IAMs) which could simulate the impact of human activities on the earth's climate. Nordhaus [30, 31] arguably developed the first IAM already in the 1970s when he coupled an energy-economy model with a simple emissions model. This simple IAM could be used to explore the impact of economic activity on energy use, and through the associated emission of carbon dioxide, on the earth's radiative balance. This was a precursor to what later became the Dynamic Integrated Climate and Economy (DICE) model [32]. Over the last two decades of the 20th century, IAMs grew to first include more complex climate models, and later added dedicated modules for simulating population growth, land-use change, and other socio-economic variables [33]. Still embodying the neoclassical lens of the energy-economy models they first evolved from, these models were instrumental in shaping early thinking on climate policy in terms of the cost/benefit of reducing emissions [34].

With increasing sophistication in their ability to represent different, interlinked socio-economic and geo-physical processes, more 'process-based' IAMs [35] were used to simulate the long-term impacts of socio-economic development on the earth system under varying assumptions about future economy and population growth, geophysical resource constraints, technology development and climate policies. Their role in climate policy-making became particularly prominent with the success of the Montreal Protocol in addressing ozone depletion. IIASA's Regional Acidification Information and Simulation (RAINS) model, an IAM, had made significant contributions to the negotiation and implementation of the protocol [36, 37] and there was hope that IAMs could be similarly useful in addressing climate change [4].

The IAMs' stock rose with the founding of the Intergovernmental Panel on Climate Change (IPCC) [33] and they became an important part of the assessments conducted by the IPCC's Third Working Group (WGIII) where they played a central role in defining quantitative emissions-reduction targets in the lead-up to the Kyoto Protocol [4, 5, 38]. They were also instrumental in the emergence of the 2 °C target [5, 39], and generated the normative scenarios used for exploring development pathways compatible with limiting warming below 2 °C and 1.5 °C in the run-up to the negotiations for the Paris Agreement [4, 6],

Developments in IAMs have been accompanied by simultaneous advances in sector-specific models like energy system models. Following in the tradition initiated by the energy-economy models of the 1970s, energy system models draw on knowledge from disciplines including economics and energy engineering to provide detailed representations of energy systems of varying geographical scope, their constituents, and the interactions between them. They have been used to model the behaviour of energy markets, evaluate pathways to achieve particular targets (e.g. time-bound emissions reduction), and explore the development of energy systems under different assumptions about the future (e.g. coal or nuclear power phase-out) [40–43].

Together, contemporary IAMs and energy system models are important tools for understanding the future of the energy transition under various scenarios. They exert considerable influence on shaping policy, and are central to not only scientific, but also public and political discourses on the energy transition, climate change, and how to mitigate its impacts. But, as we will see, they are not perfect or infallible. They have limitations which have serious implications for their use in formulating actionable policy advice.

2.2 Simulating the energy transition in quantitative models

We have seen how the emergence of IAMs and energy-economy (or energy system) models has been closely intertwined with the need for tools to analyse complex global challenges. In this section, we will delve deeper into understanding the factors incorporated in such models and the way in which they simulate energy, and other system transitions.

Initially, the energy-economy models being developed and used after the oil crisis in the 1970s were focused on the problem of finding ‘optimal’ ways to meet energy demand using a finite amount of resources. They were used to explore what this optimal energy supply mix would look like under different scenarios for economic, and energy demand growth [29–31]. For example, one could use the model to find the most (cost-)efficient way to meet annually increasing global energy demand over the next ten years under a cap on oil extraction.

The first IAMs which evolved out of these energy-economy models were used to link economic activity and energy use to emissions, and consequently estimate their impact on global temperatures. By quantifying the relationships between variables measuring economic development (e.g. Gross Domestic Product or GDP), energy use, and emissions, they facilitated estimation and comparison of the economic costs or benefits of different policies [34].

The models differentiate between ‘endogenous’ variables being calculated inside the model (such as the amount of energy production from a given source) and ‘exogenous’ parameters which are fed into models from the outside and held fixed as it runs (such as the cost of producing energy from a given source, or how much of it there is to be used in total). The two are linked by mathematical relationships and their interactions produce different outcomes depending on the constraints being modelled. Thus, one can manipulate these exogenous assumptions and constraints being fed into the model to simulate different policies and assess their effect on model outcomes. For example, a climate policy limiting temperature rise due to global warming could be operationalised by capping emissions from energy production which then constrain economic growth or increase the cost of energy supply by switching to more expensive sources with lower emissions. The economic costs and benefits of such a policy could be compared against those for a baseline scenario where unfettered economic growth drives up energy demand which is met by increasing the consumption of fossil fuels, leading to higher emissions and more warming.

Like the older energy-economy models, these cost/benefit IAMs became increasingly influential in discussions on policy and popularised the use of a cost/benefit framing in discussions about climate change mitigation [34, 44]. They were used to estimate the 'optimal' amounts of climate mitigation from an economic efficiency perspective [34], and were important in shaping climate policy in the US and beyond [45].

Meanwhile, the models were also continuously evolving. Unlike earlier models where the evolution of technology costs over time was an exogenous input, newer models could internalise technological learning through 'learning curves' [46, 47]. This allowed for the costs of initially expensive technologies to progressively decline as the model deployed more of them. Thus, models could simulate technology substitution and induced innovation more dynamically. For example, policies promoting the use of a particular technology, say solar PV, could allow it to become cost-competitive with other incumbent technologies over time.

This attempt to better represent a dynamic 'process' was representative of broader developments leading to a new class of detailed 'process-based' IAMs which sought to relate trends in specific socio-economic drivers to emissions and climate impacts [35, 48]. They marked a split from the highly aggregated cost/benefit IAMs which focused less on particular processes, and more on overall economic costs and finding optimal mitigation levels [4].

With growing influence on policy, the models also came under sharper scrutiny and started drawing criticism for the lack of perspectives from the social sciences in their frameworks [4, 7, 49]. Efforts to address these critiques initiated several new developments in modelling. One such shift was an increase in the use of process-based IAMs. This was largely driven by their better suitability for integrating socio-economic factors.

In 2000, the IPCC published a Special Report on Emissions Scenarios (SRES) [50] which introduced qualitative storylines as inputs for process-based IAMs. This approach accommodated interdisciplinary involvement and the exploration of future worlds with very different characteristics and constraints. While some storylines assumed faster diffusion of new and efficient technologies, others doubled down on the use of fossil fuels. While some assumed a stagnation of economic and population growth, others assumed accelerating growth with intensifying international trade. The SRES scenarios gave primacy to these qualitative storylines, by first describing the evolution of such socio-economic driving forces, and then modelling the resulting emissions and climate impacts. Since these storylines also included explicit assumptions about the use of energy sources and development of energy technologies, they had a profound impact on projections for the energy transition.

The Representative Concentration Pathways (RCPs) [51] followed shortly thereafter and applied a different logic. They provided a few pathways for atmospheric greenhouse gas (GHG) concentrations linked to different levels of radiative forcing levels in 2100, and simultaneously developed climate change projections and socioeconomic pathways consistent with them [51]. However, they had a problem. The complex relationship between demographic or socioeconomic development and GHG emissions meant that multiple socioeconomic pathways could lead to the same amount of radiative forcing [52]. For example a pathway with high population growth and low per capita emissions use could lead to the same emissions as another pathway with low population growth and high per capita emissions. Similarly, a given socioeconomic pathway could be consistent with a wide range of RCPs depending on the type and stringency of climate policies being modelled. For instance, the same socioeconomic pathway could lead to very different emissions trajectories depending on the presence or absence of a carbon tax in the scenario.

This was recognised and addressed by the Shared Socioeconomic Pathways (SSPs) [53–55]. The SSPs first combined socio-economic pathways with different levels of radiative forcing and defined "reference" pathways showing what might happen without new climate policies and without considering the impact of future changes in the climate [55]. Then, climate policies could be added to these reference pathways (through Shared Policy Assumptions or SPAs) to project what their effects could be [56]. These scenarios helped illustrate how both climate policies and changes in the climate itself might influence future society and development. They included drivers for factors like "population growth, governance efficiency, inequality across and within countries, socio-economic developments, institutional factors, technology change, and environmental conditions" [57]. Thus, the SSPs aimed to model diverse future scenarios by combining narrative storylines and quantified development measures. Here too, the future of the energy transition in a given scenario was influenced not only by basic techno-economic assumptions but also the exogenous socio-economic storyline and climate policies being modelled.

Meanwhile, energy system models that also grew out of the first energy-economy models continued to develop alongside the IAMs. They typically use a linear optimisation approach to decide how much of which technology to deploy in order to deliver energy services while minimising the total system cost under different resource, technology, or policy constraints. Early energy system models [58] were developed to quantitatively model conventional electricity systems dominated by steady production from sources like coal and oil. However, the emergence of renewable energy technologies like solar and wind and the increasing use of these models in exploring low-carbon energy futures raised several challenges for modellers [59]. These mainly related to the the representation of spatio-temporal variability in production due to the increasing use of variable renewable energy sources, the integration of sectors beyond the electricity system into models (also called 'sector coupling'), and the generation of transition pathways leading to the desired low-carbon system. Like the IAMs, energy system models have also continuously evolved to rise to these challenges [60, 61] and become increasingly influential in informing energy policy. However, also like the IAMs, they too have struggled to account for the effect of socio-political factors in shaping energy systems.

As we have seen, starting from the first energy-economy models of the 1970s to the gargantuan process-based IAMs of today, models have constantly evolved to incorporate more complexity and risen to the challenge of answering important questions about the future of society and the earth system. Given the dizzying number of variables they embody, they can be used to generate thousands of different pathways for the future of socio-economic development, the energy system, and the climate. Together, these models create a vast "solution space" [62, 63] containing not only those scenarios and pathways that have already been generated, but also those that could be developed in the future [9]. However, the criticisms over the models' ability to integrate socio-political and institutional factors have not disappeared. In fact, they have only become stronger [8, 9]. And now, they have also opened a whole new set of questions about the idea of feasibility and how these scenarios relate to the real world.

2.3 The limitations of contemporary models

Attempts to improve models' ability to account for socio-political factors led to developments such as the SRES and the SSPs, which tried to do so through the use of qualitative storylines which could then be translated into quantitative inputs. But therein also lies the problem. The fundamental structure of these models depends on quantitative parameters and variables which can be related and manipulated using mathematical functions and algorithms. This suits geo-physical processes like the greenhouse effect, and techno-economic variables like the quantities of different resources, installed capacities of energy technologies, or their operation costs, which are all relatively easily to quantify. Unsurprisingly, they are fairly well-represented in most models [8]. However, socio-political factors like public acceptance [64, 65], the preferences and values of individuals [64, 66, 67], resistance to change from incumbents [68, 69], geopolitics [70], governance [71, 72], or technological inertia [73] are more intangible and have thus proven much harder to integrate into quantitative models.

The hard-to-quantify nature of such factors has meant that attempts to better integrate socio-political mechanisms into models such as the SSPs [55] have been limited to a small number of socio-economic variables such as population dynamics, GDP, urbanisation, or level of cooperation in society. Moreover, the way that these variables are integrated into models through exogenous storylines also limits the interaction of these assumptions about society with other techno-economic or geo-physical variables [8]. Overall, the representation of socio-political processes in models remains quite limited.

This is a problem because these complex, interdependent factors are critical in driving and constraining energy and climate transformations [74, 75]. The current modelling paradigm risks overlooking the effects of important drivers and mediators of societal change such as the behaviour and preferences of different actors, politics, social and institutional capacities, as well as geographically and socio-economically heterogeneous circumstances and contexts [8, 76]. Moreover, given that their focus is typically global or regional, models are usually calibrated using long-term global or regional trends for energy production, supply, demand, and technology development, which risks ignoring the spatial unevenness of socio-technical processes [77–80]. A global (or regional) focus, is also not always representative of different national interests, priorities, and capacities [3, 12, 81].

The inability of contemporary IAMs and energy system models to adequately account for socio-political mechanisms has major ramifications for their ability to evaluate the relative real-world feasibilities of the myriad scenarios and pathways they can generate (see [9] for a comprehensive review of the debate on the feasibility of climate solutions).

> Infeasibility [in IAMs] is ... an indication that under a specific model parameterization the transformation cannot be achieved. It provides a useful context to understand technical or economic concerns ... but need[s] to be ... differentiated from ... feasibility ... in the real world, which hinges on a number of other factors, such as political and social concerns that might render feasible model solutions unattainable in the real world. [11]

In other words, models can only tell us if a particular scenario or pathway works inside the logic of the model. Returning to the concept of the ‘solution space’ [62], though models can identify if a set of scenarios or pathways fall outside this space (and are thus infeasible), they cannot distinguish which of the pathways inside the solution space are feasible in the real-world [11]. Moreover, as models are not able to capture all causal mechanisms influencing societal change [9], the solution space inevitably contains many scenarios or pathways which make sense inside the model, but are not feasible in the real world [82–84]. Distinguishing between infeasible and feasible pathways, and then assessing which of the latter are more, or less feasible than the others poses a significant methodological challenge which limits the use of models to inform policy.

2.4 Bridging different perspectives on energy transitions

So far, we have focused on IAMs and energy system models which follow a long ‘techno-economic’ tradition of viewing energy flows and markets through the lens of neoclassical economics. However, the study of energy transitions has a rich intellectual history extending beyond quantitative models. These transitions have also been studied through ‘socio-technical’ and ‘political’ perspectives with roots in disciplines like the sociology and history of technology, evolutionary economics, political science, political economy and international relations [3].

A socio-technical system can be defined as a *"...configuration of technologies, services and infrastructures, regulations and actors (for example, producers, suppliers, policy-makers and users) that fulfils a societal function such as energy provision"* [85]. The socio-technical perspective views technological change as a social phenomenon, and analyses it through theoretical frameworks like ‘technological innovation systems’ (TIS) [86] and the ‘multi-level perspective’ (MLP) [87, 88]. While the TIS framework focuses on innovation or the creation and diffusion of new technologies, the MLP analyses socio-technical transitions by building on the evolutionary concepts of niches, regimes, and landscapes. In the MLP, new technologies emerge in dynamic niches which interact with incumbent regimes – sets of rules and routines which define stable socio-technical systems – and try to displace them [3]. Meanwhile, these are themselves embedded in a broader socio-technical landscape which also influences the stability of regimes.

The political perspective focuses on the *state* as the primary unit of analysis and how its policies influence the changes in national energy systems [3]. It analyses policy actions and energy policies through theories of policy learning and diffusion, punctuated equilibrium or approaches like the Advocacy Coalition Framework (see [3] for a comprehensive review).

There have been attempts to integrate these perspectives to develop a more comprehensive understanding of energy transitions as the product of co-evolving systems [3]. However, the assimilation of IAMs and energy system models into such meta-theoretical frameworks has proven difficult.

The challenge of evaluating the feasibility of modelled scenarios for energy (and other societal) transitions arises out of the epistemological and analytical disparities between quantitative models and these socio-technical and political perspectives [9, 83]. It is therefore crucial to foster collaboration between modellers and social scientists in order to find a common ground and overcome these differences. Such attempts have driven the emergence of a new field of research [9, 18, 22, 89–92] which tries to bridge the gap between different disciplines and improve the representation of socio-technical and political factors in models.

Unlike past efforts such as the SSPs which focused on exogenous narratives, an alternative approach has focused on using evidence from the social sciences to explicitly incorporate societal factors in models. This is done by mapping model assumptions to current social science knowledge, and conducting new empirical research to identify generalizable patterns and causal relationships which can be included in models [8]. However, as they have been able to isolate, measure, and integrate only a limited subset of relevant mechanisms, such efforts have as yet failed to make breakthroughs in addressing the feasibility question [84, 93].

The challenge of finding reliable approaches for developing forecasts and plans is not limited to the climate and energy spheres. Kahneman and Lovallo [94] introduced the concept of the "inside" and "outside" views on such approaches, which Jewell and Cherp [9] extend to the debate on feasibility in the climate sphere. They argue that this focus on improving 'model realism' by merging evidence from the social sciences into models constitutes taking an "inside view" which tends to emphasise the uniqueness of climate change as a policy problem and the degree of control policy makers have in shaping climate outcomes. In such a setting, an attempt to improve model realism by developing more complex, detailed models "*may paradoxically increase over-confidence in the likelihood of a given storyline and is more likely to solidify the perception of scenarios as realistic, rather than improve their actual realism*" [9].

Yet another approach that has been widely used to assess the feasibility of climate mitigation pathways compares them to historical analogies. These include comparing historical evidence on the rate of declines in energy and emissions intensities, speed of historical energy transitions, growth of new technologies, as well as decline of fossil fuels to developments envisioned in scenarios [9]. By shifting the focus away from specific mechanisms and model assumptions, such analyses look for "*historical precedents which are 'similar in relevant aspects' to the solutions envisioned in scenarios*" which Jewell and Cherp [9] liken to taking an "outside view."

Thus, while the literature is replete with examples taking either the "inside" or the "outside" views, integrating the insights from these two approaches and getting them to talk to each other has proven challenging.

2.5 Feasibility spaces for technology growth and decline

The feasibility space [9] is a relatively new approach which offers a way to bridge the gap between the detail-oriented and case-specific "inside" view and the historical analogies of the "outside" view.

As we have seen so far, though IAMs and other quantitative models excel in representing many causal relationships, they struggle to capture all relevant factors, which makes assessing the feasibility of their outcomes difficult. In contrast, the "outside" view enables inductive reasoning by analogy using insights from aggregate outcomes in historical reference cases. By integrating the two perspectives, feasibility spaces facilitate comparisons between historical precedents and future scenarios.

While IAMs do not typically assign probabilities to scenarios, the historical observations, real-life interventions, and "natural experiments" studied using the "outside" view can serve as benchmarks for scenario pathways, signal the level of effort historically required to scale different processes, and highlight potential role models for future change [9].

Feasibility spaces have been used to analyze both technology growth and decline. Here, we will focus on two cases relevant to the low-carbon energy transition – the growth of renewables [18, 73, 95–97] and the decline of fossil fuels [22, 90].

Solar PV and wind expansion

The rapid expansion of solar and wind power in recent decades has positioned them at the forefront of the transition to a low-carbon energy system [2]. Low life-cycle emissions and steadily declining costs make them popular mitigation options in most climate scenarios, where they quickly and cheaply substitute fossil fuels.

There is a rich literature on the growth and diffusion of new technologies, covering the emergence of hybrid corn varieties in the US [98] to projections for hydrogen electrolysers in the EU [99]. Drawing on historical observations, these studies typically model the growth of a new technology using an S-shaped curve such as the logistic function [78, 100, 101].

$$f(t) = \frac{L}{1 + e^{-k(t-t_0)}} \tag{2.1}$$

where, L is the growth ceiling, k is the steepness parameter, t_0 is the year of the inflection point, and e is Euler's number.

The S-curve of technology adoption is characterized by four distinct phases: formative [102, 103], acceleration [104, 105], stable growth [18], and saturation [106]. A new technology starts in the formative phase, where its growth is shaped by innovation, experimentation, failures, and irregular state interventions [91, 102, 103]. Here, deployment levels are small, year-on-year growth is erratic, and growth mechanisms are specific to the niche in which the technology is being used. Once the technology reaches a critical mass, it takes off [106–108] and starts growing with a consistently accelerating pace driven by positive feedback loops or increasing returns [104, 105, 109]. As the technology undergoes more widespread deployment and approaches the curve's inflection point, it also begins to encounter more barriers [18]. The technology's absolute growth rate is at its maximum at the inflection point. Either side of the inflection point, the technology is in a stable growth phase, where the effects of mechanisms driving and constraining growth counterbalance. As the technology moves further along the curve, the barriers begin to dominate and eventually, the technology reaches saturation on achieving its peak market share [106].

S-curves fit to empirical technology use data have also been used to quantitatively measure the speed of technology adoption [18, 98–100, 107, 110–112]. Several of these studies use the logistic function (Equation 2.1) to measure the initial rate of adoption during the acceleration phase (using the steepness parameter, k), the final saturation level (by measuring the growth ceiling, L), or the overall pace of growth through the technology life-cycle (using the duration of transition, defined in the literature as the time it takes for the technology to grow from 10% to 90% of its final saturation level [100]).

Other approaches also measure year-on-year growth rates [13, 16, 73, 95–97, 113], or use a combination of metrics [107, 114]. This plurality of metrics means that the same empirical data can yield different interpretations for past and future growth. For example, averaged historical year-on-year growth rates aggregating observations over several years are often used to argue that the growth of solar PV and wind is still exponential [13, 16, 115]. However, such measurements do not differentiate between and account for the different phases of technology adoption described above. When these rates are used to project future exponential growth, they implicitly assume that technology growth can continue expanding at past speeds without running into any barriers. Approaches using S-curves take a more nuanced view and account for how the patterns of growth change across different phases of adoption. However, they too run into problems when being used with immature data from the early phases of adoption [116], where the exact shape and parameters of the curve cannot be reliably determined.

Thus, while there have been attempts to benchmark the growth of new technologies like solar PV and wind using historical analogies, there is little consensus on how to reliably extrapolate the past into the future. This methodological challenge has hindered the use of historical data to create feasibility spaces for their future deployment.

Coal decline

Calls for the phase-out of coal have gained momentum due to concerns not only over its role in climate change, but also its impact on air quality, and health.

Since the UK's pledge in 2017, an increasing number of countries have committed to phasing out coal and joined initiatives like the Powering Past Coal Alliance (PPCA). Some scholars have argued that the diffusion of climate policies internationally might help accelerate phase-out by changing norms and increasing international pressure [117, 118]. However, the international diffusion of phase-out commitments has also faced barriers including fairness concerns from emerging economies and arguments for the right to use coal for economic development [119–121].

The feasibility space approach has been used to analyse the prospects for major coal consumers joining the PPCA [89], as well as the feasibility of coal use declining fast enough to meet the climate targets [22, 90]. They show that countries committing to coal phase-out face lower costs and have higher capacity to bear them, and that despite declarations to "consign coal to history" at COP 26, the pace of coal decline and phase-out observed so far is insufficient to meet the climate targets [20–22, 90]. Phase-out has proven more difficult than commonly assumed because of the complex and non-linear nature of technological change, which is influenced not only by techno-economic factors such as the emergence of low-cost alternatives but also by socio-political and industrial inertia [23].

At the national level, there are numerous barriers to coal phase-out. These include the risk of stranded assets, backlash from industry and workers [68, 108, 122], socio-economic challenges in coal-dependent regions [123, 124], and potential electoral losses for politicians [125, 126]. Some governments have introduced compensation schemes as a means to counter some of these barriers and support negatively affected actors in a ‘just transition’ to a new energy system [119, 127–129]. At this stage, the impact of these schemes on coal phase-out remains unclear and warrants further systematic study and comparison.

Overall, the feasibility space approach has proved helpful in bridging the gap between the "inside" and "outside" views, and advancing assessments of the feasibility of different scenarios and pathways. However, it continues to face challenges relating to the identification and measurement of empirical data which captures mechanisms relevant for the case being studied. It also lacks the tools to quantify the amount of policy effort necessary to shift trajectories of technology growth or decline towards levels required for different targets or goals.

These are the challenges this Licentiate addresses.

CHAPTER 3

Present Work

3.1 Paper 1

Motivation

Over 100 countries signed up to the ‘Global Pledge on Renewables and Energy Efficiency’ at COP28 in Dubai, aiming to triple global installed renewable energy capacity by 2030 [130]. However, despite agreeing on the need to rapidly deploy low-carbon energy technologies like onshore wind and solar PV, there are widespread disagreements over fast their use can realistically expand. Scenarios used by the IPCC [2], and from the recent modelling literature [14–17] outline thousands of pathways for the growth of these technologies, but assessing their real-world feasibility [9] continues to pose a major methodological challenge (see Section 2.3).

One way to overcome this challenge is to use empirical observations capturing the aggregate outcome of all causal mechanisms influencing technology growth. However, there is little agreement over how to meaningfully extrapolate historical trends into the future (see Section 2.5). Given that both onshore wind and solar PV are still in the early phases of their respective

S-curves at the global scale, their exact shape and parameters cannot be reliably estimated using empirical data [116]. While some studies fit S-curves to global data regardless [131], others assume that both technologies are still growing quasi-exponentially [13, 16], leading to widely diverging views on the prospects of the energy transition.

Thus, efforts to use empirical data to inform projections and assess feasibility have been stymied by methodological challenges. These uncertainties around the feasibility of future pathways also hinders their use in formulating actionable policy advice. Are existing drivers of growth sufficient or will meeting the climate targets require stronger policies to accelerate deployment?

Research questions and method

We develop a new modelling approach that uses empirical, national-level technology deployment data to construct a range of global projections that illustrate more and less optimistic outcomes, informed by different national and technology cases. This introduces a new parameterisation approach which accounts for the dynamic nature of the interplay between economic, socio-technical, and political factors in shaping technology growth at distinct phases of technology diffusion. We also develop a new, hybrid model simulating an extended stable growth phase which replicates an S-curve until the inflection point and switches to linear growth at the maximum annual growth rate thereafter (Figure 3.1).

To parameterise our models, we first identify the end of the formative phase by analysing the patterns in the evolution of a technologys year-on-year growth rate with increasing penetration using a regression analysis. After filtering out the erratic formative phase, we fit growth curves to national data and estimate the acceleration phase growth rate and the maximum growth rate at the inflection point for S-curves, and the growth constant for the exponential model. We generate projections using a weighted sample of growth parameters, where each national observation is weighted according to its share in global electricity generation

We assess the forecast performance of the exponential, logistic, Gompertz, and hybrid models using hindcasting over horizons up to 20 years. We use a suite of metrics to measure the accuracy of their forecasts for the future growth of solar PV and onshore wind, as well as two reference technologies – mobile phones and nuclear power – based on parameters derived from both, global data and the distribution of weighted national-level observations.

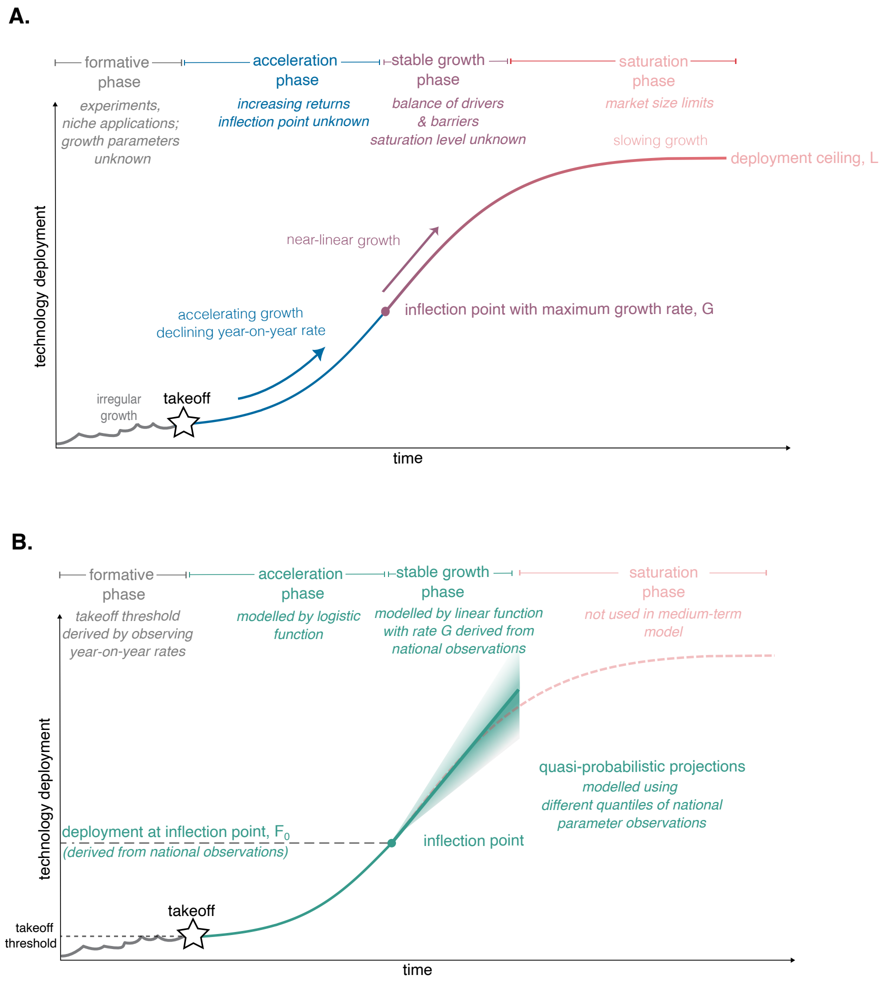

Figure 3.1: The four phases of the S-curve of technology diffusion and the gaps in available evidence limiting the ability to project growth in later phases using observations from earlier phases. (B) A proposed hybrid model and quasi-probabilistic corridor for global, medium-term deployment projections which assumes linear growth over an extended stable growth phase and derives parameter values from national observations.

What do these projections tell us about the feasibility of future pathways and the level of policy effort required to replicate them? We use the hybrid model to make a range of projections for solar PV and onshore wind deployment between 2022-2040. These projections reflect a spectrum of empirically-observed growth dynamics in various countries. We combine these projections with information on the predictive behaviour of the model to generate four feasibility zones (A, B, C, D) for future growth until 2040. We map pathways from IPCC's Sixth Assessment Report (AR6) scenarios and contemporary modelling studies onto the feasibility zones, compare their relative feasibility and quantify the level of policy effort necessary to accelerate growth to align with trajectories compatible with the climate targets.

Results and conclusions

The assessment of the models' forecast performance using hindcasting shows that models parameterised by relatively mature national-level data outperform those parameterised using early global data. The hybrid model outperforms other models and strikes a middle ground between the over-predicting exponential model and under-predicting S-curves. We posit this is because while it captures positive feedback and increasing returns which accelerate technology growth (like the exponential model) and their interaction with countervailing factors and barriers which slow it down (like the S-curves), it also depicts the ability of societies to overcome these barriers through policy commitment and learning.

Projections from the hybrid model capture a diverse set of socio-economic conditions and policies that can be used to set empirically-grounded assumptions for global scenarios, with more optimistic assumptions corresponding to more favorable conditions and faster growth in leading countries and more pessimistic assumptions reflecting worse conditions and slower growth in laggards. In our tests, future technology growth typically falls between the 10-50% weighted quantile projections for the hybrid model.

Our projections estimate the individual shares of solar PV and onshore wind power in global electricity generation will likely be between 8-12% in 2030 and between 13-19% in 2040 (Figure 3.2). This is broadly in-line with IPCC AR6 scenarios consistent with limiting warming below 2°C, and indicates that getting onshore wind and solar PV power on track with Paris-consistent pathways would require considerable policy effort.

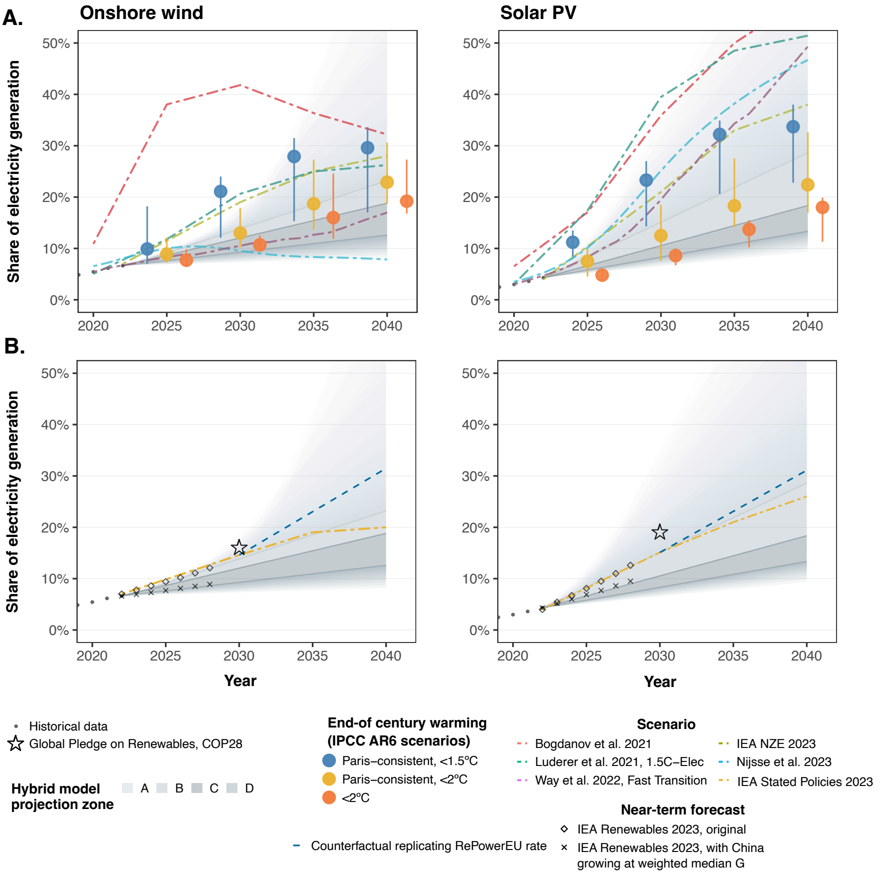

Figure 3.2: Feasibility zones for onshore wind and solar PV deployment until 2030. Black dots show historical data. (A) Coloured dots and vertical lines show the median and IQR deployment in IPCC AR6 Paris-consistent scenarios; coloured dot-dash lines show deployment in contemporary scenarios and projections from the literature. (B) diamonds show 2023-2028 forecasts from the IEA Renewables 2023 report; crosses show an adjusted version of the IEA forecast assuming China grows at the weighted median of our national sample; yellow dot-dash line shows the IEA Stated Policies scenario (SPS); blue dashed line shows a counterfactual scenario replicating growth in the European Unions RePowerEU plan during 2030-2040; stars show the Global Pledge on Renewables for 2030 proposed at COP28.

For instance, meeting the 1.5°C target requires global growth to reach Zone A, which would imply replicating deployment speeds so far observed only in a few leading countries with exceptionally favorable conditions. Such a trajectory would be unprecedented, since historically, the weighted median growth rate observed in individual countries has generally been an upper bound for the maximum global growth rate.

We also show that the IEA's new short-term forecasts assume growth with few historical precedents, and rely on China accelerating deployment to levels seen in Australia, Chile, or Spain for solar PV and similar to Germany or Denmark for onshore wind. The COP28 Global Pledge on Renewables and Energy Efficiency also falls in Zone A for both wind and solar, and would require global deployment to replicate recent trends in Germany or Spain for onshore wind and in Chile, Spain, or Greece for solar PV.

We supplement our analysis based on historical data with a counterfactual scenario assuming a state of global policy urgency, where the world follows currently stated policies until 2030 and subsequently switches to a more ambitious trajectory replicating the growth rates from the European Union's RePowerEU plan. This scenario of worldwide urgency would propel global growth post-2030 into Zone A such that the shares of onshore wind and solar PV in global electricity generation in 2040 reach levels similar to the median for the Paris-consistent <1.5°C scenarios from the IPCC.

3.2 Paper 2

Motivation

The number of countries that have announced pledges to phase-out coal have been steadily increasing [22, 89], with COP28 witnessing calls to "consign coal to history" [132]. However, current phase-out commitments are insufficient to reach the pace and extent of decline required to meet the 1.5°C target [20–22]. Many countries planning to phase-out coal are also facing sharp socio-political opposition from various actors [68, 108, 122–124]. In response, some governments have introduced compensation schemes aimed at mitigating the impact of coal phase-out on parties being negatively affected by it [119, 127–129].

In the short term, these 'just transition' policies may alleviate resistance from powerful incumbents, and facilitate an acceleration of coal phase-out [121, 133, 134]. Over the long term, they can address broader fairness concerns by supporting the recovery of coal-dependent regions, companies, and workers [121, 123, 135]. Germany, for instance, established a commission comprising diverse stakeholders including the coal industries, companies, workers, regional governments and environmental organisations to negotiate a compensation plan, with Canada and Chile also following a similar model [136].

International initiatives such as the EU Just Transition Fund and Just Energy Transition Partnerships (JETPs) have complemented national efforts. While the former offer support to EU member states, the latter are a new mechanism aiming to catalyze phase-out commitments in emerging economies with lower institutional capacities and larger coal sectors [127]. Such partnerships have been agreed with South Africa, Indonesia and Vietnam so far.

While some studies have examined individual just transition policies or conducted comparative case studies [128, 136, 137], the prevalence and structure of such schemes has not been systematically assessed. The impact of compensation policies on coal phase-out also remains unclear. This paper aims to use the unique empirical window proved by these compensation schemes to quantify the economic cost of overcoming socio-political barriers to coal phase-out and accelerating it to levels required to meet the Paris targets.

Research questions and method

To determine which countries are providing compensation for coal phase-out, we created a comprehensive database amalgamating national coal phase-out pledges and compensation policies. This database, compiled through document reviews, web searches, and expert consultations, encompasses explicit phase-out commitments, detailing the amount of compensation in 2020 United States Dollars (USD2020), the type of support offered, and the funding sources. However, it solely includes public finance and does not incorporate phase-out implications from net-zero or other climate targets.

To assess whether compensation serves as a viable metric for measuring the policy effort needed for phase-out, we estimate the avoided emissions for each country with a coal phase-out pledge to quantify the commitment's stringency and scope. We then conducted a multivariable regression analysis to evaluate the relationship between coal phase-out ambition and compensation. This analysis involved a sample of 39 countries and controlled for variables reflecting coal sector characteristics and national contexts.

Furthermore, to determine the financial flows necessary to expand compensation to major coal consumers for a global phase-out consistent with the Paris Agreement temperature targets, we derive coal compensations estimates for China and India, two of the world's largest coal consumers, based on the average compensation per ton of avoided emissions calculated from countries with phase-out pledges and compensation policies. We then benchmark these estimates for China and India against international financial support mechanisms, including Official Development Assistance (ODA) and annual climate finance pledges made at COP15.

Results and conclusions

We find there are 43 countries with specific coal phase-out pledges, and 24 countries with compensation policies. With the exception of South Africa, all countries with compensation policies also plan to phase-out coal by a certain time. Globally, these policies entail planned payouts totaling USD 209 billion (with an uncertainty range of USD 163-258 billion). We find that all countries with large coal fleets (20 GW installed capacity) and relatively ambitious coal phase-out pledges (200 Mt avoided CO2) have compensation policies. The five countries with the most ambitious phase-out pledges and largest coal fleets – South Korea, Poland, Indonesia, Vietnam, and Germany – account for 95% of the planned compensation. About half of all compensation is sourced internationally. While recipient countries in the EU benefit from funds like the EU Just Transition Fund and the Recovery and Resilience Facility, Indonesia, Vietnam, and South Africa receive funding through Just Energy Transition Partnerships (JETPs). Only five countries – Canada, South Korea, the Netherlands, France, and Finland – receive no international funding. In general, annual compensation ranges from 0.001-0.6% of GDP, with domestically-funded compensation never exceeding 0.1% of GDP. These schemes include support for 5 types of measures – regional development to regional authorities, coal power plant and mining closure, renewables and low-carbon infrastructure development, and unemployment support.

The analysis further indicates that the amount of compensation is largely proportional to the ambition of coal phase-out pledges, as evidenced by its consistent and strong correlation with avoided emissions even when controlling for the strength of the coal sector, state capacity, and access to international

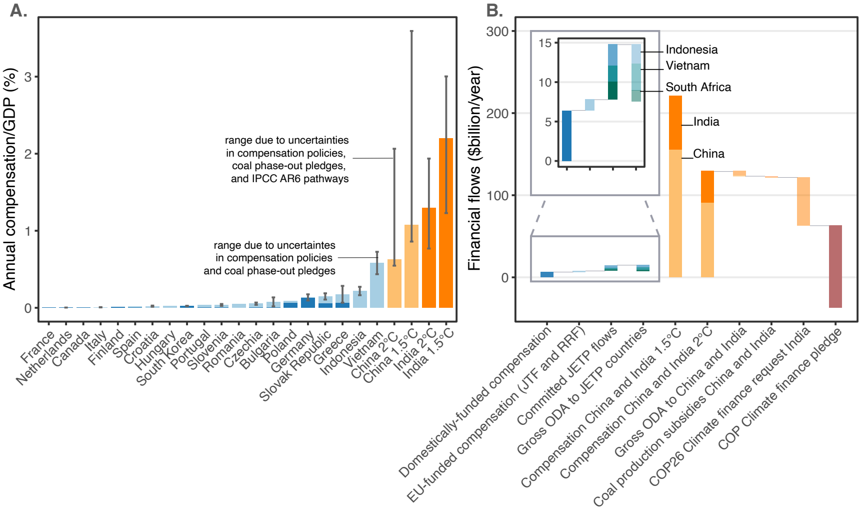

Figure 3.3: (A)Annual compensation as a proportion of GDP; blue bars represent the central estimate for all countries with time-bound coal phase-out pledges and quantifiable compensation (dark blue from domestic funds, light blue from international funds); orange bars show medians of the 1.5°C- and 2°C pathway-based estimates of potential coal phase-out compensation for India and China; vertical bars show uncertainty ranges. (B) Annual compensation for China and India compared to other international financial flows.

funding. The co-efficient for avoided emissions in our best-performing regression models ranges from USD 27-45 per ton of avoided CO2 emissions which is similar to the directly calculated compensation per ton of avoided CO2 emissions (USD 29-46/tCO2). These estimates are well within the range of the carbon price in the EU Emission Trading Scheme (ETS) over the last five years. Moreover, the average compensation per GW of installed coal capacity across all countries is estimated at USD 0.8 billion/GW, which is below the cost of new coal power capacity in Europe.

However, extending similar compensation schemes to major coal consumers like China and India would surpass existing climate finance (Figure 3.3). For China, compensation estimates range from USD 1.2-5.3 trillion under a 1.5°C-compatible pathway and USD 1.1-4.8 trillion under a 2°C-compatible pathway. For India, compensation ranges from USD 0.5-1.6 trillion under a 1.5°C-compatible pathway and USD 0.5-1.3 trillion under a 2°C-compatible pathway. Notably, these figures far exceed existing compensation worldwide and would necessitate substantial increases in international funding to support coal phase-out efforts aligned with the Paris Agreement temperature targets.

CHAPTER 4

Discussion and Outlook

The energy transition entails a massive shift from a system dependent on carbon-intensive sources like coal to low-carbon technologies like wind and solar power [2]. While contemporary IAMs and energy system models are able to outline thousands of possible paths that it could take, it has been challenging to determine which of them are feasible in the real world.

This Licentiate contributes to efforts to bridge the gap between quantitative modelling and an empirical, "outside" view of factors shaping technology growth and decline. It does so by developing methods to: (a) project empirically-grounded feasibility zones for the future growth of solar PV and onshore wind which account for the balance of techno-economic and socio-political mechanisms driving and constraining technological growth (Paper 1), and (b) quantify the cost of overcoming socio-political opposition to coal phase-out (Paper 2).

Paper 1 focuses on constructing feasibility zones for the future growth of low-carbon energy technologies in solar PV and onshore wind. The identification of specific socio-political mechanisms shaping the growth of solar and wind power has proven methodologically challenging as these technologies are still in the early phases of deployment globally. This has also limited efforts to assess the feasibility of their growth in different climate mitigation scenarios or other energy transition pathways. By introducing a new modelling approach centered around a hybrid growth model, we leverage empirical, national-level data to project global technology deployment. This helps us capture real-world outcomes which aggregate all causalities and overcome the challenge of identifying specific causal mechanisms. By using observations from a diverse set of socio-economic conditions and policy environments, we are able to explore a range of more, or less optimistic projections reflecting the growth dynamics observed in countries leading or lagging in deployment. The feasibility zones created in Paper 1 help narrow the uncertainty in contemporary technology growth projections, and offer insights for policymakers about the level of policy effort required to achieve targets. For example, we demonstrate that meeting the 1.5°C is unlikely if the world continues on its current trajectory, but could be achieved in a scenario where the whole world replicates the policy ambition of the European Union's RePowerEU plan.

In Paper 2, we use the unique empirical window offered by government schemes to compensate actors negatively affected by coal phase-out to quantitatively analyse socio-political barriers to phase-out and the monetary cost of overcoming them. Our empirical analysis of compensation policies from countries across four continents shows that policymakers find it necessary to offer compensation in order to accelerate coal phase-out, with more ambitious phase-out pledges inviting larger compensation. This illustrates that coal phase-out driven solely by the logic of techno-economic efficiency might not be enough to meet the climate targets, and that the socio-political barriers not always accounted for in modelling analyses also play a substantial role in dictating the speed of the transition. We demonstrate that political will and social acceptance have a tangible economic component, and thus Paper 2 can serve as a model for how they can be measured and used to inform the real costs of climate policies. Moreover, these estimates of the monetary costs of overcoming socio-political barriers also quantify the level of policy effort that is required to accelerate coal phase-out.

Through these conceptual, methodological, and empirical contributions, this Licentiate also opens up multiple avenues for future research. The methodological advances from Paper 1 open up discussions about the applicability of the hybrid model for investigating the growth of low-carbon energy technologies in large systems such as the European Union, the US, India or China using empirical data. Such analyses could inform assessments of the compatibility of their current trajectories with what is required to meet the global climate targets, and/or their own policy goals. It is also argued that global deployment could accelerate in the future as countries adopting solar and wind later reap the benefits of accumulating global technological learning and deploy them faster [113]. Though we do not find evidence of such an acceleration so far, there is still a possibility that it could happen. This later-faster effect remains at the heart of a vibrant scholarly debate that is as yet unresolved, and ripe for further investigation. It is also possible that new sub-technologies driven by a different set of mechanisms, such as distributed solar, emerge and contribute to faster growth. When it comes to politics and policy, there are open questions about the effects of state policies on renewables growth, and the kind of policies that could accelerate it.

Meanwhile, our findings on the relationship between compensation and coal phase-out in Paper 2 raise questions about the future of compensation as a policy instrument and its diffusion to other countries and contexts. Could compensation schemes also be used to support the phase-out of other carbon-intensive industries, or alleviate public opposition to low-carbon technologies like onshore wind power? There are also open questions about the implementation of these compensation schemes, if they will succeed, how the relationship between compensation and coal-phase out will evolve, and how coal decline or phase-out proceeds in countries that do not opt for compensation policies. Finally, there is also a case for investigating the impact of integrating these compensation costs into scenarios exploring the energy transition.

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