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Simen Rostad Sæther

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A mixed methods study of the power and transportation sector

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Norwegian University of Science and Technology
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Summary

The world's climate goals suggest a rapid energy transition of a kind never before witnessed in history. The current transition is also unprecedented in the sense that much of the climate effort will have to be policy-induced. Until now, many of the climate efforts have only produced incremental change—supplementing, not replacing, the current fossil-based energy system. The uncomfortable truth is that these incremental efforts fall short of the goals set by the Paris Agreement, and what is in fact needed is structural change.

A crucial question, then, becomes which policies policy-makers can pursue that create structural change and that are, at the same time, less likely to be diminished by incumbent vested interests seeking to prolong the current fossil paradigm through extended carbon lock-in and political carbon capture.

The dissertation provides insights on a range of topics within the energy transition. It first looks at which climate policies and mixes of policies have been effective at reducing CO_2 emission intensity in the power sector, before moving on to the transportation sector, where lessons from both electric mobility in Europe and the electrification of the Norwegian ferry sector are studied. Finally, the dissertation delivers some insights on what types of democratic governance styles matter for achieving the energy transition.

The overall findings lend support to a view that market-based instruments have not been particularly effective, especially so in the power sector especially. While these instruments and personal financial incentives have played a role in the transportation sector, they have only so far produced incremental change. Rather, the main findings suggest that technology policy—both aimed at deployment and diffusion of low- and zero technologies and innovation- and technological development policies have been effective. These policies, combined with an active state that supports and facilitates energy transition enabling infrastructure and strategic use of public procurements aimed at transition, are more likely to produce structural change. In this view, these policies of structural change drive down the cost of energy transition technologies and thus create a virtuous cycle of deployment.

When it comes to the questions of democratic governance of the energy transition, the results are less obvious. In much of the literature there is an assumption that egalitarian democracies

are better for the environment than liberal democracies. In this dissertation I however find little difference between egalitarian and liberal democracies on most indicators, whereas on CO_2 intensity, egalitarian democracies clearly perform worse than liberal democracies rather than better. This supports a suspicion that egalitarian democracies struggle with energy transitions, and that structural change may be a bigger problem here. The magnitude of the effects however also suggest that the results are driven as much by consumption as by governance type.

The dissertation argues that technology policies, not market-based policies, have been at the center of the energy transition. While not as cost-effective, the technology support policies introduce energy transition technologies and reduce their cost to a point where they become competitive. In addition to technology costs, structural change in the transportation sector requires transition-enabling infrastructure and is less likely to fully materialize without focusing on both technology policy and infrastructure.

The central conclusion of the dissertation is that policy-makers need to focus on policies that induce and create structural change, where technology policy and a commitment to transition-enabling infrastructure set up more cost-effective policies for success. As these crucial transition technologies mature and their costs go down, the problems besetting market-based policies are slowly diminishing to the point where their adoption becomes more feasible and will have a less drastic effect on the overall economy. In such a scenario, these more cost-effective market-based instruments supplement technology policy, accelerating the structural change needed to reach the world's climate goals.

Sammendrag

Verdens klimamål fordrer en omstilling av verdens energisystem i en skala og hastighet vi aldri før har vært vitne til i historien. Denne omstillingen er også enestående i den forstand at mye av klimainnsatsen må være politisk indusert. Frem til nå har det meste av klimainnsatsen kun produsert inkrementelle endringer—som kompletterer, ikke erstatter, det nåværende fossilbaserte energisystemet. Den ubehagelige sannheten er at disse inkrementelle bidragene kommer til kort for å nå målene som er satt i Parisavtalen, og at det som faktisk er nødvendig er strukturell endring.

Et avgjørende spørsmål blir derfor hvilken politikk beslutningstakere kan gjennomføre for å skape strukturell endring, samtidig som man unngår at særinteresser makter å forlenge det nåværende fossile paradigmet gjennom «karbon lock-in» og innflytelse og kontroll over det politiske systemet.

Denne avhandlingen gir innsikt i en rekke temaer innen energiomstillingen. Den ser først på hvilken klimapolitikk og tiltaksmiks som har vært effektive for å redusere CO_2-utslippsintensiteten i kraftsektoren, før den går videre til transportsektoren, hvor lærdom fra både elektrisk mobilitet i Europa og elektrifisering av den norske ferjesektoren studeres. Til slutt gir avhandlingen innblikk i hvorvidt ulike typer demokratiske styringsformer har noe å si for å oppnå en rask energiomstilling.

Avhandlingens overordnede funn gir støtte til et syn om at markedsbaserte instrumenter ikke har vært spesielt effektive, i kraftsektoren spesielt. Selv om disse instrumentene, inkludert personlige økonomiske insentiver, har spilt en rolle i transportsektoren, har de så langt stort sett bare produsert inkrementelle endringer. Hovedfunnene tyder heller på at teknologipolitikk—både rettet mot distribusjon og spredning av lav- og nullutslippsteknologi og politikk som støtter innovasjon og teknologisk utvikling har vært mer effektiv. Disse politiske tiltakene, kombinert med en aktiv stat som støtter og fasiliteter omstillings-muliggjørende infrastruktur og strategisk bruk av offentlige anskaffelser rettet mot omstilling, gjør det mer sannsynlig å produsere strukturell endring. Rasjonalet bak disse politiske tiltakene for strukturell endring, er at kostnadene for energiomstillingsteknologier går ned og dermed skaper en positiv utbyggingssyklus.

Når det gjelder spørsmålene om demokratisk styring av energiomstillingen, er resultatene mindre åpenbare. I mye av litteraturen er det en antagelse om at egalitære demokratier er bedre for miljøet enn liberale demokratier. I denne avhandlingen finner jeg imidlertid liten forskjell mellom egalitære og liberale demokratier på de fleste indikatorene, mens egalitære demokratier klarer seg klart dårligere enn liberale demokratier, snarere enn bedre for CO_2-intensitet. Dette støtter en mistanke om at egalitære demokratier sliter med energiomstilling, og at strukturell endring kan være et større problem her. Omfanget av effektene tyder imidlertid også på at resultatene drives like mye av forbruk som av styringstype.

Avhandlingen argumenterer for at det er teknologipolitikk, ikke markedsbasert politikk, som har stått i sentrum av energiomstillingen hittil. Til tross for at de ikke er like kostnads-effektive, introduserer og støtter teknologipolitikk energiomstillingsteknologier i markedet og bidrar dermed til å redusere kostnadene på disse til et punkt der de blir konkurransedyktige. I tillegg til reduserte teknologikostnader krever strukturell endring i transportsektoren også infrastruktur som muliggjør en omstilling. Derfor vil sjelden en full omstilling i transportsektoren materialisere seg uten at det fokuseres både på teknologipolitikk og infrastruktur. Den sentrale konklusjonen i avhandlingen er dermed at beslutningstakere må fokusere på politikk som induserer og skaper strukturell endring, der teknologipolitikk og et engasjement for omstillingsmuliggjørende infrastruktur på sikt gjør at mer kostnadseffektive tiltak kan lykkes.

Etter hvert som viktige omstillingsteknologier modnes og kostnadene går ned, reduseres problemene som ofte plager markedsbaserte tiltak, inntil de når et punkt hvor adopsjonen av disse blir mer gjennomførbar og vil ha en mindre drastisk effekt på den samlede økonomien. I et slikt scenario supplerer disse mer kostnadseffektive markedsbaserte instrumentene teknologipolitikken, noe som akselererer de strukturelle endringene som trengs for å nå verdens klimamål.

Foreword

I owe the greatest debt of gratitude to my supervisor, and friend, Espen Moe for steadfast support and guidance over the years, I could not have done this without your belief in me. I continuously learn and make sense of complex societal issues with the analytical toolbox you have taught me. I hopefully look forward to our continued collaboration. I would also like to extend my gratitude to my co-supervisors over the years, Thomas Halvorsen and May Thorseth, and although, not a formalized co-supervisor, Indra de Soysa, for all your high-quality feedback over the years.

I also had the pleasure to work with the ECHOES project-team, which taught me a lot and gave me many joyful moments. I would also like to mention Jo-Kristian Stræte Røttereng, I truly value our friendship and discussions on all kinds of topics. I would also like to extend thanks and gratitude to my fellow PhD candidates, many of whom I consider close friends, Marianne Skaar, Lisbeth Elvira Levang Løvik, Lisa Reutter, Martin Nesse and Thea Johansen making long days bearable and enjoyable. Finally, a big thanks to all members of the Energy, Environment and Sustainable Development research group for valuable input during the years, and last but not least the ISS administration, and Oddrun Strand in particular, which makes PhD life as smooth as possible.

To friends and family outside work, I extend my deepest gratitude for all encouragement and support over the years, it has kept me going. A special heartfelt thanks to my closest family and especially my mother, May, for your tireless commitment to me and showing me the value of curiosity, dedication, and making the best out of what we are given, you are my biggest role model.

And lastly, my dearest Elena, you came into my life at a crucial moment, and despite a global pandemic and an extended and tiresome run-in of the PhD, we stuck together through everything. I am forever grateful for your endless support and willingness to sacrifice for me to keep me upright. Now I look forward to new adventures with you!

Simen Rostad Sæther 06.08.2021

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1. Introduction

Reaching the world's climate goals requires an energy transition of a rapidity never witnessed before in history. The current transition is also unprecedented in the sense that much of the climate effort is policy-induced (Grubb et al., 2021; Patt, 2015). Until now, climate effort has, in general, produced only incremental change, supplementing, not replacing, the current fossil-based energy system. The uncomfortable truth is that these incremental efforts fall short of the goals set by the Paris Agreement (UNFCCC, 2015). What is in fact instead needed is structural change.

Thus policy-makers must pursue policies that create structural change. This is made difficult by—amongst other factors—the prevalence of major vested interests in the energy and transportation sector—actors that constitute the biggest industrial giants the planet has ever seen, and who have a stake in the perpetuation of the existing fossil-based system (e.g. Olson, 1982; Moe, 2015; Unruh, 2000).

This dissertation is thus an inquiry into some comprehensive and pressing questions surrounding the politics of the energy transition. It delves into critical questions around the effects of climate policies, and which policies and support systems policy-makers can pursue to create structural change and thus politically accelerate the transition in the power and transportation sector. Finally, the dissertation looks at the question of governance in the energy transitions, by investigating if and how different democratic governance styles matter in the energy transition.

The 2015 Paris climate agreement states that nations worldwide are committed to cut their emissions and stay in line with the 2 °C target, but to strive for 1.5 °C (UNFCCC, 2015). Our current trajectory, however, is seeing us heading toward 3 °C above preindustrial levels. This means adverse consequences such as more extreme weather events like heatwaves, droughts, and flooding and a further worsening of unequal impacts related to water scarcity and food insecurity. There is also an increasing risk of crossing the tipping point that could further accelerate global heating (Pachauri et al., 2014; O'Neill et al., 2017). Rüdiger & Voldsgaard (2021) warn that "if policy-makers, civil servants, economists, and civic actors hold too static and pessimistic a view of the potential for economic restructuring, the global political response to the challenges may be stalled. Rather, the opportunities for induced innovation to lower costs give us reason for accelerating the transition with optimism" (Rüdiger & Voldsgaard, 2021 p.2). Their warning could be seen as an important call to action akin to the recent 2018 IPCC special report on 1.5 °C which lays out an even more challenging reduction pathway for global emissions, asserting that emissions must decrease by 45% by 2030 using a 2010 baseline and reach net zero around 2050 (IPCC, 2018).

In fact, the dynamics of climate change are complex, yet grounded in well-understood physics and chemistry. Moreover, while some parts of the climate system are still not fully understood[1], their main components are. The effect of greenhouse gases is one of them. A greenhouse gas (GHG) is any gaseous compound in the atmosphere capable of absorbing infrared radiation, thereby trapping and holding heat in the atmosphere. Their relative share in the atmosphere ranks the greenhouse gases—water, or more specifically, water vapor (H_2O), then the greenhouse gas that gets the most attention; carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and chlorofluorocarbons (CFCs). After the ratification of the Montreal Protocol, we have seen these chlorofluorocarbons be replaced by hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)[2] (Ehhalt et al., 2001; EPA, 2021; Lallanilla, 2019). Scientists measure the impact of greenhouse gases by observing their relative global warming potential (GWP) over 100 years. The various greenhouse gases can then be measured by their estimated GWP and thus be compared, providing useful information about their relative impact on the climate. To ensure comparability and standardization across measurements and models, UNEP and the IPCC have agreed on the generic term "CO_2 equivalents" (CO_2e) which now constitutes the most commonly used measurement of greenhouse gas emissions (Hansen et al., 2005)

As the natural sciences have provided—and continue to provide—ample evidence for the problem, its mechanism, and feedback loops, the technologists have recommended many new (and old) solutions that will help solve it. However, it has now fallen partly on the social sciences and the humanities to come up with social and political solutions to the problem.

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[1] For instance, the effect of clouds on the overall climatic system. But the science and understanding is progressing quickly, see for example Mülmenstädt et al., 2021.

[2] In addition to greenhouse gases, climate scientists also account for and observe the effect of short-lived climate pollutants (SLCP). Not all of them are gases, but a common feature of them is that they are short-lived in the atmosphere compared with some of the greenhouse gases, which can stay in the atmosphere for decades or even a century (Bowerman et al, 2013; Pierrehumbert, 2014).

The near-hegemonic influence of neoclassical economics in mainstream climate policy debates has resulted so far in an increased focus on, and advocacy for, pricing carbon through carbon taxes and emissions-trading schemes, and the less politically contested issue of increased spending on research and development (R&D) (see for instance: Nordhaus, 1993; Stern et al., 2006; Nordhaus, 2007; Bowen, 2011; World Bank, 2019; OECD, 2021; IMF/OECD, 2021). Against this view, evolutionary and institutional economics look closer at the role of the state and its ability to promote and facilitate growth and deal with complex societal issues such as climate change through targeted innovation and industrial policy (e.g., Mazzucato, 2013; Patt, 2015; Moe, 2015; Cullenward & Victor, 2020; Rüdiger & Voldsgaard, 2021; Sæther & Moe, 2021). Cherif & Hasanov (2019) and Andreoni & Chang (2019) also find that some of the insights from these approaches have been entertained and adopted by economists to an increasing extent over the last decade, thus challenging some of the most ardent defenses of a purely neoclassical market-based approach to the challenge of dealing with man-made climate change (see for instance: Sandén & Azar, 2005; Rodrik, 2014). For instance, research by the economist Daron Acemoglu highlights the importance of early (temporary) subsidies and support for cleaner technologies and warns of the dangers of an overreliance on, and excessive use of, carbon taxes (Acemoglu et al., 2012; Acemoglu et al., 2016).

As the science of climate change is less ambiguous than ever, rapid technological development and innovation, especially in three core technologies—solar PV, wind, and batteries—has seen the energy transition toward cleaner technologies become all but inevitable. So the question is no longer if the world is transitioning but rather how fast. Despite the undeniable progress that has been made on many fronts, the scientific community and climate and energy experts show us that the transition is not proceeding quickly enough. The vast transitions literature expands on the dynamics of transitions, historical transitions the world has been through, and what we might learn from past transitions to understand and act on the current one.

Thus what is sorely needed is research on politically accelerated transitions. The strength of political science in studying these transitions, is the field's emphasis on the political dynamics of the energy transition. Such a focus is obvious for two reasons. Firstly, the political economy is real and energy transitions involve extremely arduous and difficult political processes where easy solutions are hard to come by. And secondly, we clearly do not live in an optimal, first-best world; in fact, there is reason to believe we do not even live in a second, or even third best world, which in sum means that you have trade-offs between solutions which cannot, by definition, be perfect or optimal. Vested interests and their political influence matter, especially if these actors are threatened by a transition that will reduce and eventually erode that influence. Thus, as we shall see, the energy transition will consist of plenty of (theoretical) contradictions and an ingrained messiness that is not easily modeled and projected. The paradigm and narrative of incremental, cost-effective adjustment to change simply does not adequately account for the very real forces of political economy, vested interests, and human behavior that we see dictating the progress of the energy transition.

The dissertation thus takes on the topics of the climate and energy related politics and policies of the energy transition in the power sector and transportation sector. The first article tackles the question of the effects of various climate policy choices on CO_2 intensity in the OECD and BRICS power sector. The second article looks at the effect of electric mobility policies and charging infrastructure on the share of plug-in electric vehicles in Europe. The third article is co-authored with Professor Espen Moe and analyzes the politically accelerated transition of the electrification of Norwegian ferries. The last topic, which constitutes the smallest part of the dissertation, revolves around questions of governance. The interest for this topic arrived slowly and by lucky coincidence through collaboration with my supervisors, Professor Espen Moe, and Professor Indra de Soysa at NTNU. In fruitful discussions over my Ph.D. period, we decided to collaborate on the article, which is the fourth and final one in this dissertation.

With this backdrop, in sum, the dissertation adds to the literature on politics, policies, and governance of electrification and energy transitions in the power and transportation sector and contributes to the transition literature and the academic debate around incremental versus structural change.

1.1 Personal motivations for the research focus

From a broad perspective, this dissertation analyzes various aspects of the current energy transition. During the Ph.D. project specifically, and also as a result of my involvement in the

Horizon2020 project ECHOES[3], I have developed keen research interests in a multitude of related areas and sought to study and answer some of the most pressing questions surrounding the speed and feasibility, and the drivers and barriers, of the energy transition.

From the outset, I wanted to investigate the empirical effect of climate policies on emission reduction, focusing primarily on the power sector. The strongly held confidence in silver bullet market-based solutions always seemed too simplistic and reminiscent of a world that only exists inside stylized models. As a political scientist, I have learnt that the world—and especially the political world—is chaotic, riddled with vested interests and power games, (both on the national and the international level) and in international politics and collaborations even more so. In other words, we simply do not live in a world where it is very feasible to get optimal solutions. The political economy is too complex, and while putting the 'right' incentives in place is a noble and worthy effort, history shows us that it probably should not be our main path forward. I therefore willingly admit I am puzzled whenever prominent individuals preaches a global carbon tax as a panacea for solving climate change. ETH Zürich professor and contributing lead author in IPCC Fifth assessment report, Anthony Patt in his 2015 book *Transforming Energy: Solving Climate Change with Technology Policy* was indeed an eye-opener in this regard. Patt suggests that a single-minded pursuit of market-based instruments is a very narrow path that has so far dealt with the climate problem incrementally, flickering and tinkering at the margins, leading us toward lower emissions, but at a pace that will never be anywhere near fast enough and with no guarantee that we will get there in the end. They take us on a path of incremental change. What, however, became ever clearer to me during my work was that what is needed is structural change.

Finding an operational definition of structural change is difficult. The term structural [economic] change is central to evolutionary economics—a branch of economics, coined by Veblen (1898)—which focuses on shocks, disequilibria, and technological change; hence the focus is on what creates qualitative changes within the economy, the energy or transportation system or the political system and its institutions. To evolutionary economists, "Technological progress is not a neutral process of gradual accumulation of incrementally more efficient technologies" (Moe, 2007 p.13). Where neoclassical economic theories have essentially treated all technologies the same, as a simple input that enables us to produce at a

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[3] https://echoes-project.eu/

lower cost, i.e., improved productivity, the evolutionary economists contend that in addition to improved productivity;

> “some innovations are particularly important as they have the potential to transform the economy. Radical innovations disrupt existing economic structures and force new institutional setups and routines on the economy. They give rise to new growth industries and destroy old ones” (Nelson, 1995 p.76; Freeman & Soete, 1999 p.329; Verspagen, 2001 p.5, in Moe, 2007 p.13).

In *Capitalism, Socialism and Democracy*, one of the most saluted advocates of this line of reasoning, Joseph Schumpeter, writes that the:

> “process of industrial mutation—if I may use a biological term—that incessantly revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one. This process of Creative Destruction is the essential fact about capitalism.” (Schumpeter, 1942 p.83).

Thus, for Schumpeter it is structural economic change that is the driver of the political economy. Transferring this to the study and understanding of energy transitions thus implies looking at economics, technology, and institutions as part of the same framework. A country needs institutions that are both compatible with and supportive of new growth technologies in order to be able to make the most out of them. By extension, institutions built around and suited for an earlier technological paradigm may indeed be entirely inappropriate for a new paradigm, whether paradigms of industry or of energy (Freeman & Perez, 1988; Nelson, 1995; Gilpin, 1996; Moe, 2007; Patt, 2015; Moe, 2015).

Drawing on Schumpeter, the endpoint of a structural change in the energy system would be a new energy system where not only renewable energy has been phased in, but where fossil fuels are for all practical purposes phased out and not allowed to thrive and co-exist next to renewables. For the transportation sector, the endpoint would be a close to zero-emission transport system. Setting hard criteria for when these systems are characterized by structural change rather than incremental change is difficult, thus, rather than formulating an exact criterion, my guideline has been the following rather looser criteria, which I follow in this dissertation: We observe structural change when we see that renewable energy is replacing fossil fuels, rather than supplementing it, and that electric vehicles and other low- and zero emission vehicles replace vehicles with an internal combustion engine, rather than both growing at slightly different speeds. This also means that to some extent it is a bit of a judgment call whether or not the energy system is undergoing structural or merely incremental change.

Thus, a question that has worked as a guiding light in my project is whether or not the climate and energy policies governments enact lead to structural or incremental change. This was something that emerged from discussions with colleagues, interactions with the literature, and by thinking more deeply about what, in fact, my empirical results actually meant. Hence, incremental vs. structural change slowly emerged as a theoretical overlay and framework to give more meaning to the discussion of climate policy choices.

1.2 A project with four independent contributions to the literature

While in the dissertation's first chapter I showcase a thorough and expanded literature review and central research questions, the subsequent four chapters represent four independent scientific research articles, respectively. All the articles cover topics related to the energy transition, and the first two articles focus on the two largest sectors to decarbonize, namely the power and the transportation sectors. The third article continues to look at the transportation sector, but at a very specific transition, the electrification of Norwegian ferries. The final topic of the dissertation, represented by the fourth and final article, concerns the topic of governance in the energy transition. Below follows a brief summary of the four independent articles, while in Chapter 4 I present a longer summary of each article and its place in the overall dissertation. Table 1 shows the overview and current publication status as per August 2021.

The first article investigates the empirical effects of various climate policy choices on OECD and BRICS power sector CO_2 emission intensity. It provides important insights into the debates around market-based policies and deployment and innovation- and development support policies in the energy sector. The main finding suggests that despite its strong theoretical foundation, the market-based instrument investigated—the emissions trading system—does not appear to have been particularly effective at reducing CO_2 emission intensity in the power sector. Although not as cost-effective, deployment and innovation- and development support policies have significantly contributed to CO_2 intensity reduction.

The second article moves us from the power sector to the transportation sector and is a study of the effects of electric mobility policies and infrastructural developments on the market share of plug-in electric vehicles (PEV) in Europe. The study's main finding is that, while there is evidence for the positive effect of personal financial PEV incentives, the results strongly suggest that charging infrastructure in general increases the PEV market share and that fast-charging infrastructure, in particular, is a key enabler for higher PEV market shares. The study provides evidence for a transition view that conceptualizes the state's key role as coordinator and facilitator of enabling infrastructure for the energy transition, leading to structural rather than incremental change.

The third article is a study of the electrification of ferries in Norway as a case of a politically accelerated transition. Accelerated transitions are sorely understudied, as is the electrification of the maritime sector. We propose four main explanatory factors: First, what we label "the Norwegian ferry innovation system" was instrumental in providing an environment conducive to electrification. Second, the Norwegian state acted entrepreneurially, by moving beyond merely being a de-risker through playing an active role in market creation and transformation by means of public agencies and support schemes. Third and fourth, we argue that the relative lack of strong opposing vested interests, combined with an oil shock, worked to create favorable conditions for structural change. While our findings are undoubtedly partially case-specific—there are good reasons for why Norway would be expected to be a frontrunner in precisely this area—we believe that the case holds important lessons in terms of the interaction between the public and the private sector and ultimately in terms of how transitions—even in hard-to-decarbonize sectors—can be politically accelerated.

The fourth and final article takes us from studies of energy transition processes in different sectors to the question of the more general governance of energy transitions. While data is limited to 46 developed and developing countries, with the added caveat that we are still at an early stage of the renewable energy transition, what we were interested in was if it was possible to detect whether different democratic styles of governance make a difference to the speed at which countries are transitioning. Although the existing literature is far from conclusive, it is often argued that more egalitarian democracies are expected to better in general at building broader consensus around important issues (e.g. Christoff & Eckersley, 2011; Rothstein, 2005; Wilkinson & Pickett, 2009). However, we argue that there are theoretical reasons to believe that with respect to actually implementing climate policies and engaging in energy transitions, these advantages do not necessarily apply. Thus, this paper was in part triggered by skepticism toward parts of the established literature that assert that egalitarian democracies are better at pursuing environmentally friendly policies and partly prompted by a theoretically founded suspicion that egalitarian democracies may, in fact, have a distinctly hard time with processes of structural change. To explore this empirically, we used the Varieties of Democracy (V-Dem) framework to investigate the effect of egalitarian and liberal democratic governance styles on renewable energy production share, public environmentally related R&D expenditure and CO_2 intensity in 46 OECD, BRICS and European countries from 1990-2018. Our main findings suggest that while there is no major difference between egalitarian and liberal democracies when it comes research funding or the share of renewables in the power mix, egalitarian democracies actually perform worse than liberal democracies with respect to CO_2 intensity. Thus, the suspicion that egalitarian democracies struggle with energy transitions is supported by the data. Structural change may indeed be a bigger problem here. The magnitude of the effects however also suggest that the results are driven as much by consumption as by governance type, and that the greater opportunities for broad-based consumption in egalitarian democracies may be what leads them in the direction of higher CO_2 emissions.

1.3 Author declaration

In the first two articles of the dissertation, *Climate policy choices: An empirical study of the effects on the OECD and BRICS power sector emission intensity* and *Mobility at a crossroads —electric mobility policy and charging infrastructure lessons from across Europe*, I am the single author.

The dissertation's third article, *A green maritime shift: Lessons from the electrification of ferries in Norway*, is co-authored with Professor Espen Moe. While I, Simen Rostad Sæther, did most of the interviewing and attended most of the conferences and workshops, we both contributed to the conceptualization and formal analysis as well as the writing, reviewing and editing the manuscript.

The dissertation's fourth article, *Do Democratic Governance styles matter in the Energy Transition? An empirical inquiry into 46 developed and developing countries from 1990 to 2018*, is co-authored with Professors Indra de Soysa and Espen Moe. Here, I, Simen Rostad Sæther, was responsible for the gathering of the data for the quantitative analysis as well as conceptualization and operationalization. Espen Moe's main contribution has been within the area of conceptualization, theory, and literature, while Indra de Soysa has done most of the quantitative analysis. We have all contributed to the writing and editing of the article.

Table 1. Overview of articles in the dissertation and current publication status - August 2021.

Title	**Main theme**	**Empirical scope**	**Theoretical focus**	**Method**	**Publication status August 2021**
Climate policy choices: An empirical study of the effects on the OECD and BRICS power sector emission intensity	Analysis of the effect of climate policy choices on OECD and BRICS power sector emissions	OECD and BRICS countries (2000-2018)	Energy transitions, power sector, climate policy, CO_2 intensity	Quantitative, fixed effects regression techniques	Published in *Economic Analysis and Policy, 71,* (2021): 499-515.
Mobility at a crossroads —electric mobility policy and charging infrastructure lessons from across Europe	Analysis of the effect of electric mobility policies and charging infrastructure on share of plug-in electric vehicle sales in 30 European countries.	30 European countries (2009-2019)	Energy transitions, electric mobility, infrastructure, incentives, structural vs incremental change	Quantitative, fixed effects regression techniques	Revise and resubmit in *Transportation Research Part A: Policy and Practice* Revision re-submitted to journal
A green maritime shift: Lessons from the electrification of ferries in Norway	The electrification of the Norwegian ferry sector as an example of an accelerated transition in the maritime sector	Case study of the electrification of Norwegian ferries	Energy transitions, accelerated transitions, vested interests, structural vs incremental change, shocks	Qualitative, semi-structured expert interviews and workshops	Accepted for publication with minor revisions in *Energy Research & Social Science*. Co-authored with Professor Espen Moe

Do Democratic Governance styles matter in the Energy Transition? An empirical inquiry into 46 developed and developing counties from 1990-2018	Analysis of the effect of democratic governance styles on renewable energy generation, environmental R&D and CO$_2$ Emission intensity	OECD and BRICS and seven European countries (1990-2018)	Energy transitions, governance, democratic styles	Quantitative, fixed effects regression techniques	Under review in *Energy Policy*. Co-authored with Professors Indra de Soysa and Espen Moe

2. Theoretical framework and literature review

In the following I will clarify the dissertation's theoretical framework and the literatures that I have engaged the most actively with. First and foremost, I have engaged extensively with two main bulks of literature. First, the literature on large-scale transitions more broadly, of which energy transitions—including the present energy transition—is a subcategory (e.g. Smil, 2010; 2018; Moe, 2010); covering topics on structural vs incremental change (e.g. Nelson & Winter, 1982; Freeman & Perez, 1988; Freeman & Louçã, 2001; Schumpeter, 1942; 1983 [1934]), transition dynamics and speed (e.g. Sovacool, 2016; Schmitz, 2016), technological change (e.g. Mokyr, 1992; Schumpeter, 1997 [1949]; Perez, 2003; Moe, 2007), and the role and impact of vested interest (e.g. Gilpin, 1996; Olson 1982; Moe, 2015; Mildenberger, 2020; Stokes, 2020) and the role of the state (e.g. De Long, 2000; Moe, 2007, Mazzucato, 2013; Patt, 2015). Secondly, the literature on the effects of climate policy, where the debate between market-based instruments and policy-induced development and deployment-supporting policies are most effective is central. Finally, I engage with literature that suggest a more balanced and practical approach to climate policy, namely a focus on policy mixes.

Cherp et al. (2018) suggests that there are three main perspectives for understanding energy transitions: First, the techno-economic perspective, drawing on theories from the Earth sciences (for instance hydrology, geology, climatology), engineering, and economics. "Within the techno-economic perspective, the concept of supply-demand balance is often used in conjunction with the neoclassical economic idea of market equilibrium" (Cherp et al., 2018 p.179). Second, the socio-technical perspective with its focus on technological change and the emergence and diffusion of new technologies studied by a range of disciplines including evolutionary economics, sociology of technology, and science and technology studies (STS). There is a vast literature on energy transitions based on socio-technical perspectives, such as the multi-level perspective (MLP) and technological innovation systems (TIS) studies (e.g. Geels, 2002; 2004; 2005; Geels & Kemp, 2007; Geels & Schot, 2007; Genus & Coles, 2008; Grin, Rotmans & Schot, 2010; Markard, Raven & Truffer, 2012; Geels et al., 2016). Third, and lastly, the political perspective, where the central focus is on change in policies which affect energy systems. Because most climate and energy policies are adopted and implemented by governments acting on behalf of nation states, the state is the main unit of analysis in the political perspective.

> "This neglect of the political perspective may at least in part be explained by the fact that scholars of historical energy transitions disagree on the significance of deliberate government interventions in the past evolution of energy systems, though there is a general consensus that such interventions may play a larger role in the future energy transitions driven by climate concerns and other normative social goals" (Fouquet & Peason, 2012 in Cherp et al., 2018 p.184).

Following this, although I engage heavily with and draw from both the techno-economic and the socio-technical perspectives, the dissertation is first and foremost firmly planted in the political perspective with the state as the level of analysis and most important actor.

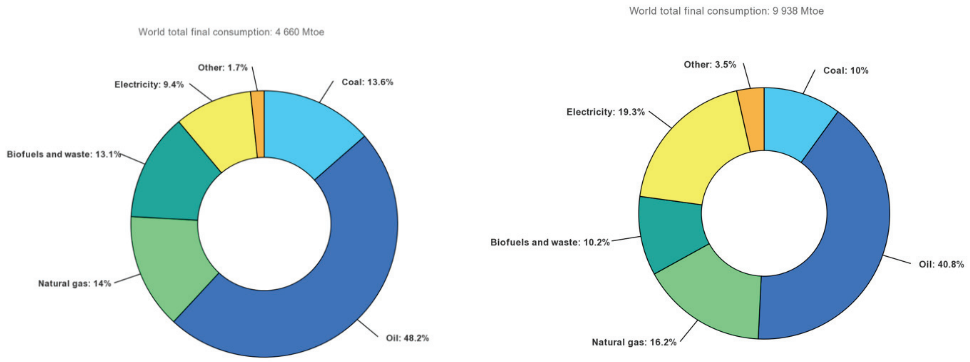
2.1 A brief history of energy transitions

Ever since humans started harnessing fire, our existence has revolved around exploiting and making use of energy for our own purposes. From fire to wood, from wood to coal, and from coal to oil and gas, and now, from coal, oil, and gas to the promise of renewable sources like solar and wind. Vaclav Smil starts his book *Energy and Civilization: A History* with the following: "Energy is the only universal currency: one of its many forms must be transformed to get anything done" (Smil, 2017 p.1). Such has been the quest of human societies from prehistoric times until now; populations grow in tandem, closely linked to the amount of energy and production society yields and thereby their ability to feed. The marked shift from wood to coal signaled the first great energy transition in modern societies, and while charcoal was somewhat utilized alongside fuelwood for at least 1,000 years BCE, the first notable use of coal can be found around 400 CE but it didn't, in fact, overtake fuelwood for another 1300-1400 years, as coal surpassed 50 percent of primary energy consumption only in the 17th century.

The early Industrial Revolution was powered by what can easily be thought of as small technological revolutions in otherwise familiar technologies like waterwheels. Without the major improvements in waterpower and the active diffusion of the technology throughout Britain, any industrial revolution would have been seriously delayed. The next energy transition was that of coal, which slowly started to percolate into the energy mix in Britain by the early 1800s, and which became crucial to the continuation and acceleration of the Industrial Revolution. Britain was clearly ahead of most other Western nations. In their main rival, France, coal did not surpass water and wind until after the 1850s. Coal also produced a transportation revolution, being inextricably linked with steam power and the growth of the railways. At the end of the 19th century, electricity—and as a result the electricity industry (as well as electro-chemicals)—initiated another energy transition and a different kind of industrial revolution. Electrical power could easily be transmitted via power lines over distances, thus enabling massive economics of scale as machinery no longer needed to be in close proximity to a prime mover. While oil had been extracted since the second half of the 19th century in both Baku and Texas, it was not really until the first few decades of the 20th century that oil really became the new driver of the world economy. Like coal, oil also led to a transportation revolution. The car, with its promise of freedom of movement, transformed societies. Inevitably, the oil industry and the car industry grew in tandem, and still to this day constitute some of the biggest and most influential companies on the planet. Beyond cars, the British navy realized even before World War I that warships fueled by oil had a far greater range and thus much reduced vulnerability than ships fueled by coal. And of course, without oil, the most revolutionary means of transport, the airplane, would realistically never have happened. Nuclear energy was the energy transition that was never fulfilled. In the post-war era, for many decades, nuclear energy was the new miracle fuel that was pointing to the future. However, several high-profile nuclear accidents ultimately made sure that, to this day, this remains a stillborn transition. Which is a sobering thought with respect to renewable energy as well. Despite the attempts at politically accelerating this transition to an extent that none of the previous transitions ever experienced, there is no guarantee that the renewable energy transition will be completed, or that it will happen fast enough. As will be described more in detail later in this dissertation, compared to previous energy transitions the present transition faces the additional difficulty of having to accomplish not just the phase-in of renewable energy, but also the explicit phase-out of fossil fuels (Smil, 2005; 2010; 2017; 2018; Moe, 2010; Brown, 2015; Mokyr, 2018). A more thorough and detailed review of the major energy transitions since 1750 and the politics underpinning them, can be found in Moe (2010).

Figure 1 with IEA data from 1973 to 2018 shows that despite massive efforts to accelerate the renewable energy transition, the total share of fossil fuels in final energy consumption is still dominant. With the world's final energy consumption more than doubling from 1973 to 2018, the share of fossil fuels remains paramount. The share of electricity is growing, but there is still a significant share of fossil fuels in the world's electricity mix. In early 2021, low-carbon sources (wind, solar, nuclear hydropower, and other renewables) accounted for 39.5% of the world's electricity generation, a share that surpassed coal generation in late 2019 (IEA, 2020c).

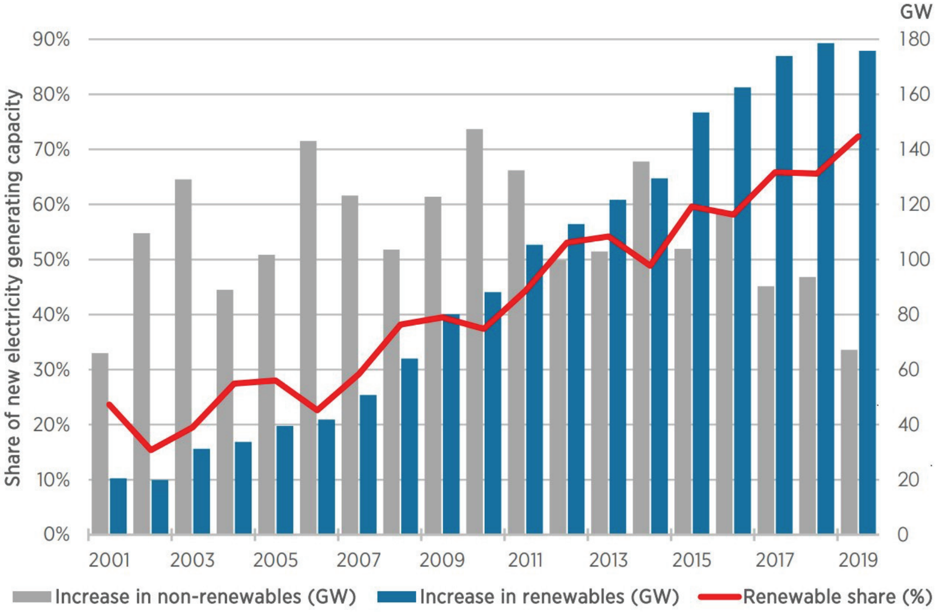
Figure 1. World total final consumption by source, in 1973 and 2018.



Source: IEA (2020a; 2020b)

Figure 2 shows that renewable energy has dominated new capacity (IRENA, 2021). However, despite its massive uptake, it is still barely replacing increases in new demand for energy (REN21, 2020), indicating the massive challenge ahead. York & Bell (2019) suggest a transition away from fossil fuels requires a lot more than growth in renewable energy, and that a narrow focus on the growth of renewables might more accurately be labeled "energy additions" rather than an energy transition.

Figure 2. Renewable share of annual global power capacity expansion, 2001-2019.



Source: IRENA (2021)

Luckily, electrification usually entails massive energy efficiency gains (see for instance extended review in Article 2), as fossil fuels, despite being energy-dense, undergo significant heat waste in their energy conversion (about 2/3rds of the energy is lost) (IEA, 2018; LLNL, 2020). For instance, a parallel process of electrification of transportation and decarbonization of electricity yields massive cuts in both emissions and fossil fuel consumption (e.g. IEA, 2020d). Thus, despite some promising trends and characteristics of the renewable energy transition, the history of past energy transitions tells us that they tend to be considerably slower and messier than anticipated. Moe (2010) shows us that they also had obvious political components. There are clear-cut examples of countries that pursued policies that definitely delayed previous transitions, (although it may be more difficult to say exactly what the countries who were successful did correctly in political terms), but past transitions were never actively accelerated by policies for a purpose other than energy for energy's sake. Thus, success today requires that we are able, by political means, to cut down the time the current transition takes—in other words to politically accelerate the transition. Hence, in the following, I will review some of the main themes of the literature on energy transitions.

2.2 The energy transition literature

Climate change could very well be the defining challenge of our time, and at the center of both the problem and the solution, is energy. An unprecedentedly rapid energy transition from predominantly fossil fuels to renewable sources is needed to avoid catastrophic climate change. Moe (2020) defines energy transitions as fundamental, long-term, structural changes in the energy system, which is the definition I rely on in this dissertation. Smil (2010) however asserts that the historical energy transitions have been slow, taking many decades to fully materialize, in fact sometimes centuries (Grubler, 2012; Fouquet, 2016). Given the psychological and slowly building political external force of a changing climate, the impetus is for the current renewable energy transition to accelerate unlike any other transition in history. Smil (2010) warns us that the more profound the current paradigm, the longer a substitution will take. Considering the fossil fuel dependent world that we currently live in, the task is daunting.

In Schumpeter's famous 1939 work *Business Cycles*, he outlines his theory about the occurrence of long waves, or business cycles, of economic growth, which are driven by technological breakthroughs, thus establishing the impact of major and radical technological breakthroughs in economies at the center of Schumpeterian theory (Verspagen, 2004). The starting point of the Schumpeterian wave is the occurrence of one or more interrelated basic or radical innovations that provide an opportunity for increasing growth rates. This results in an upward swing of a new long wave or business cycle. These basic innovations are introduced by a distinct class of businessmen Schumpeter called entrepreneurs. In his view, the entrepreneur was an especially visionary businessman, who was able to recognize the commercial opportunities long before any other ordinary businessmen or consumers even dreamt of the new possibilities the basic innovation would open up (Schumpeter, 1939; Verspagen, 2004). Schumpeter's subsequent foray (1942; 1983 [1934]) into what is now often called evolutionary economics and his "waves of creative destruction", combined with Mancur Olson's (1982) focus on vested interests, provides a powerful theoretical framework for understanding structural change.

Industries rise by providing new and revolutionary solutions, and they fall because these same solutions eventually become technologically commonplace and obsolescent. Hence, there is a steady rise and fall of industries linked to technological progress. Indeed Mokyr (1992) and Moe (2007b) show us that this has happened repeatedly in history. Structural change creates winners, but it also produces losers. Technological change has consequently hurt those most heavily invested in an existing paradigm, resulting in widespread resistance to new technologies (Mokyr 1992; Moe, 2007). These transition 'losers' have ample time to organize, ensure beneficial regulations and institutions, and gain political influence. Indeed Olson (1982) warns against the inevitable build-up of rigidities in the economy. Incumbent carbon emitting industries are deeply-rooted and entangled in institutional structures and political economies through decades of lobbing and the successful building of effective alliances. These industries have thus worked against policies on global warming and protected themselves against structural change (Moe, 2015; Mildenberger; 2020; Stokes, 2020) leveraging these powerful coalitions with a vested interest in the perpetuation of a fossil fuel energy system against the political system. Mildenberger (2020) adds to this sentiment by asserting that the current transition is particularly pernicious because large carbon emitters represented by both labor and business actors across political lines have captured policymaking on both the left and the right.

Unruh (2000) describes the current situation as a carbon lock-in where the influential fossil fuel interests have created a techno-institutional complex (TIC) with powerful feedback loops between technological infrastructure and institutions that are very difficult to replace (Erickson et al., 2015; Seto et al., 2016). Unruh describes the present TIC as the most powerful in human history. The stronger the TIC, the harder it is for a state to break away from this complex. Politically, it's then extremely risky to vote for decision with major redistributive consequences that shake up the status-quo. The political reality is that it is easier and safer to back established interests and avoid immediate structural change, thereby pushing the energy transition ever further into the distant future, in effect protecting the most powerful vested interests (e.g. Moe, 2015; 2017). Thus, the present lock-in fuses the political and economic structures to an extent that, according to Aklin & Urpelainen (2018), it is only dissolvable by major exogenous shocks that shake the entire system.

Presently then, the onset of cheap and abundant renewable energy—primarily wind and solar PV and batteries (lithium-ion) that enable electric mobility and storage and direct (e.g. heat pumps and space heating) and indirect electrification (e.g. renewably-powered electrolyzers for hydrogen production)—threatens the very existence of the fossil-based techno-institutional complex. History tells us it would be naive to think that vested interests will act differently in the present energy transition.

As we shall see, however, there are some plausible paths forward which indicate a possible transformational process of 'would-be' transition losers. Nina Kelsey (2018) suggests that under certain conditions, vested interests will cease to resist and embrace the structural change. Kelsey divides industrial actors into four categories—winners, losers, convertibles and management—winners being actors who are set to gain from the transition and losers those who will indisputably lose by it. While the management category is not particularly suited to this work, the convertible category is. Convertible industries "are industries that make polluting products but do have the capability to switch to non-polluting products" (Kelsey, 2018 p.620). This proposes a very promising mechanism under which some incumbent vested industries can potentially convert their industry to the new paradigm.

Providing an alternative view of transitions, Benjamin Sovacool (2016) lists ten short contemporary case studies, which he suggests show that under certain circumstances transitions can be rapid as well as politically accelerated. Schmitz (2016; 2017) also highlights examples of rapid transformations, in cases where green policies have been politically accelerated. Both Socavool and Schmitz stress that there is no magic formula, and even no real overarching theories of rapid transitions. To some extent, this is in the nature of the beast. Transitions are complex, context-specific, path-dependent and reliant on timing, and different states have different institutional structures, political systems, resources, and energy-security situations.

This suggests some of the shortcomings of the transitions literature, and our limited understanding of what politically drives transitions. Stokes & Breetz (2018) highlight that while many studies examine technical, economic and policy drivers, little attention has been given to the political dynamics of energy transitions. Roberts et al. (2018) emphasize that while the current energy transition is being actively pushed by policy-makers in a manner unlike any other transition on record, "the crucial issue of the *politics surrounding their* *deliberate acceleration*, remains under-examined" (Roberts et al., 2018: 305). Thus, to understand the dynamics and effects of climate policy, we must put politics at the center (Victor, 2011). A focus then on the *political* acceleration of energy transitions suggests that it is essential to study agency and which actors accelerate the processes of change, as well as examining the effect of climate policy choices, which is the focus of the dissertation's third article (Sæther & Moe, 2021).

Markard, Raven & Truffer (2012) even suggest an entirely new field of study to solve these pressing issues, calling it "sustainable transitions studies". While Mowery, Nelson & Martin (2010) assert that what are needed are new policy models that focus on a policy-induced acceleration of the transition. They argue, for instance, that technology policy must take a more central role in order to accelerate the transition. In any case, Wilson & Grubler (2011) argue that political efforts to overcome vested interests will be crucial and that countries that succeed will likely do it with a combination of strong public investment in transition-enabling infrastructure (Moe, 2010), and institutional and regulatory efforts to create and protect immature niche transition markets from incumbent and established players (Schot & Geels, 2008).

2.3 The state of the electricity and transportation sectors

In May 2021, the IEA published an eye-opening reality check for what type of societal transformation is needed for mankind to have a 50% chance of staying below 1.5C in 2050 (IEA, 2021a). Figure 3 shows the kind of radical shift needed in all sectors of the economy. The significant growth needed in technologies like solar PV, wind and batteries, and the overall electrification of society to stay below 1.5C projected by the IEA underlines the relevance of this dissertation and clearly points to the glaring need for structural change in both the power and transportation sectors. As an example, in the net-zero scenario, IEA presupposes that by 2035, there should be no new internal combustion car sales and almost 70% of global electricity generation is from solar PV and wind in 2050 (IEA, 2021a). Many attempts have been made to model the decarbonization of the energy system[4]. Some model the global energy system (e.g. Jacobson & Delucchi, 2011; Delucchi & Jacobson, 2011; Akashi et al., 2014; Bibas & Méjean, 2014; Jenkins, Luke & Thernstrom, 2018), while other

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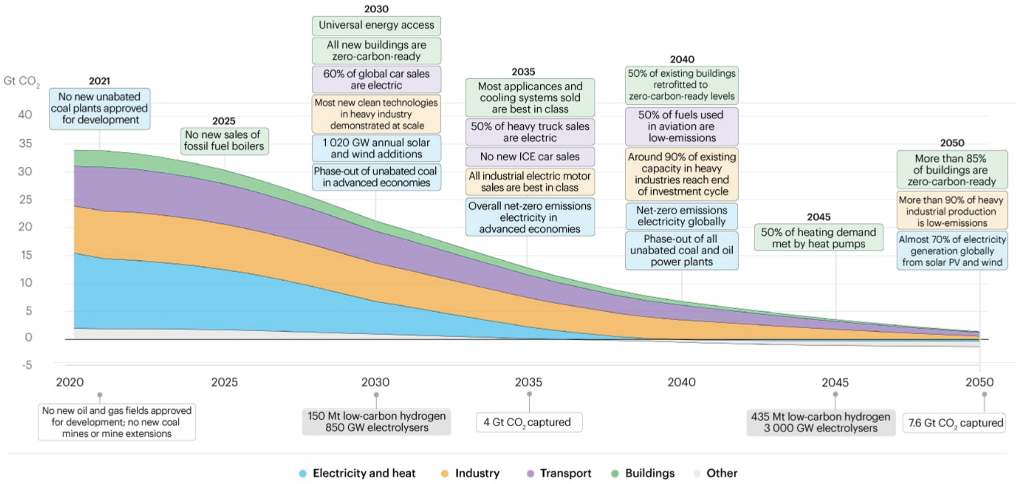
[4] See Jenkins, Luke & Thernstrom (2018) for a thorough review.

look at regions like Europe and the EU (e.g. Connolly, Lund & Mathiesen, 2016; Plessmann & Blechinger, 2017; Brown et al., 2018; Schlachtberger et al., 2018) and yet others look at single countries like the US (e.g. Mai et al., 2014; Becker et al., 2014; Jacobson et al., 2015; MacDonald et al., 2016; Frew et al., 2016). What they all have in common is that high renewable and storage penetration is both feasible and cost-competitive (from 80% to 100%). Where they differ is the role played by conventional generation (like natural gas and nuclear) and technologies like carbon capture and storage (CCS), hydrogen, and bio-related methods. Some, like Xiao et al., (2021) even argue we are underestimating the speed of technological development to a point where current energy scenarios are lagging far behind.

Figure 3. Net zero milestones by 2050.



Source: IEA (2021a)

2.3.1 Solar PV and wind

The global financial advisory, Lazard, publishes annual, levelized cost of energy (LCOE[5]) data for each electricity generation technology (Lazard, 2021). Within the power sector, wind and solar power are now competitive on price in most countries (Naam, 2019), with the costs of solar power having come down by close to 90% and wind power by about 70% over the past decade (IRENA, 2020; Lazard, 2020). Figure 4 shows the LCOE of wind and solar compared with a selected range of conventional technologies.

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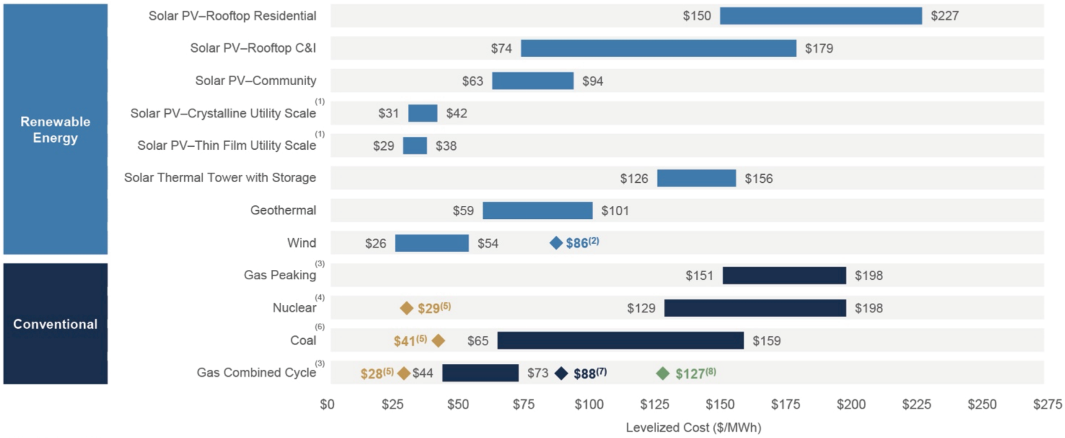
[5] Often used as “levelized cost of electricity”, but as Lazard compares storage as well, energy is used.

Figure 4. Levelized cost of energy comparison—Unsubsidized analysis of selected renewable energy technologies and conventional generation technologies.



Source: *Lazard estimates.*

Note: Here and throughout this presentation, unless otherwise indicated, the analysis assumes 60% debt at 8% interest rate and 40% equity at 12% cost. Please see page titled "Levelized Cost of Energy Comparison—Sensitivity to Cost of Capital" for cost of capital sensitivities. These results are not intended to represent any particular geography. Please see page titled "Solar PV versus Gas Peaking and Wind versus CCGT—Global Markets" for regional sensitivities to selected technologies.

(1) Unless otherwise indicated herein, the low case represents a single-axis tracking system and the high case represents a fixed-tilt system.

(2) Represents the estimated implied midpoint of the LCOE of offshore wind, assuming a capital cost range of approximately $2,600 – $3,675/kW.

(3) The fuel cost assumption for Lazard's global, unsubsidized analysis for gas-fired generation resources is $3.45/MMBTU.

(4) Unless otherwise indicated, the analysis herein does not reflect decommissioning costs, ongoing maintenance-related capital expenditures or the potential economic impacts of federal loan guarantees or other subsidies.

(5) Represents the midpoint of the marginal cost of operating fully depreciated gas combined cycle, coal and nuclear facilities, inclusive of decommissioning costs for nuclear facilities. Analysis assumes that the salvage value for a decommissioned gas combined cycle or coal asset is equivalent to its decommissioning and site restoration costs. Inputs are derived from a benchmark of operating gas combined cycle, coal and nuclear assets across the U.S. Capacity factors, fuel, variable and fixed operating expenses are based on upper- and lower-quartile estimates derived from Lazard's research. Please see page titled "Levelized Cost of Energy Comparison—Renewable Energy versus Marginal Cost of Selected Existing Conventional Generation" for additional details.

(6) High end incorporates 90% carbon capture and storage. Does not include cost of transportation and storage.

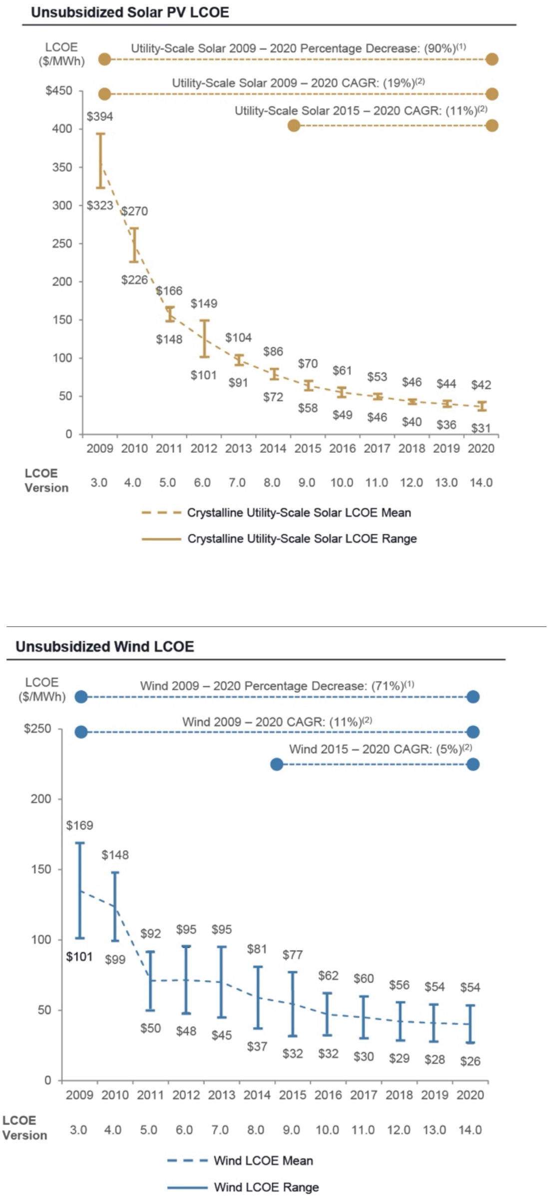
(7) Represents the LCOE of the observed high case gas combined cycle inputs using a 20% blend of "Blue" hydrogen, (i.e., hydrogen produced from a steam-methane reformer, using natural gas as a feedstock, and sequestering the resulting CO_2 in a nearby saline aquifer). No plant modifications are assumed beyond a 2% adjustment to the plant's heat rate. The corresponding fuel cost is $5.20/MMBTU.

(8) Represents the LCOE of the observed high case gas combined cycle inputs using a 20% blend of "Green" hydrogen, (i.e., hydrogen produced from an electrolyzer powered by a mix of wind and solar generation and stored in a nearby salt cavern). No plant modifications are assumed beyond a 2% adjustment to the plant's heat rate. The corresponding fuel cost is $10.05/MMBTU.

Source: Lazard (2020)

Figure 5 shows the historical decline in the unsubsidized LCOE of solar PV and wind since 2009. Notably, onshore wind costs fell by 2% and utility-scale solar projects fell by 9% over the past year. Thus, while the reductions in costs continue, their rate of decline has slowed, especially for onshore wind. Costs for utility-scale solar have been falling more rapidly than onshore wind—11% per year compared to 5% per year, over the past five years (Lazard, 2020). Although Lazard find slowing (onshore) wind cost declines, a recent publication in *Nature Energy* by Wiser et al. (2021) found that wind experts in 2020 expected a wind cost decline of between 37% and 49% by 2050, which is nearly 50% lower than predicted by the same group five years earlier. The study cites the massive cost reductions and technological development witnessed over the intervening period as reasons for the upward projection.

Figure 5. Unsubsidized levelized cost of energy—Solar PV and wind



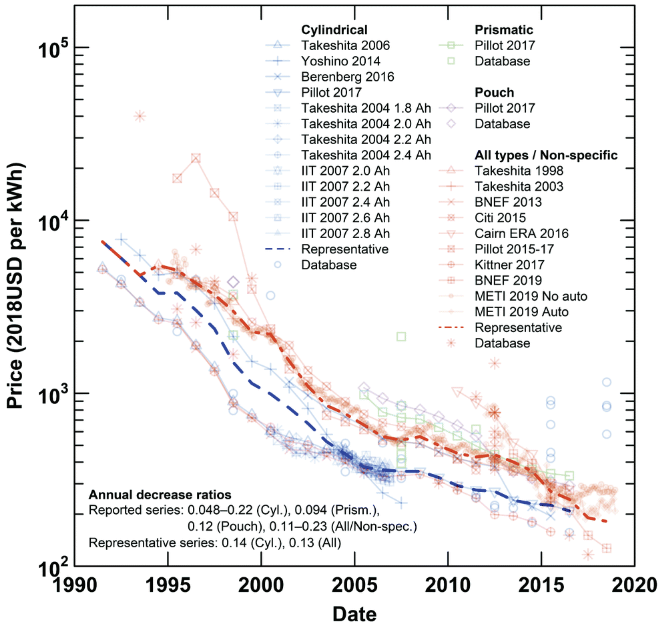
Source: Lazard (2020)

2.3.2 Batteries, energy storage and electric mobility

MIT researchers Micah Ziegler and Jessika Trancik (2021) recently published a re-examination of lithium-ion technology learning rates and found that the real price of lithium-ion cells, scaled by their energy capacity, has declined by 97 percent since their introduction in 1991. Figure 6 shows the estimated decline in real price per energy capacity from 1990-2020. It shows a 13 percent drop per year for all types of cells and cylindrical cells from 1992 to 2016 and decreases of 20 percent for all types of cells and 24 percent for cylindrical cells for every doubling of the cumulative market size. This suggests that we should not underestimate the cost declines of battery technologies as, in hindsight, it seems obvious that most experts did with solar PV and partially with wind.

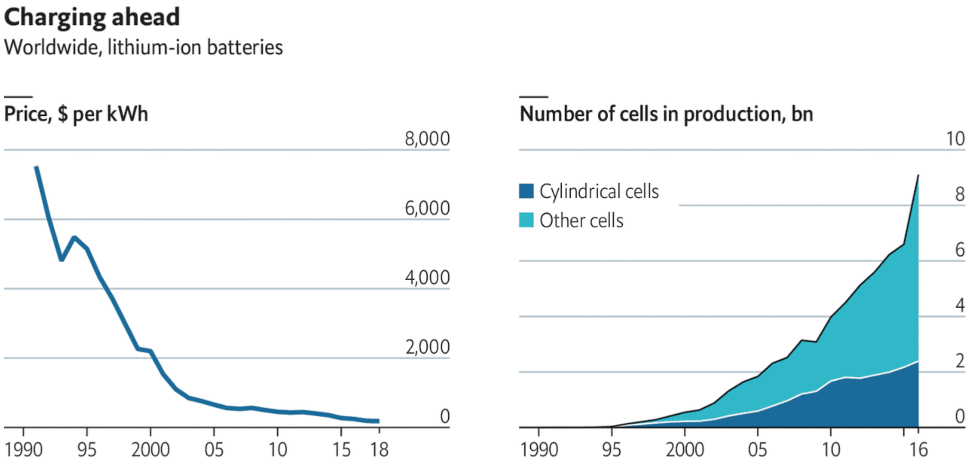
The research shows that there is agency and power of intervention from governments and consumers to increase the uptake of electric vehicles, thereby accelerating future doublings of these respective cumulative markets (see figure 7) (Ziegler & Tranick, 2021; The Economist, 2021).

Figure 6. Lithium-ion cell prices 1990-2020.



Source: Ziegler & Tranick (2021)

Figure 7. Worldwide price reductions and cell productions of lithium-ion batteries.



Source: Ziegler & Tranick (2021) in *The Economist (2021).*

In July 2021, the International Council on Clean Transportation (ICCT) published the latest reputable life-cycle assessment (LCA) of GHG emissions of passenger cars at the time of this writing (A more thorough analysis can be found in the literature review of Article 2). The analysis takes a deeper look at four major global new passenger car markets, Europe, China, India, and the United States, in 2021, thus covering a wide variety of the global market. Additionally, based on the available stated policies in the four markets, the study estimates how the life-cycle GHG emissions of passenger vehicles expected to be registered in 2030 compare with vehicles registered today, considering the changing fuel and electricity mixes during the lifetime of the vehicles for both 2021 and 2030 cars (Bieker, 2021).

Figure 8 unequivocally shows that the life-cycle emissions assessment over the lifetime of a medium-sized battery electric vehicle (BEV) registered today in Europe, the United States, China, and India are already lower than a comparable gasoline internal combustion engine vehicle (ICEV) by 66%–69% in Europe, 60%–68% in the United States, 37%–45% in China, and 19%–34% in India. For medium-size cars projected to be registered in 2030, as the electricity mix continues to decarbonize in line with stated goals, the life-cycle emissions gap between BEVs and ICEVs increases to 74%–77% in Europe, 62%–76% in the United States, 48%–64% in China, and 30%–56% in India (Bieker, 2021).

Figure 8. Life-cycle GHG emissions of average medium-size gasoline internal combustion engine (ICEVs) and battery electric vehicles (BEVs) registered in Europe, the United States, China, and India in 2021 and projected to be registered in 2030.

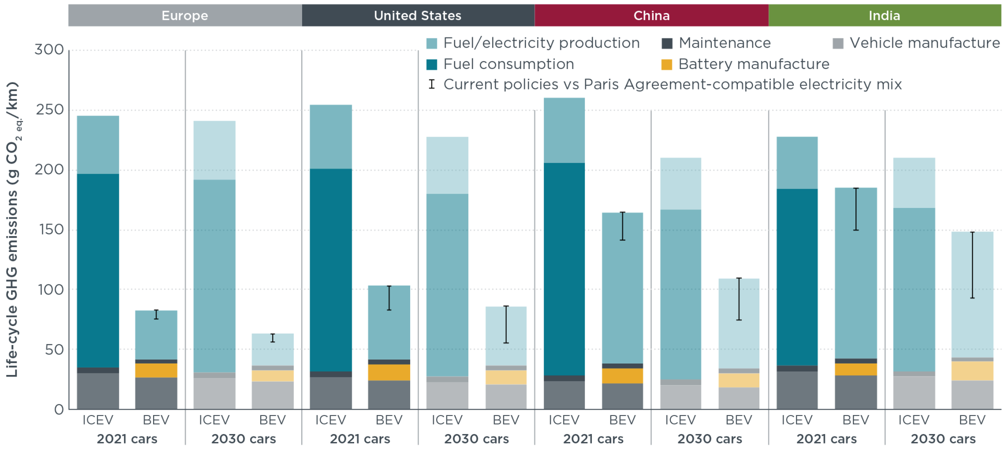


Figure ES.1. Life-cycle GHG emissions of average medium-size gasoline internal combustion engine (ICEVs) and battery electric vehicles (BEVs) registered in Europe, the United States, China, and India in 2021 and projected to be registered in 2030. The error bars indicate the difference between the development of the electricity mix according to stated policies (the higher values) and what is required to align with the Paris Agreement.

Source: Bieker (2021)

2.4 Classification of climate policy

Conceptually, there are various ways of classifying, labeling and sorting climate policies. For instance Green & Denniss (2018) make a distinction between *supply-side* and *demand-side* climate policies and further divide these into *restrictive* and *supportive* (see figure 9) and argue that supply-side climate policies are undervalued and often overlooked in policy

Figure 9. The climate policy toolkit

	Supply-side	**Demand-side**
Restrictive	*Restrictive supply-side climate politics* (e.g. fossil fuels subsidy reductions; fossil fuels supply tax; fossil fuels production quotas; fossil fuels supply ban/moratorium)	*Restrictive demand-side climate politics* (e.g. carbon tax; carbon cap and trade; mandatory CO_2 emission standards)
Supportive (of substitutes)	*Supportive supply-side climate politics* (e.g. direct government provision of low-carbon infrastructure; R&D subsides; renewable energy feed-in tariffs)	*Supportive demand-side climate politics* (e.g. government procurement policies; consumer subsidies for energy-efficient or low-emitting substitutes)

Source: Taken from Green & Denniss, 2018 debates (for similar arguments see: Lazarus, Erickson & Tempest, 2015; Lazarus & van Asselt, 2018; Erickson, Lazarus & Piggot, 2018).

Another classification in broader literature is between “technology-push policies” that focus providing incentives that reduce cost and increase supply of technologies (e.g. Nemet, 2009) and “demand-pull policies” that foster technological change by stimulation demand for technologies through financial incentives and regulation (e.g. Peter et al., 2012), and their ability to produce desired policy outcomes and emissions reductions. This type of labeling is often found in the literature on policy mixes and innovation studies (e.g.; Flanagan, Uyarra & Laranja, 2011, Rogge & Reichardt, 2016). Some conditional findings of this literature concern the potent combination of policy mixes to produce complementary effects and foster (environmentally beneficial) innovation (see for instance: Rennings, 2000; Peters et at., 2012; Hansen et al, 2018; Nuñez-Jimenez et al., 2019) and the fact that they are “necessary, but not sufficient, for innovation to result; both must exist simultaneously” (Mowery & Rosenberg (1979).

In my overall dissertation I have opted for a somewhat simplified classification based loosely on Patt (2015), focusing mostly on market-based instruments (which bears some resemblance to the demand-pull and restrictive demand-side climate politics) and technology policy (which overlaps with technology-push and supportive supply-side climate politics).

2.5 The policies of power sector electrification and the energy transition

The first sector of the energy transition I focus on in this dissertation is the power sector. In the following I review the literature related to two key questions. First, what electrification and climate policy options do policy-makers have at their disposal which will reduce the impact of climate change in the power sector, how effective have they been, and, based on this, can we say something about how effective they are likely to be in the future?

Secondly, which of these policy choices create structural change and which spur incremental change? Many of the market-based instruments are similar in both the power sector and the second sector I tackle in this dissertation—the transportation sector—hence they are presented in the following sub-section, while more sector specific policies are presented in each section.

2.5.1 Market-based approaches

Economists have long been adamant that market-based approaches, such as a price on carbon, either in the form of a carbon tax or through an emission trading scheme, represent the most cost-effective way of solving the problem of climate change (Baumol & Oates, 1971; Pearce & Turner, 1990, Pearce, 1991; Köppl & Schratzenstaller, 2021). Through pricing the (negative) *externality* i.e. the greenhouse gases in the case of climate change, an incentive has been created to drive innovation and decisions toward less GHG intensive activities. The first to propose a market mechanism to deal with externalities was British economist Arthur Cecil Pigou (Pigou, 2013[1920]). The OECD, among others, define externalities as "situations when the effect of production or consumption of goods and services imposes costs or benefits on others which are not reflected in the prices charged for the goods and services being provided" (OECD, 2003). Externalities can be either positive (e.g. roads, railways, broadband networks etc.) or negative, with pollution being the classic example of a negative externality (Khemani & Shapiro, 1993). Thus, in order to correct for the negative externality, governments ought to put a price on the polluting activity or polluting agent in order to incentivize firms and consumers to change behavior or make them pay for the environmental degradation their activities are causing. This line of reasoning is often referred to as the "polluter pays" principle (OECD, 2001).

Historically, traditional environmental policies involved more direct regulation, such as emissions or technology standards. They were often referred to as "command-and-control" regulation. Economists often branded them inflexible and rigid (Portney & Stavins, 2000), but these are still quite popular policy tools for policy-makers. In contrast, Pigouvian taxes or instruments provide a market mechanism to allocate resources and capital while reaching environmental goals at the lowest possible cost (Baumol & Oates, 1988; Hahn, 1989). Compared to regulatory command-and-control measures these market-based instruments "harness market powers, because if they are well designed and implemented, they encourage firms (and/or individuals) to undertake pollution control efforts that both are in those firms' (or individuals') interests and collectively meet policy goals" (Portney & Stavins, 2000 pp.31-

32.) Kete (1994) also highlights that firms—and to a lesser extent consumers—can be incentivized through a pricing mechanism (i.e. a carbon tax or allowance) to recognize that economic issues and environmental problems are two sides of the same coin. This is because pollution, either in the form of poisonous compounds or in the case of climate change, a greenhouse gas, imposes costs on actors in both the production or manufacturing process (e.g. from a tax or regulation on emission or pollution) and on society as a whole through its negative externality such as increased climate change or issues related to waste and its adverse effects.

Across the world, the dominating paradigm in climate policy discussions is centered around market-based solutions pushed by powerful organizations on the world scene such as the OECD, the International Monetary Fund (IMF) and the World Bank (World Bank, 2014; IMF/OECD, 2021; OECD, 2021; Green, 2021).

2.5.2 Global coverage of carbon pricing policies

Despite being hailed as the most cost-effective solution to the problem of climate change, at the end of 2019 carbon pricing initiatives only covered around 20% of worldwide GHG emissions (REN21, 2020). There are two main carbon pricing instruments, a pure carbon tax and an emission trading system (ETS).

2.5.2.1 Carbon taxation around the world

A carbon tax directly sets a price on carbon by putting a tax rate on either the greenhouse gas or the carbon content of fossil fuels (World Bank, 2014). By the end of 2020 only 25 countries had an active pure carbon tax (World Bank, 2021). The Nordic countries are famous for their carbon taxes which were introduced early in the 1990s, except for Iceland which introduced its carbon tax in 2010. These carbon taxes are also considered to be relatively high. Figure 10 shows their current carbon price at the end of 2020. Interestingly, all Nordic countries are also part of the EU emission trading system (EU ETS) and have exempted several industries and sectors with emissions that are covered by the EU ETS, such as the power and heating sector and energy-intensive industry.

Figure 10. Nordic carbon tax prices by the end of 2020.

Sweden	SEK1200/tCO2e (US$137/tCO2e)
Norway	NOK590/tCO2e (US$69/tCO2e)
Finland	Transport fuels: EUR62/tCO2e (US$72.8/tCO2e) Other fossil fuels: EUR53/tCO2e (US$62.3/tCO2e)
Denmark	Kr.178.5/tCO2e (US$28/tCO2e)
Iceland	Fossil fuels: ISK4400/tCO2e (US$35/tCO2e)

Source: World Bank Carbon Pricing Dashboard (2021)

Perhaps due to its limited global coverage, the empirical literature on the effect of pure carbon taxes is less comprehensive (see for instance: Andersen, 2004; Kosonen & Nicodème, 2009; Goulder et al., 2019; Andersen, 2019). Furthermore, most studies focus on the Nordics, with a few articles on the UK Carbon Price Support, and the British Columbia carbon tax. Lin & Li (2011) compare the effect of carbon taxes on emissions in five north European countries with a control group. The general findings suggest very different mitigation effects on emissions in each country, with only the Finnish carbon tax producing a statistically significant negative effect on emissions. They point out that the tax rate and tax exemption practices are the primary reasons for the difference in results. Shmelev & Speck (2018) found that the general carbon tax had no effect on aggregate emissions in Sweden except in the case of petrol while Wier et. al (2005) speculate that the Danish carbon tax might have been regressive as a result of the tax being imposed on energy consumption in households as well as on industry and businesses, with undesirable distributional effects. In the case of British Columbia, a mixed picture emerges from the literature. On one hand, Metcalf (2019) finds that the carbon tax in the Canadian province has consistently contributed to CO_2 reductions since its introduction in 2008. Pretis (2020) on the other hand, finds no aggregate reduction in emissions, apart from a 5% reduction in the transportation sector, a finding which is in line with research done by Rivers & Schaufele (2015). The few studies done on the UK Carbon Price Support suggest it has been quite effective at reducing emissions as a complementary policy to the EU ETS (Leroutier, 2019; Abrell, Kosch & Rausch, 2019).

2.5.2.2 The European emission trading scheme and other cap-and-trade systems

Emissions trading schemes, or cap-and-trade systems, are far more widespread around the world than pure carbon taxes. The system or scheme works by placing a cap or limit on the total amount of GHG emissions allowed to be emitted by participants covered by the scheme.

The emission reducing mechanism in the system is that the permit cap is decreased and adjusted down over time. Thus, in a simplified way, one might say that the efficiency of the ETS is determined by how fast regulators can and will decrease the total supply of permits in the system. In order to make this massive intervention in the economy politically feasible, ETS systems have had to adhere to a mechanism by which incumbents have time to adjust to the new reality. A practice known as "grandfathering" has been used to issue free permits to existing actors as a way of slowly drawing industries and actors into the system.

Of the active schemes, the European Emission trading system (EU ETS) is both the largest and oldest. The EU ETS was implemented in 2005 using the cap-and-trade principle. The ETS is now in its fourth phase, running from 2021 to 2030, and covers almost half of the EU's greenhouse gas emissions (European commission, 2021). The first and second phase of the ETS shows how difficult it is to get these systems right. The grandfathering and the financial crisis of 2008 resulted in a huge oversupply of permits which plagued the ETS for a decade (Patt, 2015). Things are looking better after the third and now fourth phase which have seen European policy-makers tighten their grip and introduce the market stability reserve and increase the removal of excess allowances (see Wettestad & Jevnaker, 2016). As Europe raises its climate ambitions, along with massive price reductions in renewable energy, it signals that the European allowance price does not need to be very high to affect coal fired power plants and render them increasingly uneconomic. Wettestad & Gulbrandsen (2019) also show that there has been significant international learning between emission trading systems, and that lessons from the EU ETS have contributed to shaping systems all over the world, from China, the US, Kazakhstan, Korea, to New Zealand.

On the studies on the European ETS, Anderson & Di Maria (2010), Marti, Muûls & Wagner, (2016) and Bayer & Aklin (2020) find that the scheme cut emissions, while far more studies report either limited (Ellerman & Buchner, 2008; Egenhofer, Alessi, Georgiev & Fujiwara, 2011; Laing et al., 2013; Ellerman, Marcantonini & Zaklan, 2016; Dechezleprêtre, Nachtigall & Venmans, 2018; Marcu et al., 2020, Sæther, 2021a) or no significant effect (Gloaguen & Alberola, 2013) on emissions.

If we look outside of the European ETS, in the US, Cullenward (2014) finds that the California carbon market has suffered from severe carbon leakage, resulting in meager actual emission reduction when accounting for leakage. Fell & Maniloff (2018) on their side, found that when looking at the Regional Greenhouse Gas Initiative (RGGI) which is located in the Northeastern US, covering states like Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, and Virginia, CO_2 emissions were down 8.8M tons per year. However, similar to Cullenward's findings in California, the researchers found that the RGGI states leaked about 4.5M tons per year to nearby "leaker states" thus cutting the actual reduction to just about 4.3M tons per year.

Among the BRICS, China has just recently started its national carbon-trading scheme from 2021 after successfully experimenting with eight regional pilot-carbon market projects from 2013 (BNEF, 2017; IEA, 2020e). The decision to establish the emission trading system was decided all the way back in 2010, illustrating well the time it can take to establish a major policy initiative (Guo, Zusman & Moe, 2014). Looking then at the effecst of the Chinese pilot ETS programs, Gao et al. (2020) find some emission reduction effect and that the effect has been greater on production-based emissions than on consumption-based ones. A modeling of the impact of the Chinese ETS by Lin & Jia (2017) finds that while the ETS will substantially reduce cumulative emission by 12.05 Bt-CO_2[6] by 2030, it will increase commodity prices. The researchers suggest that if ETS revenues are transferred to the population, the ETS can play a significant role in promoting social welfare. Yan et al. (2020) also find significant improvement in air pollution as an attributable effect of the Chinese pilot-ETS carbon markets studied. Choi, Liu & Lee (2017) reported similar results in their study of the effects of the Korean ETS, finding a 2.5 percent emission reduction effect, from the base case, after its implementation in 2015. However, they detected an electricity price increase of nearly 4 percent.

A more thorough overview of the empirical research on carbon pricing worldwide can be found in the dissertation's first article, Sæther (2021), Köppl & Schratzenstaller, 2021 and in Green's (2021) excellent meta review of ex-post quantitative studies of carbon pricing policies around the world since 1990. Briefly, Green's conclusions can be summed up in four main findings. Firstly, that while carbon pricing dominates political discussions around effective policies to combat climate change, only 37 studies, mostly focused on Europe, look

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[6] For reference, the Global Carbon Project (2020) calculates the remaining carbon budget, in order to retain a 50% chance of keeping global average temperatures under 1.5c, is around 440 billion tons of CO_2. Thus 12.05 Bt-CO_2 equals about 3% of the remaining budget.

at the actual empirical effects of emission reduction from such policies. Secondly, almost all studies in the review suggest that emission reductions from carbon pricing policies are at best limited and highly dependent on sectors. Thirdly, most studies by far are looking at the EU ETS, which, while perceivably the most successful and also the oldest emission trading system in the world, has only produced an estimated 0-1.5% annual emission reduction, suggesting a very limited impact compared to the efforts needed to reach ambitious climate goals. Finally, she finds that pure carbon taxes, while more difficult to implement, perform better than emission trading schemes (Green, 2021). Goulder & Schein (2013), Haites (2018) and Stavins (2019) also finds that, generally, carbon taxes have lower administrative costs and that the absence of price volatility for the pure carbon taxes is commonly seen as an advantage over ETS.

As the price per ton of CO_2e is highly correlated with the system's effectiveness, it is cautiously encouraging to see ETS allowance prices closing in on €50 per ton of CO_2e in early May 2021 (Ember, 2021).

2.5.2.3 Why carbon pricing is hard to adopt

The story of global carbon pricing efforts is rather bleak, but nevertheless they continue to be the focus of the climate policy debate. And the conflicts are presumably more intense at the domestic level and even worse in the highest-emitting developed nations like the US, Australia and to some extent Canada, which have all had deeply contested and intense political debates over carbon pricing policies (Harrison, 2012; Mildenberger & Stokes, 2020; Stokes, 2020; Mildenberger, 2020; Green, 2021).

Research shows that carbon pricing policies experience difficulties for plenty of reasons, but the most obvious is what we might label political feasibility. Carbon pricing nearly always creates higher energy prices, which usually has adverse effects in the economy, and in general, vested (especially fossil) interests use their lobbying power to negotiate exemptions or lower the ambitions of these policies as they cause havoc with the bottom line. In addition to these immediate effects, there are some barriers on the horizon for those who envision a powerful global carbon tax in the near future, which we can label the 'institutional obstacle'.

Environmental taxes and emission trading schemes nearly always entail some form of lost profits and change of practice for incumbents. If the industry and actors feel that these interventions are too invasive, in form of unfair distribution or rapid implementation, one would expect them to engage in evasive maneuvering, such as outsourcing, thus leading to carbon leakage and increased lobbying (Tobin & Cho, 2010). Daugbjerg & Svendsen (2003) show that companies are likely to oppose environmental taxes because they will have to pay both the tax and the abatement costs.

Pricing carbon also leads to very direct economic effects. The way carbon pricing affects markets will, according to Patt; “translate directly and immediately into higher energy prices” (Patt, 2015 p. 81). This is often referred to as the “CO_2 cost pass-through effect” on wholesale electricity prices, although the evidence for the effect is mixed (see for instance: Fezzi & Bunn, 2009; O’Gorman & Jotzo, 2014; Patt, 2015; Wang & Zhou, 2017; Woo et al., 2018; Ganapati, Shapiro & Walker, 2020). Nevertheless, most studies show that this effect occurs in varying degrees in places with carbon pricing policies, and without adjustment, these policies tend to be regressive. Higher electricity prices are not necessarily a bad thing, as increases in electricity prices stimulate energy saving and efficiency measures. It does however usually increase hostility and engender declining social acceptability among consumers, as well as sparking opposition from energy-intensive industry, e.g., through loss of competitive advantage and lower margins resulting from higher electricity prices as well paying the price on pollution (Tobin & Cho, 2010).

2.5.2.4 The institutional obstacle to global carbon pricing

The theoretical and empirical international relations literature is telling us that international cooperation is incredibly hard and we should thus expect it to be no less challenging when it comes to climate and environmental issues. Indeed, the literature on climate negotiations is rather pessimistic about the state of climate negotiations (see for instance: Hovi, Skodvin & Aakre, 2013 and discussion in Underdal, 2017). The lack of an overarching governance structure able to police free-riders is problematic for compliance and sanctioning. States know this, and they know that other states know they can free ride. This inherent problem of global affairs suggests enforcement and compliance is exceptionally hard. The Paris climate agreement is built with this assumption in mind (Dimitrov, 2016; Falkner, 2016). Therefore, our base assumption should likely be that governing and enforcing a global carbon tax or price will be difficult if not downright unlikely and will require an institution of global reach akin to the World Trade Organization.

Dryzek (2013) suggests that one explanation for the lack of impactful market-based policies lies in the simple inertia of established institutional practices, mainly resistance to change of established routines. Patt (2015) among others suggests that the only good exception to this rule is the World Trade Organization (WTO), but WTO power, reach and its ability to sufficiently sanction took nearly 70 years to acquire. This immensely well-oiled institution is simply one of a kind. So a hypothetical global price on carbon raises a series of questions about feasibility, enforcement, and compliance, even before one talks about a price, or a level of introduction. There is a simply no institution in the world today with the kind of reach needed to enforce a global carbon tax (Bueno de Mesquita, 2009; Mildenberger, 2020) And if one were to be formed—say under the UN umbrella—history tells us that the time needed to build up the kind of institutional capacity needed will take several decades. That is not to say, of course, that such efforts are in vain, it is simply a question of whether or not the world should use all its time and efforts on such an endeavor, as timely as the challenge of climate change is.

On the question of institution capacity, Cullenward & Victor (2020) suggest that the European emission trading scheme is the most prominent and successful carbon pricing scheme in the world. But they assert that the scheme took considerable time to develop and that it has been more effective in some sectors than others, like the power sector, precisely because industrial policy and targeted technology policy have made substituting possible. They highlight that the state capacity of the European Union is another likely contributing factor to the success of the EU ETS and that few other places in the world have anything remotely like it, with perhaps the exception of China.

What then seems like a more realistic path forward is national and in some cases linked to regional (e.g. the EU ETS), carbon markets which work together in conjunction with other more targeted climate, energy and industrial policies.

So, to summarize the literature on market-based instruments, it’s generally agreed that carbon/environmental taxes and cap-and-trade schemes are, in theory, the optimal way to limit emissions at the lowest possible cost. But in order to do so they rely on conditions and certain assumptions to be as effective as promised in theory. In order to provide sufficient emission cuts, the price of carbon needs to be at a level where it matters, and history shows us that getting it high (enough) is easier said than done. Time and time again, ambitious carbon pricing schemes have been riddled with exemptions, grandfathering schemes, excess allowances and reduced ambitions. In the end, it is not enough to only *have* a price on carbon, it actually has to be high enough to matter. A recent article by Lilliestam, Patt & Bersalli (2021) even goes so far as to conclude that there is no empirical evidence for the effectiveness of carbon pricing in stimulating innovation and zero-emission investment. Against this view, there are some encouraging signs that the drop in the costs of renewables, batteries and by extension, electric vehicles and storage options effectively means that the price point on carbon needs to be far less in future to be effective. In this view, technology, deployment and targeted industrial policy have set up these more cost-effective policies for success, which is one of the main findings of the dissertation's first article (Sæther, 2021a).

2.5.3 Governmental support for research and development

The least politically contested policy for any side of the debate, supported by left and right and labor and business alike, is likely to be research and development (R&D) expenditure or subsides. The OECD's Frascati Manual defines research and development (R&D) as a term covering basic research, applied research, and experimental development (Frascati Manual, 2002). New technologies and manufacturing processes are typically expensive to research and develop. Here, government support can assist in developing demonstration projects as a way of reducing the risk and uncertainty of immature, but potentially promising, technologies. Typically, governmental R&D subsidies can promote development in already known technologies which might need additional cost reductions to become competitive. Most transition scholars and economists agree that governmental R&D funding is beneficial and could even be a prerequisite for innovation, development, and overall competitiveness. Therefore, many see increased R&D expenditure as politically feasible budget spending which can increase the competitiveness of cleaner technologies, support early phase funding and the development of potentially transformative technologies, and at the same time, be a way of meeting climate commitments. Mazzucato (2013) asserts that governmental R&D funding is an important component of increasing innovative performance but is by no means adequate on its own.

Empirically, several studies (including this dissertation's first article, Sæther (2021) suggests an indirect link between increased R&D spending in environmental-related technologies and greenhouse gas emission reduction (Tobin & Cho, 2010; Lin & Li, 2011).

A new global clean energy R&D initiative called "Mission Innovation" was announced in 2015 with the objective of funding the clean energy technology of tomorrow:

> In support of economic growth, energy access and security, and an urgent and lasting global response to climate change, our mission is to accelerate the pace of clean energy innovation to achieve performance breakthroughs and cost reductions to provide widely affordable and reliable clean energy solutions that will revolutionize energy systems throughout the world over the next two decades and beyond (Mission Innovation, 2016).

Currently 24 counties, including the US, China, and the European Union, are participating with a goal of increasing their governmental clean energy R&D expenditure, and by 2021 the initiative has enabled a $4.6 billion USD increase in annual public investments in clean energy innovation and just released its updated Mission Innovation 2.0 Vision (Mission Innovation, 2021).

However, advocates within evolutionary and institutional economics go further than merely supporting R&D subsidies, but instead envision well-specified industrial and technology policies. These are policies that break up technological lock-ins and reduce risk, and deployment programs that create virtuous cycles of cost reductions through learning curves and economies of scale.

2.5.4 Technology and deployment- supporting policies

If the problem of climate change was easily solved by putting a price on carbon, we would likely have done it by now. Thus, while carbon pricing is on paper cost-effective, it is 'tinkering at the margins', and a way of trying to adjust our way out of the crisis. This alternative perspective suggests that we should look at what creates structural, not merely incremental, change. The objective of climate policy, then, should be to create transformative, structural change, not purely focus on metrical emission reduction. Roberts et al. (2018) show us that no historical energy transition has happened by means of a pure market mechanism. Rather they were driven primarily by technological innovation.

Technology policies tend to target slightly different policy objectives than more ‘cost-effective’ policies. These policies attempt to wrestle with the inherently difficult sides of policy-making, namely lock-ins, risk and political feasibility in the present political economy. Additionally, one could argue that their long-term objective is to make cleaner technologies more cost-competitive and set up the more cost-effective policies for success. Technological lock-ins, in this case fossil-based technologies, have an advantage in the market simply by virtue of the fact they are incumbent and established. New solutions always bring considerable technological risk, which makes it less likely for actors to opt for them. Good technology policies focus on reducing this risk and create conditions for de-risking and trial and error. Finally, the policies are aimed at making them politically appealing to a vast range of actors, groups and individuals. Patt (2015) labels these as *clumsy solutions* as they are not optimal for any single actor or group, but they work simply because all stakeholders find them acceptable.

Another key objective of technology policy is to make a new technology gradually more attractive to users. As the use and adoption of the technologies goes up, production increases and overall costs of the technology decrease (Sandén & Azar, 2005). These cost reductions can happen by different mechanisms. The first is simply through the scale effects of increased production, often referred to as economies of scale, i.e. increases in production reduce the unit costs of manufacture often measured by learning curves—that is the percentage decrease in costs for a given technology that occurs with every doubling of the cumulative market. Cost reduction is also achieved through learning by doing, as production, workers and optimization of manufacture improve and become more efficient. Adoption of new technologies into the broader markets also reduces uncertainty about the technology, which again increases uptake.

In other words, the benefits of new technologies increase with higher adoption over time (Naam, 2019; Grubb et al., 2021; Tibebu et al., 2021) and herein lies the *virtuous cycle of deployment policies*; technology policies that drive deployment costs down, which increases broader uptake, driving down costs further. This is, luckily, even more true for some of the very technologies in the current energy transition, namely solar PV, wind and batteries. Looking ahead a bit, it might also be the case for electrolyzers for hydrogen production and some CCS technologies. The catch for society is that these policies are expensive and not the most cost-effective. But the technologies in the present energy transition did not end up as viable technologies simply because of price mechanisms. If anything, in the short term, pricing mechanisms produce incentives to pluck the lowest hanging fruits first. Therefore, at best, they might produce less-emission intensive technologies, but at worse, overlook policies that actually can lead to structural and transformative change. If the prime metric is cost-efficiency, we risk delaying policy opportunities that, while not being the most cost-effective, actually reduce the cost of the technologies and make them mature and ready to replace existing fossil-based technologies. The aforementioned technologies have all required early support from "increased public research and development, demonstration, niche market creation, support for networks within the new industries, standard settings and infrastructure policies" (Sandén & Azar, 2005, p. 1557).

2.5.4.1 Technology policies in the power sector

The dominant policy promoting rapid deployment and cost reduction of renewable energy technology has been feed-in tariffs (FIT). Feed-in-tariffs policies are widespread and have created strong domestic markets for solar PV and wind deployment in particular, with Germany the best known example. But FITs are currently in effect in 113 nation states or provinces around the world (REN21, 2020). FITs can be put in place for a range of renewable technologies, but have so far been mostly focused on solar PV and wind, and to some extent, small-scale hydropower. A feed-in tariff policy is thus not a technology neutral policy, but can be adjusted over time as a given technology matures in the marketplace (Böhringer, Fischer & Rosendahl, 2014; Poruschi, Ambrey & Smart, 2018). FITs are usually designed with three key elements; 1) a long term price-purchasing agreement (PPA) lasting 15-25 years with 2) sell-back priority or guaranteed grid access for any excess power production, with 3) a premium, usually calculated by the government by looking at the current levelized cost of electricity (LCOE) for a given technology and adding a premium to that price. The long-term contract reduces risk and provides cost-visibility for investors and consumers. This predictability is seen as key success factor for FITs (Menanteau, Finon & Lamy, 2003; Tamás, Shrestha & Zhoua, 2010; Jenner, Groba & Indvik, 2013; Patt, 2015). Lesser & Su (2008) also suggest FITs might encourage innovation in a broader set of technologies, and research by Finon & Menanteau (2003) and Del Rio & Bleda (2012) finds similar effects on innovation. Some would define FITs as a market-based policy, and while they work with some price mechanisms, they operate through a very different mechanism than traditional market-based instruments and should therefore arguably be described as a technology policy geared at deploying and scaling up renewable energy technologies (OECD, 2020a). Alizamir, de Véricourt & Sun (2016) thus assert that the political objective of feed-in tariffs is to make renewable energy cost competitive before more cost-effective politics and market forces can take over as these technologies reach maturity and cost-competitiveness.

In the previous decade, as renewable energy slowly started to increase its share of generation, the European Commission stated unequivocally that "well-adapted feed-in tariff regimes are generally the most efficient and effective support schemes for promoting renewable electricity" (European Commission, 2008). While FITs are by and large successful measured by their objectives, they are not without drawbacks. Research shows that their success and cost management also depend on the level the tariff is set at and how well governments are able to adjust this level over time as technologies mature and develop. Higher tariffs can make less efficient deployment projects viable at a very steep price to taxpayers. Conversely, lower tariffs could see only the most efficient projects become investable and can thus defeat the purpose of rapidly scaling up renewable energy. Therefore, policy-makers must balance these two factors, which very well may change over time (Mendonça, Jacobs & Sovacool, 2009).

2.5.5 A range of alternative market-based and hybrid market-based policies in the power sector

While carbon taxes and emission trading schemes are definitely at the center of attention, there are several other market-based or hybrid-market-based policies that could also be seen as technology and deployment policies which are deployed around the world. In the power sector, two powerful policies have emerged, namely renewable portfolio standards and renewable energy auctions.

2.5.5.1 Renewable portfolio standards

Renewable portfolio standards (RPS) have been another popular market-based policy in several countries around the world. Following the REN21 definition, an RPS policy is "an obligation placed by a government on a utility company, group of companies or consumers to provide or use a predetermined minimum targeted renewable share of installed capacity, or of electricity or heat generated or sold. A penalty may or may not exist for non-compliance"

(REN21, 2019 p.247). In 2018, 33 countries and states/provinces had active RPS policies, and it has been a particularly popular policy in many US states. The share of renewable energy production mandated differed quite significantly across those jurisdictions where RPS policies have been implemented (REN21, 2019). As RPS relies on the private market, implementation should thus in theory support competition and efficiency as well as innovation that delivers a mandated renewable energy share at the lowest possible cost to the utility or power producers and, in time, allows these technologies to compete with fossil fuel-based production. A recent Becker Friedman Institute for Economics working paper by Greenstone & Nath (2019) looked at the cost and effectiveness of RPS policies in the US and concluded that while US states with RPS do reduce carbon emissions, they do so at a high cost. This hidden cost of RPS policies suggests that while other market-based instruments like a carbon tax would provide a more cost-effective system, they would still need to be politically feasible to pass legislatively, and have not been passed so far, thus incurring a far higher cost of emission abatement on the system. Furthermore, Menanteau et al. (2003) suggest that quantity-based policies, such as RPS, incentivize competition between various renewable energy technologies as they all count toward the mandated quota.

Dong (2012) finds in his study of the effectiveness of RPS vs. FITs in promoting wind capacity that historically FITs have been more effective at promoting wind capacity but that since 2005 no statistically significant difference in effectiveness between the two policies is evident. Generally, the literature suggests that FITs are better at lowering risk due to the long-term stability for investors. As discussed, RPS should, in theory, incentivize more competition, while feed-in tariffs do not encourage competition and innovation in the same way as they guarantee the price of electricity production for a long time, while some research suggests this is not always the case (e.g., Butler & Neuhoff, 2008).

2.5.5.2 Renewable energy auctions

For all their success, feed-in tariffs policies have proved quite expensive and an alternative policy is slowly taking their place, namely renewable energy auctions or tenders (see Fitch-Roy, Benson & Woodman, 2019). According to IRENA, renewable energy auctions, or “demand/procurement auctions” are auctions where the “government issues a call for tenders to install a certain capacity of renewable energy-based electricity. Project developers who participate in the auction submit a bid with a price per unit of electricity at which they are able to realize the project. The government evaluates the offers on the basis of the price and other criteria and signs a power purchasing agreement with the successful bidder" (IRENA, 2013 p. 6). As the renewable energy sector continues to mature, support policies should also be adopted to reflect the changing conditions. IRENA (2019) finds that due to falling technology costs of renewables, governments and policy-makers have been eager to find way and policies that can get renewable electricity built at the lowest possible price, while simultaneously fulfilling other policy goals, and going forward, allocating some of the support to other less mature technologies for the energy transition. However, it is still early days for renewable auctions. To illustrate, renewable energy auctions were only present in 20 countries in 2009, and have increased to 109 by 2019, compared with feed-in tariffs which were present in 80 countries in 2009 and 113 by the end of 2019 (REN21, 2020). To encourage policy uptake and innovation, IRENA published a guide for policy-makers in 2015 on how to design effective renewable auctions (IRENA & CEM, 2015). The European Commission also highlights the promise of renewable energy auction, to supplement and in the longer-term replace, more lucrative policies like feed-in tariffs: "A well-designed auction can lead to significant competition between bids revealing the real costs of the individual projects, promoters and technologies, thus leading to cost-efficient support levels, and limiting the support needed to the minimum" (European Commission, 2013 p. 6).

The academic literature on auctions is, understandably, less comprehensive, but focuses mainly around either design aspects or evaluation, or comparative evaluations of national renewable energy auctions schemes. Of the studies looking at design, Haufe & Ehrhart (2018) finds that auctions that focus on securing sufficient and serious competition between bidders generally have the most success, and are at least as important as the pricing level. Gephart, Klessmann & Wigand (2017) explore the fundamental trade-off in auctions, namely, the encouragement of sufficient amount of project volumes and the minimizing of the bidder's risk, and find that while there some success criteria such as well-specified qualification requirements and penalties to avoid underbidding, there is no overall blueprint for a good auction design. Del Río (2017) and Matthäus (2020) come to similar conclusions. As more governments are finding auctions to be a most cost-effective way to promote renewable energy deployment, several studies have evaluated their success and effectiveness and the empirical literature is, so far, mostly encouraging.

Bento, Borello & Gianfrate (2020) find that auctions schemes in 20 developed countries between 2004 and 2014 have had the strongest effect on the promotion of net renewable capacity, even surpassing feed-in tariffs. Eberhard & Kåberger (2016) find that auctions have performed very well in South Africa since 2011, after an unsuccessful attempt at fully implementing a feed-in tariff scheme. Elizondo et at. (2014) find that generally auctions have performed well in Brazil, China, and India and have contributed to kick-starting several of these countries renewable programs. However, they stress that the auction schemes must be fully integrated with other regulatory, policy and economic strategies to be fully effective. Toke (2015), however, argues that costs reductions that are often attributed to auctions schemes are not caused by the auctions themselves, but follow more closely the general cost declines of renewables. Anatolitis & Welisch (2017) also find that auctions can decrease smaller actors' long-term competitiveness in the market.

This concludes the literature review of the general market-based instruments and specific policies in the power sector. Thus, while there is a clear overlap of general market-based instruments like carbon taxes and cap-and-trade policies, others, both market-based and here defined as technology policies, are different in the transportation sector. In the next section I will thus review the relevant literature on policies aimed at decarbonizing the transportation sector.

2.6 The policies of decarbonizing the transportation sector

The transportation sector is the second energy transition sector this dissertation focuses on. Like the power sector, its effect on global greenhouse gas emissions is massive, accounting for about 15% of total emissions. In fact, while power sector emissions are falling, transportation sector emissions are increasing and are even projected to rise toward 2050 if current trends continue (Harvey, Orvis & Rissman, 2018). BloombergNEF's latest Electric Vehicle Outlook (EVO) 2021 concludes that despite the massive projected growth in the number of electric vehicles, road transportation is not on track to reach stringent climate and carbon neutrality goals by 2050 and asserts that aggressive policy effort is still needed to accelerate the transition (BNEF EVO, 2021). Therefore, the focus on the transportation sector is crucial and research on how best to accelerate the energy transition in the sector is central to reaching the world's climate goals. The dissertation continues to focus on the key questions of politics and effect of policies in the transportation sector, and which policies and support systems lead to incremental change and which facilitate structural change. The dissertation's second article focuses on electric mobility, specifically plug-in electric vehicle uptake in Europe while the third article spotlights a specific case of a politically accelerated transition in the maritime sector, namely the electrification of Norwegian ferries.

2.6.1 Transportation policy

It should of course be noted from the outset that the transportation sector is massive and every sub-segment of transportation has some distinct policies that are targeted specifically for that part of the sector. Thus, compared with the power sector, the transportation sector is very different, all the way from two and three wheelers to massive container ships. If calls for a single market-based instrument are contested in the power sector, it is even more controversial in the transportation sector. While the theoretical framework presented in the previous chapter for market-based instruments like carbon pricing is no different in the transportation sector, very few actual carbon-pricing policies cover this sector to the extent that they cover other sectors like industry, heating and power. For instance, transportation is not currently covered by either the EU ETS or the Chinese ETS, although there is talk of future inclusion in both (IEA, 2021b; European Commission, 2021; EURACTIV, 2021). For road transport specifically, various forms of purchase incentives, like PEV subsidies, rebates, VAT exemptions, or lower ownership and road taxes for PEV, can of course all be labeled market-based instruments. And while some of them resemble what we could classify as technology policies, and even deployment policies (like EV subsidies), it is not entirely clear if they trigger more than incremental change. However, few would argue against the importance of these policies in the beginning of the transition toward electric mobility. In fact, the findings of the dissertation’s second article suggest that what is more likely is a focus on driving down costs of electric vehicles but even more importantly, the support and facilitation of transition-enabling charging infrastructure, which enables a structural low- and zero carbon shift in transportation, rather than merely supplementing the current fossil one (Sæther, forthcoming).

2.6.2 Electric mobility policies in transport

Policy-makers can deploy a range of policies and measures to decarbonize road transportation. For instance, the list of countries with explicit EV targets is growing rapidly, in addition to increasing efforts to push for an end-date for sales of new ICE vehicles (REN21, 2020). Of the command-and-control regulations, the vehicle performance standards are the most widespread for road transport. They are powerful as they force manufacturers to improve fuel efficiency and reduce emissions of new vehicles sold to consumers. For manufacturers, these standards are known well in advance and can therefore promptly focus their attention on complying with upcoming standards in due time before enforcement. Even though research shows that these standards are effective (see, for instance, the review in Harvey, Orvis & Rissman, 2018), they covered only 37 countries by the end of 2019 (REN21, 2020). Research by Fritz, Plötz & Funke (2019) shows that the manufacturers themselves have even more stringent targets than the policy-makers.

In addition to policies and regulation targeting manufacturers, policy-makers can stimulate the purchase and increased use of electric mobility by what we can classify as personal financial incentives. The literature is quite comprehensive and more or less agrees that these policies work to promote PEV adoption. Studies on the effect of financial incentives like purchase subsidies, rebates, tax and VAT deductions or exemptions, and general reductions in fees and taxes of ownership, find a varying but positive effect on EV purchases (see for instance the review in Hardman et al., 2017; Hardman, 2019). Many studies look at the effect of policy, primarily financial incentives on plug-in electric vehicles globally (e.g. Sierzchula et al., 2014; Mock & Yang, 2014; Zhou et al., 2015; Lieven, 2015; Cazzola et al., 2016; Bunsen, et al., 2018; Axsen, Plötz & Wolinetz, 2020; BNEF EVO, 2021). Others focus on the effect on a regional level (e.g. Plötz, Gnann & Sprei, 2017; Kester et al., 2018; Münzel et al., 2019; Fluchs, 2020; Sæther, forthcoming), while many studies concern themselves with the national and city level (e.g. Jin, Searle & Lutsey, 2014; Vergis & Chen, 2015; Aasness & Odeck, 2015; Mersky et al., 2016; Wang, Pan & Zheng, 2017; Gong, Ardeshiri & Rashidi, 2020).

In sum, most of these studies broadly suggest that financial incentives work, but also recommend that personal financial incentives must be complemented with other electric mobility policies as they are not alone enough to accelerate a structural change in transportation. These are findings that are similar to the ones I make in the dissertation's second article. The literature is less specific on what these supplementary policies need to be, but there is growing evidence for the importance of charging infrastructure.

2.6.3 Transition-enabling infrastructure in transport

The academic literature is less comprehensive when it comes to the effect of transition-enabling infrastructure (see for instance the review in Funke et al., 2019). For electric mobility, many studies suggest that charging infrastructure is important for the transition (e.g. Bakker & Trip, 2013; Kester et al., 2018; Hardman et al., 2018) and while there are some attempts at modeling the effect of charging infrastructure (e.g. Javid & Rejat, 2017; Miele et al., 2020; Haustein, Jensen & Cherchi 2021; Wei et al., 2021), only a couple of investigations have tested it empirically (e.g. Sierzchula et al., 2014; Sæther, forthcoming). Both these studies find that the effect of charging infrastructure was in fact even more substantial than that of financial incentives.

In the maritime sector, critical transition-enabling infrastructure will have to be facilitated and commercialized in order to accelerate the transition toward decarbonization. In the dissertation's third article, we find that the facilitation and enabling of charging infrastructure for the ferries was key to an accelerated transition (Sæther & Moe, 2021).

2.7 Market creation and transformation

A final note on market creation and transformation is needed. While the literature review so far has a focus on market-based policies and technology policy and their ability to effectively reduce emissions and drive down costs, I have not yet discussed the question of market creation and what is often called niche support or management.

Famously, Mokyr (1992) called new technologies "hopeful monstrosities", as they are "hopeful" because of their promise of a better (and hopefully cleaner) future, but "monstrous" because they perform crudely in the beginning. Economic historian, and one of the giants of the field of innovation studies, Nathan Rosenberg (1976), argued that most inventions are relatively inefficient and rather crude when they are recognized as being a new invention. These new inventions are, almost as a necessity, poorly adapted to most of the uses they will eventually be used for as they mature. As a consequence, new technologies are at a stark disadvantage at the beginning and cannot immediately compete in the market against mature and established equivalents. Schot & Geels (2008) and Kivimaa & Kern (2016) suggest governments must ensure that immature and niche technologies are protected in their earlier stages.

As we shall see more in detail in the third article of the dissertation, this early stage support is invaluable for new technologies/new configurations (like batteries). For instance, in the case of the electrification of the ferries in Norway, the early pilot projects backed by the government created ‘proof-of-concept’. Thus, extensive use of public procurements that weighted low- and zero emission solutions—combined with strategic and tailored support schemes that supported the facilitation of transition-enabling infrastructure—made it possible for these solutions to win contracts.

2.8 Setting policies up for success

To sum up the literature review, some final thoughts are in order. While market-based instruments provide the strongest theoretical argument for the most effective way to reduce emissions, technology and targeted industrial policy has arguably provided us with the best practical examples of effective emission reduction (Patt, 2015; Cullenward & Victor, 2020, Grubb et al., 2021), which is precisely what I am testing and finding in articles one, two and three of the dissertation. Technology policies like feed-in-tariffs and electric vehicle subsidies aim to make renewable energy and electric vehicle technology cost-competitive with current fossil-based electricity production and ICE vehicles. Mass deployment of these technologies leads to massive cost-reduction from technological learning curves. Combined with active public procurement and support for transition-enabling infrastructure, markets can quickly be transformed and structural change can be more easily pursued (Edler & Georghiou, 2007, Sæther, forthcoming, Sæther & Moe, 2021), in time, setting up more cost-effective market-based instruments for success.

2.9 Governance of electrification and climate action

The last part of the academic literature I engage with in this dissertation relates to questions around governance, more precisely whether governance matters in the energy transition. In the fourth and final article we ask which form of democratic governance style—egalitarian or liberal—is more conducive to producing a renewable energy transition.

The literature can roughly be divided into literature on transitions in democratic vs autocratic regimes and a much less comprehensive literature on democratic governance styles. The larger 'democracy and climate change' literature contains ample evidence that democracies have been better at dealing with climate change mitigation (e.g. Dryzek, 2013). Through elections and an active and participatory public sphere, the citizens of an open democracy can demand that their governments place the climate and the environment higher up the political agenda. This arguably also increases the legitimacy of policymaking. Thus, democratic institutions, the participation of civil society, and a free media, all conceivably play a role in a country's efforts and agenda setting toward solving climate and environmental issues (e.g. Congleton, 1992; Neumayer, 2002; Neumayer, Gates & Gleditsch, 2002; Bättig & Bernauer, 2009; Bernauer & Koubi, 2009; Niemeyer, 2013). Li & Reuveny (2006) and Bättig & Bernauer (2009) both find that democracies tend to adopt stricter climate and environmental policies as well as cooperate more in international treaties that concern environmental and climate issues, thus making them more likely to curb their emissions. More recent research post-Paris on Nationally Determined Contributions (NDCs) finds that that a country's level of democracy and vulnerability to climate change correlates positively with NDC ambition, while coal rent and GDP have negative effects on the levels of ambition (Tørstad, Sælen & Bøyum, 2020). Aldy et al. (2016) finds that wealthier countries have pledged to undertake larger GHG emissions reductions, with higher costs, and that the marginal costs rises almost proportionally with income while Stephenson, Sovacool & Inderberg (2021) refines these findings adding that "national low-carbon ambitions are strongly cultural, contingent upon how any particular nation sees the role of energy, and the choices, policies, investments and actions that flow from this" (Stephenson, Sovacool & Inderberg, 2021 p.1).

Against this view, several scholars have pointed out that democracies can end up with irrational outcomes, as voters routinely choose contradictory policy positions on a range of issues, and consistently fail to punish politicians for policy failures (Schumpeter, 1942; Achen et al., 2017). Democratic leaders are often prone to shortsightedness and a focus on the pressing issues of the election cycle and promises of economic growth and public goods (Roeland & de Soysa), rather than a commitment to dealing with longer-term issues like climate change. As previously discussed, vested interests seeking to perpetuate the status quo also constitute a problem for democracies trying to accelerate the energy transition (e.g. Moe, 2015; Mildenberger, 2020; Stokes, 2020).

While there is quite a substantial literature on the aggregate efforts of democracies on climate and environmental issues, Povitkina (2018) asserts that there much less research on the how these various democratic regimes actually perform. Of the few studies that look at the topic, Roeland & de Soysa (2021), for instance, find no empirical support for the argument that greater inclusivity increases the prospects of reducing climate emissions. This is the part of the literature that the fourth and final article engages with and adds to (Sæther, de Soysa, Moe, forthcoming). The article also reviews in more detail the various typologies used to classify regimes and governance styles.

3. Research design and methodology

In this section I will first elaborate on the overall project and place it in the landscape of philosophy of science. In the following chapters, I review the quantitative and qualitative aspects and decisions I have made during the project. As the dissertation consists of both quantitative statistical work and a qualitative case study, I argue that the overall dissertation can loosely be labeled as a mixed methods project (Johnson, Onwuegbuzie & Turner, 2007; Brady & Collier, 2010). I finish with some reflections on methodological limitations and improvements.

3.1 The project in the philosophy of science landscape

The project and its conceptual system mainly fit within the positivist tradition. The research relies principally on deductive logic by the formulation of hypotheses and developing operationalization and then testing those hypotheses in order to derive conclusions. Epistemologically speaking, my project is mostly naturalist in nature, being empirical and deductive, relying primarily on statistical analysis after theory-driven developed hypotheses in three of the four papers in the dissertation. However, in the social sciences, the line between a strictly deductive and an inductive approach is blurred and one finds oneself utilizing both. This is evident in the case study of the electrification of ferries in Norway, in Article 3. The paper is clearly a project aimed at explanation, based on theory and variables we 'test' on the empirical data. So while the qualitative case study places a greater onus on thick description rather than explanation compared to the other articles in the dissertation, which are more in line with interpretative/constructivist epistemology, it lies well within the boundaries of a naturalist/positivistic project (Benton & Craib, 2011).

Ontologically speaking, the dissertation is mainly a positivist project with some constructivist elements, with realism as its ontological position. However, as is often the case in the social sciences—this dissertation being no exception—while attempting to adhere to the tenets of empiricism, one is faced with the social world and its complex and hard to operationalize phenomena (Benton & Craib, 2011). Thus, the question of classifying its strict ontological position seems less meaningful and I would rather look pragmatically at it by stating that the aim of this dissertation is to provide problem-solving, empirical-based knowledge. This approach resembles a view of knowledge known as scientific realism (Moses & Knutsen, 2012) or critical realism (Bhaskar, 2013), which blends some elements of a strictly realist positivist view of knowledge with elements of relativistic constructivism.

So here one distinguishes between observable and non-observable phenomena, where through rigorous scientific methods the researcher can examine the structures, processes, and mechanisms that the actors are involved in but do not yet have any concept for (e.g. the concept of a national system of innovation in Article 3), which are nevertheless tangible because they have real consequences (Goertz, 2006; Carolan, 2005; Benton & Craib, 2011; Røttereng, 2017). Scientific or critical realism thus recognizes that there are patterns in the social world which are fixed in nature, but nevertheless can be hidden under many and often obscured ontological layers, which themselves can be misinterpreted. In other words "a Real World *does* exist, but it resists our immediate inquiries as it lies at the end of a long chain of intermediaries; a chain in which each particular link complicates our relationship with the Truth" (Moses & Knutsen, 2012 p. 303). This view of knowledge thus encourages a certain humility about what one can know and not know about the incredibly complex social phenomena we study.

3.1.1 Concepts and operationalizations

According to Becker (1998) scientists work with and develop concepts all the time. Without concepts, we would have a hard time knowing what we are looking for, where to look, and how to notice and recognize things we are looking for if we eventually find them. We often refer to the process of transforming, reducing or expanding concepts or definitions to measurable variables as ‘operationalization’ (Sohlberg & Sohlberg, 2013).

In the three quantitative articles I have attempted to do as thorough a job as possible to get hold of, and where needed construct or find reasonable, theory-driven and ‘best-available’ variables of hard-to operationalize phenomena. I will go deeper into detail about this in the next chapter.

I have thus applied a deductive or hypothetical-deductive method, in order to produce testable and falsifiable hypotheses (Popper, 2005 in Benton & Craib, 2011). I then test them empirically using my datasets and see whether the findings support the hypotheses or not (Hussain, Elyas & Nasseef, 2013; Kivunja & Kuyini, 2017).

As part of the ECHOES project, I conducted or participated in many interviews in which some very interesting patterns emerged. Together with Espen Moe, I continued working on them, and they eventually turned into several more ferry-specific interviews which became part of the empirical data collection for Article 3. Thus, we can classify part of the work in ECHOES as following an inductive methodology (Sohlberg & Sohlberg, 2013). This inevitably means that Article 3 has an inductive component to it, carried over from the ECHOES work. Beyond that, the article has a clear theoretical focus. Our concepts and operationalizations are mainly theory-driven, and adhere mostly to a deductive methodology.

As my aim in the dissertation is twofold—first, to empirically test my theory-driven hypotheses on historical data, e.g. what has *actually* had an effect, and second, to attempt to explain the phenomena so as to provide some suggestive policy considerations.

3.1.2 Explanations and proving causality and generalization

According to Abbot (2004), there are three things that make a social scientist say that something is an explanation. Firstly, a researcher can say something is an explanation when it allows us to intervene in what we are trying to explain, e.g. we have explained something about the effect of climate policy choices in the energy transition when we can, with reasonable precision under ‘normal or average’ conditions, predict their outcomes.

Explanations in the social sciences often hold a more probabilistic character (i.e. under these and these conditions or in most, or in general circumstances this and this applies), rather than law-governed explanations in the natural sciences, such as the laws of thermodynamics.

Secondly, we can say that an account explains *something* when we stop looking for further accounts of that *something*. Thus, an explanation is an account that is sufficient to explain that particular something, be it a phenomenon like civil war, democratization or climate change. A satisfactory explanation of a particular phenomenon frees us to pursue other problems and to try to explain those. Notably in the social sciences, the concept of a satisfactory explanation is incredibly rare, as the world we study is for the most part messy and unpredictable to a fault. In relation to this dissertation, the unpredictability—notwithstanding the argument of some that we are all rational market actors—is high and the motivations of actors not always clear or obvious. Nor should we assume linear relationships when it comes to the adoption of new technologies, especially in a world where climate change is increasingly becoming an external force for changing behavior and policy action.

Thirdly, we usually say we have an explanation of *something* when we have made a certain *argument* about it. According to Abbot, "in a (…) sense, an account is an explanation because it takes a certain pleasing form because it somehow marries simplicity and complexity" (Abbot, 2004 p. 9). In contrast to the natural sciences, where one might romanticize about making a single master equation that explains the universe (often referred to as *the theory of everything*), social sciences have little room for messy, let alone elegant, equations. So rather than striving for perfect equations, social scientists can investigate phenomena using various inferences.

In the strictest form, for a causal explanation to be valid, we have to prove cause and effect, i.e. that A causes B. In physics, the speed of light could just as well have been called the speed of causality. As far as we know, nothing travels faster than the speed of light. Thus, an effect cannot happen before its cause. The use of the speed of light as a causality criterion is, of course, downright impossible to apply in social science and even in most other natural sciences, excluding physics. In the social sciences we thus have to rely on laxer criteria for causal inference with an implicit knowledge of its limitations (we obviously strive for strict criteria, but we cannot derive effects and causes with such astronomical precision). We thus have to rely on likelihoods and more probabilistic statements about causality such as statements like: “With reasonable certainty, having controlled for x, y, and z which previous research highlight being important” or “here we have a plausible explanation of this phenomena, given the theoretical framework and controlling for x, y, and z”. Implicitly, the statistical analyses by themselves do not say anything about the *why*. As a researcher, of course, you strive to make theory-driven hypotheses which you test based on the quantitative works alone, but what a qualitative case study allows us to do is to dive deeper into these mechanisms. The ferry case study is of course both highly relevant and interesting as a stand-alone contribution to the literature on energy transitions and the politics of electrification, but it also serves as an attempt to look closely at some of the theoretical mechanisms in the overall project.

In that sense, Article 3 lends some support to the general findings of the statistical articles (especially the power sector article and the electric mobility article). As such, the ferry article constitutes a broader example of a specific case where we show that market-based instruments alone would likely have yielded a very different timeframe to get to a low-emission solution. Rather it was targeted technology policy and an active entrepreneurial state which used its procurement power to get low- to zero emission solutions. In addition to Article 3, there are a very few, but good, examples, which look at these accelerated transitions in much the same way as we investigate the ferry case (see for instance: Rüdiger & Voldsgaard (2021) on the transformation of DONG energy to Ørsted and Johnstone et al. (2021) on case studies of energy transition and industrial policies in Germany, the United Kingdom and Denmark). Finally, working on the dissertation’s fourth and final article, my co-authors and I all found that the framework in which we test our hypotheses dips into very interesting questions about democratic governance styles that we were only able examine on the aggregate level. Indeed, we feel that there are particularly interesting qualitatively focused studies to be done by looking closer at each democratic governance style’s ability to produce structural change.

3.1.3 A mixed methods project

In conclusion, the overall project can be classified loosely as a mixed methods project. It builds on the strengths of both quantitative and qualitative methods, as I test my hypotheses on empirical datasets, combining them with case-specific knowledge and thereby enable a deeper look at some of the same mechanisms investigated in the quantitative work in more detail. Within the positivistic tradition, many would argue that generalizing from a single case is not prudent (King, Keohane & Verba, 1994), although Popper would claim that, in principle, a single deviating case is enough to falsify a hypothesis (Moses & Knutsen, 2012). However, there is a growing appreciation in the tradition that case studies actually generate very useful specific knowledge, and this is of course especially apparent in the social sciences. Also, case studies have been shown to work particularly well when combined with statistical (regression) and comparative approaches (like Qualitative Comparative Analysis—QCA) (Moses & Knutsen, 2012). There is thus a growing recognition that combining methodological strengths while addressing method-specific weaknesses can be very fruitful. As pointed out by Fearon & Laitin (2008), "multimethod research combines the strengths of Large-N designs for identifying empirical regularities and patterns, and the strength of case studies for revealing the causal mechanism that give rise to political outcomes of interest" (Fearon & Laitin, 2008 p. 758 cited in Moses & Knutsen, 2012 p. 134). By investigating case studies, the researcher can examine whether patterns, trends or results from the regression analyses are consistent with the findings of case studies. If the results are consistent in both methods, causal explanations might have stronger support. And if the results are not consistent, the researcher can either underline the various inconsistencies or revise and update the statistical modeling (e.g. based on case insight, or change variables if better alternatives are found or are a better fit).

In conclusion, most aspects of my project's analysis sit well within the programmatical confines of the positivist tradition. For the quantitative articles I have attempted to construct several concepts and operationalized them into measurable variables for the analysis to infer some contingent causal explanations, which I will go more into detail about in the next section. In the qualitative article we have investigated a very specific case of an accelerated transition in the maritime sector but within a general framework fitting the overall dissertation. As the bulk of the dissertation is quantitative in nature, I have thus relied heavily on a deductive methodology for the statistical analysis, with some inductive elements. While the ferry case study is deductive in its design, it naturally has a stronger inductive component. So overall the project uses a hypothetical-deductive method, with elements of an inductive based approach for Article 3. I also use inductive inference (Sohlberg & Sohlberg, 2013) based on the findings from the articles to provide support for the main conclusions of the dissertation.

3.2 Quantitative data analysis and techniques

Articles 1, 2 and 4 are overwhelmingly quantitative in nature and based on panel datasets of countries (OECD, BRICS in article 1, plus seven European countries in article 4, and European countries in article 2) over extended time periods, thus classifying as time-series cross-sectional data. Large quantitative data sets increase the external validity and strengthen the researcher's ability to generalize based on statistical analysis (King, Keohane & Verba, 1994; Ringdal, 2013).

3.2.1 Time-series cross-section and panel data

Beck (2008) defines time-series cross-sectional (TSCS) data as consisting of "comparable time series data observed on a variety of units. The paradigmatic applications are to the study of comparative political economy, where the units are countries (often the advanced industrial democracies) and where for each country we observe annual data on a variety of political and economic variables" (Beck, 2008, p.1). TSCS data and panel data are often used interchangeably. While some strictly classify panel data as data consistent with a large number of observations, often survey respondents are observed over a number of years and time-series cross-sectional data has the opposite structure, often a small to medium number of observations (e.g. of countries, firms, or municipalities) over longer time periods. Both panel data and TSCS data are structured hierarchically and can be labeled multilevel data with additional structures. They suffer from the same problems; both spatial and temporal autocorrelation and heteroscedasticity. Temporal dependence, or autocorrelation, is when the error term correlates across the panel over time and can inflate the standard errors and lead to biased results. Spatial dependence or cross-sectional dependence means that the units (e.g. the countries in the sample) correlate systematically with each other across space. Both problems need to be controlled in order to produce unbiased estimates (Beck, 2008; Mehmetoglu & Jakobsen, 2016).

3.2.2 Panel data regression techniques

In order to control for these issues with the data set structure I have used a fixed-effects estimator and Driscoll-Kraay standard errors in all the statistical analyses in the project.

By using the fixed-effects estimator, I do the equivalent of unit centering all observation—in other words collapse all data points across one year from all observations into the mean of all observations in a given year in order to investigate deviations from the mean in each unit over time (Petersen, 2004). In practice this excludes two major elements from the analysis. One is that a fixed-effect model only estimates *within*-country variation, thus making comparison between units impossible—in order to do that, one has to run a random-effect or between-effects estimator. The second drawback is that a fixed-effects model cannot use time-invariant variables in the analysis (Petersen, 2004; Beck, 2008).

In order to make ordinary least squares (OLS) regression analysis robust and control for spatial correlation and heteroscedasticity, I have used Driscoll-Kraay standard errors which control for both in all the quantitative articles, in addition to employing a time-fixed effects control of allowing one year of lag (Discroll & Kraay, 1998; Hoechle, 2007).

3.2.3 Databases and samples used in the dissertation

The main sources of data have been the OECD.stat database (OECD.stat, 2021), the World Bank Development Indicators database (World Bank, 2021), the European Alternative Fuels Observatory database (EAFO, 2021a) and the IEA database (IEA, 2021c). All these databases are incredibly diverse and at the highest possible quality available for researchers, and while most data are free, I had to purchase access to data on CO_2 emission intensity from the IEA. In fact, I was the very first client to receive the newly updated data in 2020, which are used in both Article 1 and 4. From these datasets there are two main samples used. In article 1, the sample consists of 34 OECD and the five BRICS countries, constituting a total of 39 countries. In Article 4, we use the same OECD and BRICS countries plus seven European countries. In Article 2, the sample is 30 European countries. In all three quantitative articles, it is fair to say that the sample size has been limited to the availability of data on the given topic.

On one side, having OECD and the BRICS countries in the same sample means that I cover about 82 percent (OECD: 42%, BRICS: 40%) of the world's electricity production (IEA, 2021d, OECD, 2021)[7], which of course is very useful for generality and lends strength to

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[7] World total electricity generation in 2018: 26.750 TWh—OECD: 11250 TWh (42%), BRICS: 10760 TWh (40%), and the rest of the world: 4740 TWh (18%).

policy recommendations. On the other side—which in fact was pointed out by one of the reviewers for Article 1—OECD countries are mostly developed countries while the BRICS countries are mostly developing one and we might thus expect differences in the level, scale and coverage of climate policy. And while I did deploy several controls for economic and industrial development, I also ran separate models as robustness checks in order to see what these differences in the sample did with my results. The process yielded some interesting conclusions, which I elaborate on in the robustness analysis section of Article 1.

For article two, while the European Alternative Fuels Observatory has been a goldmine of data on electric mobility it is restricted to Europe only. This limited the scope of Article 2, but one would hope that data on global electric and low and zero emission mobility will be available for researchers in the near future.

3.2.4 Operationalization of the dissertation's main quantitative variables

In the literature review, I have presented the theoretical backdrop for the dissertation and while all methods chapters have a thorough operationalization of variables, I will now present some more detailed thoughts on the process and the decisions that went into the conceptualization and operationalization of the main variables used in the quantitative articles. As there is some overlap between the variables used in Article 1 and 4, these are discussed together, unless specified otherwise.

3.2.4.1 A difficult task: Operationalizing carbon pricing

Operationalizing carbon pricing is both tricky and difficult as carbon pricing policies vary both in coverage and price and usually come with a variety of exemptions. In the process of finding an adequate measure of carbon pricing in the power sector I went through a range of possible variables. First, an outright carbon tax, but to my surprise none of the countries that *had* a carbon price in the first place were either part of the EU ETS (e.g. Norway, Sweden), which meant that the 'carbon price' in the power sector was covered by the EU ETS or they simply exempted their power sector from its coverage (e.g. Japan, where the tax is very low and only applies to oil, gas and coal imports), and in some cases contingent on the levels of the ETS. Secondly, the OECD.stat database collects data on what they label *Environmentally related tax revenue*, on four mutually exclusive tax-base categories: energy, transport, pollution, resources, and total. The interesting variable for Article 1 would be Energy, which includes Energy products (e.g. fossil fuels and electricity) and those used in transportation (e.g. petrol and diesel). This includes all CO_2-related taxes (OECD, 2020b). While undoubtedly interesting, I found that the scope also covered tax revenue from electricity, which does include renewable energy as well as fossil energy, thus creating a problem for me looking at how market-based instruments like carbon pricing policy affects CO_2 intensity. Thirdly, OECD.stat also has a dataset called the 'OECD Environmental Policy Stringency Index' (EPS) (OECD, 2017). The index data is "a country-specific and internationally-comparable measure of the stringency of environmental policy. Stringency is defined as the degree to which environmental policies put an explicit or implicit price on polluting or environmentally harmful behavior. The index ranges from 0 (not stringent) to 6 (highest degree of stringency). The index covers 28 OECD and 6 BRICS countries for the period 1990-2012. The index is based on the degree of stringency of 14 environmental policy instruments, primarily related to climate and air pollution" (Botta & Kozluk, 2014). Here the time-period with data was simply too narrow, running only to 2012. Finally, a simpler but often used indicator has been a simple dummy variable, along the lines of 1 = carbon pricing, 0= no carbon pricing. The problem with such an approach is the level of ambition, in other words the lack of a price level, which as we have seen in the literature is so crucial to the effect of carbon pricing. In sum, the variable I decided on, the inflation adjusted price in a given year in the emission trading system, arguably seems like the best possible measure of carbon pricing in the power sector. It covers both actual carbon pricing policy which 1) covers power sector emissions, and 2) controls for the price level of the given policy in a given year to the best extent possible.

3.2.4.2 Hitting the mark? Operationalizing of technology- and deployment policy and innovation support policy

The variable used to measure feed-in tariffs in Article 1 is found in the OECD.stat database and is arguably the one with most refined data out there. It was only recently available for researchers (2018), so in the earliest analysis I only used a dummy variable constructed from the REN21 global renewable status report. However the new variable contains country-level data of the mean feed-in tariff in US$/KWh and covers seven renewable technologies: wind, solar PV (concentrated solar power is excluded), geothermal, small hydro, geothermal, marine, biomass and waste, while I only use wind and solar PV in Article 1. According to OECD.stat, the dataset is drawn from official governmental sources and research institutes and is cross-referenced against other renewable energy related databases like IEA, IRENA and REN21 (OECD.stat, 2020). It is also possible to use the OECD Environmental Policy Stringency Index (EPS) described in the previous section, where higher feed-in tariffs in a given country score higher on the index. This variable measures precisely what we want, namely not only if a country has a policy but at what level or how stringent the policy is. However, as mentioned, the dataset ends in 2012 for all countries, although it stretches until 2015 for some selected countries.

As for measuring governmental support for R&D and innovation, several databases have interesting data for the researcher on the country-level over time. In Article 1 and 4, I have used the most comprehensive one, which is the OECD.stat variable that is part of the Green Growth Indicator dataset called 'Environmentally related government R&D budget, % total government R&D'. The variable is simply the most suitable in terms of coverage of the countries and years included in our samples. A more specific variable like the 'Renewable energy public RD&D budget, % total energy public RD&D' would be preferable, but unfortunately the data is too fragmented and only covers about half the countries in our sample. Another option would be to use the variable: 'Environmentally related R&D expenditure, % GDP', but it, too, suffers from the same problem of insufficient coverage (OECD, 2020c). Another relevant database is the IEA Energy Technology RD&D Statistics (IEA, 2021c), which groups RD&D expenditure into seven categories: 1) energy efficiency; 2) fossil fuels: oil, gas and coal; 3) renewable energy sources; 4) nuclear; 5) hydrogen and fuel cells; 6) other power and storage technologies, and 7) other cross-cutting technologies and research (IEA, 2020f). This data is incredibly rich, but is unfortunately limited to only 30 countries and quite fragmented in a significant number of them.

3.2.4.3 PEV or BEV, that is the question!

As alluded to in the literature review, the classification of low- and zero emission vehicles varies a lot depending on what sources one uses. In the end, the choice of which classification to use was fairly easy, as I used data from EAFO, which uses Battery-electric vehicle (BEV), Plug-in hybrid electric vehicle (PHEV) and Plug-in electric vehicle (PEV), which combines BEV and PHEV. However, one of the main difficulties I encountered my analysis in Article 2 was precisely whether or not to include hybrids in my sample, i.e. use PEV rather than purely BEV. I decided on focusing on PEV in the main model and providing a robustness test of the results in the appendix using a BEV-only sample. My reasoning was primarily that I wanted more data. Hence using PEV gave me more data points early on (2009-2010) and also accounts better for the early shift toward electrification as well as reflecting that hybrid is (at least up until now) the prominent 'low-emission choice' in many European markets. Thus having a less stringent 'electric mobility' measurement made it possible to also include that side of the transition. I also argue that I got the best of both worlds since I was able to run the models on a BEV-only sample (although without 2009). In future research, say having data from 2015-2025, I would see myself doing the opposite; using the PEV sample as the robustness test.

3.2.4.4 Personal financial incentives and charging infrastructure for electric mobility

The EAFO database was also an invaluable source of data for measuring for personal financial incentives. The incentives listed in the EAFO database are the following: purchase subsidies, registration on tax benefits, ownership tax benefits, company tax benefits, VAT benefits, other benefits, production, and infrastructure (EAFO, 2021b). It should be noted that the list has been slightly updated since the time I collected and constructed the data in terms of production and infrastructure incentives, which I will discuss in the next section. As the EAFO database does not have a time series for the incentives, I used it as an starting point and then cross-referenced the various incentives with annual overview reports by the European Automobile Manufacturers Association (ACEA) going back to 2014, and the rest with national accounts, as from electric mobility associations, all the way back to 2009.

A more refined analysis of financial and personal incentives has already been done by Münzel et al. 2019, who use the actual monetary / subsidy / tax abatement value of incentives. So in the end, I decided to stick with the dummy variables that resulted from the cross-referencing of the EAFO database, which also made it possible to construct the electric mobility policy packages.

Looking at the operationalizing of charging infrastructure, the only practically obtainable data source was, again, the EAFO database. It has data on a range of charging infrastructure parameters, such as total number of public charging (normal and fast) points (in 2021 the name was formally updated to: "normal and high-power public recharging points"), fast charging points per 100 km highway (2021: high-power public recharging points per 100 km highway), normal public charging points <= 22kw (2021: normal power public recharging points (<= 22kw)), high-power public recharging points (> 22kw) and PEV per public charging point (2021: PEV’s per public recharging point) (EAFO, 2021a). In the end, I landed on using fast charging per 100 km of highway and PEV per charging point as my primary variables due to their useful characteristics, with the fixed effects panel data regression models which I ran in Article 2. Additionally, having charging infrastructure incentives as a dummy would have been an interesting and valuable test variable, but regretfully, the data on this variable was not yet fully available when I constructed the quantitative data for the regression analysis in Article 2.

3.2.5 The master dataset

Thus a key part of the PhD project has been the ongoing process of creating robust and state-of-the-art datasets for the three quantitative articles. The meticulous and often manually coded data gathering has been a significant and often time-consuming part of the day-to-day activity. The combined dataset follows a well-organized structure and is published and updated on the academic open access data portal, Mendeley, thereby giving other researchers and interested parties the ability to use the data material for their own research purposes. The unique combination of power and transportation sector indicators, together with a range of climate, energy, industrial, innovation and R&D policy variables, makes the data incredibly valuable for qualitative researchers and is an additional outcome of the dissertation project as a whole. A large number of economic, developmental and socio-demographic variables, useful for controls, are also part of the dataset. All in all the dataset constitutes a sophisticated panel dataset with most of the data being from 1990 to 2019, and the electric mobility related data from 2000 to 2019. The dataset can easily be merged with other datasets like the V-dem dataset, as we did in the dissertation’s fourth article. The dataset can be freely downloaded and used by researchers here: “Energy transition dataset 1990-2019”, Mendeley Data, V1, DOI: 10.17632/68jzngnc8s.1 (Sæther, 2021b).

3.2.6 Limitations of a quantitative approach for fast-moving phenomena

One issue that has been prevalent throughout the whole project is the fast-moving nature of technological development in general, and the tempo of renewable energy deployment and adaptation of plug-in electric vehicles. As discussed in chapter 2.3 the costs of solar and wind power have plummeted by up to 90% and 70% in the last ten years, and batteries follow similar cost curves (Lazard, 2020). And just in the last few years the share of plug-in vehicles has accelerated. This makes it incredibly difficult to study as a researcher, because I need to have the best available data, but I also need *verified* data. Thus, while I believe that I have obtained the absolute latest possible *verified* data available, there is always the feeling of being slightly outdated already. Of course, there is no way around this other than to make conclusions based on the most recently available data at any given point in time, or keep updating the analysis every other year and see if the conclusions still stand. In any case, it seems useful to reflect on what is called the Lucas critique, after economist Robert Lucas. He argued that it is naïve to attempt to predict the effect of changes in policy—for instance, in climate or economic policy—purely on the basis of relationships we observe in (especially highly aggregated) historical data (Lucas, 1976).

3.3 Qualitative data and methods used in the dissertation

According to George & Bennett (2005) a case is a well-defined empirical context that showcases an interesting phenomenon relevant for research, and not a historical event in itself. The strength of the qualitative method lies in its potential to unveil and highlight causal mechanisms by investigating decision-making and historical processes in greater detail (Ragin & Becker, 1992; Benton & Craib, 2011). According to Becker (1998), case studies can potentially lead to more complete explanations and deeper understanding of the phenomena we are investigating. Ragin (2014) suggests that it is useful to develop and use a common language and common ideals for qualitative and quantitative research, King, Keohane & Verba (1994) agree and assert that qualitative and quantitative research share the same goal, namely general inference. While some researchers using qualitative methods discard the notion of deploying a variable-oriented language in their methodological tilt, on the basis that it resembles a positivist labeling (Moses & Knutsen, 2012), arguably for most Norwegian political scientists, the variable-oriented language is the norm, as is also the case in my dissertation. As an example, some excellent case studies by Moe (2010; 2012) show how one can use variable-oriented language in a case study. Espen Moe and I used a similar approach in the ferry article (Sæther & Moe, 2021).

3.3.1 Case selection and participation in the ECHOES project

The data collection for the article about the electrification of ferries in Norway was done primarily through expert interviews as part of my participation in the EU Horizon2020 project ECHOES, which stands for "Energy CHOices supporting the Energy Union and the Set-Plan"[8]. The participation resulted in my involvement in several project reports presented to the European Commission. I was one of the project leaders on two of these reports, and first author on one report, entitled: *D6.1: Policy Recommendations: An analysis on collective and energy related decision-making processes of three formal social units* (Sæther et al., 2018)[9] and the first author for the Norwegian section of another report entitled: *D6.3 Suggestions and Recommendations for a Better Understanding of the Factors Driving Collective Energy Choices and Energy Related Behaviour* (Biresselioglu et al., 2019)[10]. At the end of 2017, I interviewed several key stakeholders for the data collection for the D6.1 report and the topic (and success) of the electrification of ferries were brought up several times during the data collection. One interviewee in particular—a county project manager—suggested a very interesting point of study from a social science perspective, involving the interaction of changing procurement practices, climate policies, and industrial policy. Later, in 2018, I convinced the ECHOES Work Package leadership team that an interesting case study of the electrification of a regional ferry connection could serve as an example of a best practice case for report D6.3, in which we would later present 13 case studies and the analysis of best practices and successful implementations concerning energy choices and energy-related behavior in seven European countries, the ferry case being one of the Norwegian contributions. As the ECHOES project progressed, I found that the single case of a regional ferry connection could be expanded to cover the whole process of electrifying the Norwegian ferry sector. This became the article: *A green maritime shift: Lessons from the electrification of ferries in Norway* (Sæther & Moe, 2021). In addition, the case study on the regional ferry connection is published in the journal *Frontiers in Psychology* under the title: *The Significance of Enabling Human Consideration in Policymaking: How to Get the E-ferry That You Want* (Berntsen et. al., 2021).

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[8] https://echoes-project.eu/

[9] https://echoes-project.eu/sites/echoes.drupal.pulsartecnalia.com/files/D6.1.pdf

[10] https://echoes-project.eu/sites/echoes.drupal.pulsartecnalia.com/files/D6.3.pdf

3.3.2 Interview techniques and qualitative method used in the qualitative article

In total, either alone, in participation with Espen Moe, with other ECHOES team members or with master's students[11], I interviewed 13 respondents and hosted two focus group interviews for the data collection of Article 3. The topic of some interviews and focus groups were not exclusively on electric ferries, but it was either explicitly discussed or related issues were debated in the interview setting, warranting inclusion as empirical documentation for this study and thus yielding some significance to the overall data collection. The interviews were conducted as what we can label "elite interviews", which is a fairly open-ended interview where the researcher uses a semi-structured thematic guide (Goldstein 2002; Leech 2002).

When interviewing respondents for Article 3, for the most part I followed the qualitative guidelines and preparations based on a methodology developed by Strauss & Corbin (1990) and Kvale (1996) and inspired by grounded theory[12]. The purpose here was to investigate and potentially discover common and emerging themes, and distinctive patterns, aspects, and sequences in the decision-making process. The interview guide used in the interviews connected to the ECHOES project can be found in appendix A1. Following the context-specific nature of the qualitative approach, I could focus on interpretation to gain deeper understanding of the phenomenon and decision-making processes of interest.

All the interviews were done in Norway and in Norwegian. As mandated by our project guidelines, all interviews had to be transcribed in the respondents' native language and subsequently translated into English. During the analysis, my research team and I systematically read all transcriptions and coded them according to some emergent main themes in the data. Thereafter, we used open coding to break down and conceptualize and label the data. We discussed the coding and labelled and grouped similar phenomena, using broad terms like; "market instruments", "role of networks", "distribution of costs", "incentives". Following the open coding and grouping, the second stage was axial coding. Here, we sorted all codes and groupings into the sets of main themes. Some examples from the ferry case study are: "public sector support schemes", "public procurement", "vested interests", "battery supply chains". Finally, we applied a more selective coding, where the

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[11] Three of the interviews were done together with two master's students from the Department of Industrial Economics and Technology Management at NTNU, supervised by a professor affiliated with the ECHOES project, as their master's thesis project overlapped with the ferry case.

[12] This being the methodology the ECHOES project followed.

core themes were highlighted and we also highlighted especially relevant quotations that might be used in the reports and articles. In the ECHOES interviews we also applied some forms of triangulation to increase the validity and trustworthiness of the extraction from the data material, such as having multiple researchers looking at the same data first individually, then together.

3.3.3 From ECHOES to the ferry case study

Qualitative interviews with relevant stakeholders provided valuable insights that would have been nearly impossible to obtain by only assessing official documents and statements. The qualitative data collection that Article 3 is based on thus uncovers and highlights several aspects of this national transition that are not well known, providing interesting and relevant insights. After reviewing our empirical data at the end of 2019, we found that we still had remaining questions and sought to find more respondents to shed light on our questions. All respondents were chosen for their expertise and viewpoints with the aim to sufficiently cover the most relevant aspects of the political and technological process of the electrification of Norwegian ferries, with the final interviews conducted in December 2019 and early 2020 for the specific purpose of the ferry article. The interview guide used in these interviews looks very similar to the original guide, but is more specific and can be found in appendix A2. Additionally, we relied on official documents, governmental white papers, and national and regional sector strategies in order to get a broad understanding of the case. We also had access to a range of media statements from relevant stakeholders, both from the private and public sectors which we deem part of the case material. All these have contributed to our cross-referencing and understanding of the dynamics and nuances of the transition toward electric ferries in Norway. Finally, we attended six conferences and workshops, the first being the Zero Conference in 2018, an annual climate and environmental conference held in Oslo, Norway hosted by the environmental NGO, Zero. In the fall of 2018, we attended a very relevant workshop on the electrification of the maritime sector in Bergen, arranged by Zero where the topic of the ongoing electrification of the ferries was highlighted from multiple angles. In 2019, we attended three relevant conferences and workshops—namely the Ocean Week in Trondheim, Norway, and a workshop on mobilization for green growth in Trøndelag county, where Trondheim is situated—finally attending the Zero Conference in Oslo in November. In January 2020, we attended the Enova conference in Trondheim. Attendance, and having obtained presentation materials as information for the case study, gave us specific insights and enabled additional cross-referencing material to adjust, support, or disregard statements from interviews, official and media statements as well as providing discussion points during the interview setting.

Ultimately, we chose to fully anonymize the respondents and only label them broadly (e.g. county project manager or technical manager in a shipyard), as there were some respondents who did not wish to be identified and there were some sensitivity issues surrounding contracts, support schemes, and general opinions given in the interview setting, which also led us not to use any direct citations in the article. Instead, wary of the dangers of drawing strong conclusions from single interviews, we rather focused on providing information that represented the majority of the respondents, unless explicitly specified.

4. Summary of articles

This chapter summarizes the findings of the four independent articles in the dissertation and is concluded with a summary of the finding across the four articles. Each article looks at a specific research question related to the study of energy transitions and adds to the accumulation of knowledge within the overall research design. Although the articles are written as part of this dissertation, they are also written as stand-alone research papers submitted to international peer-reviewed journals. The order of the articles follows the progression of the dissertation's theoretical focus and empirical scope. From the questions of climate policy choices in the power sector, to the policies of electrifying the transportation sector, to the political acceleration of the transition in a hard-to-decarbonize sector like the maritime sector, and finally, to whether democratic governance styles matter for the energy transition.

4.1 Article 1: Climate policy choices: An empirical study of the effects on the OECD and BRICS power sector emission intensity

An absolutely crucial and challenging part of the worldwide energy transition is the decarbonization of the power sector. As governments struggle to pass politically feasible emission-reducing policies that also align with other policy goals, empirical studies can provide insights for policy-makers on the question of whether various climate policies have effectively contributed to reducing emissions. Thus, in the dissertation's first article I investigate the effect of several key climate policies policy-makers have implemented to reduce CO_2 emission intensity in the power sector in 34 OECD countries and the 5 BRICS countries, using newly constructed panel data from 2000 to 2018.

The main findings suggest that despite its strong theoretical foundation, the market-based policy tested in this analysis does not display a significant negative effect on CO_2 intensity. On the other hand, technological innovation support policies and deployment supporting policies like feed-in tariffs for wind correlate negatively with CO_2 emission intensity. Feed-in tariffs for solar PV and public environmental R&D expenditures do not show a significant effect on emission intensity.

Theory suggests that market-based policies can get us over the line. Research, however, indicates that this will happen only after they become politically feasible and raised to a point where they are high enough to really matter. This is because they will likely only deliver on their promises if policy-makers decide to implement them in conjunction with other policies that support renewable technology deployment, as well as with policies that stimulate technological innovation and development. In conclusion, the results of this study suggest that policy-makers should focus on a mix of policies where deployment supporting- and technological innovation supporting policies drive the costs of renewable technologies down and set up more cost-effective policies for success.

4.2 Article 2: Mobility at a crossroads—electric mobility policy and charging infrastructure lessons from across Europe

The transportation sector accounts for a significant part of European emissions and is one of the few sectors with rising emissions. Thus, one crucial part of the European strategy to reduce overall emissions is a shift to low-emission mobility and electric mobility in particular, in the transportation sector. As European governments and policy-makers consider feasible ways of supporting the transition, one central question is whether the policies and actions they enact should aim to create incremental or structural change, here operationalized as personal incentives vs. charging infrastructure. Thus, the dissertation's second article investigates the effects of electric mobility policies and charging infrastructure on plug-in electric vehicle (PEV) market shares in Europe from 2009 to 2019. Charging infrastructure, and fast charging infrastructure in particular, exhibits by far the strongest and most robust results of the analysis, having a significantly positive effect on PEV market shares in all models. The analysis also suggests that purchase incentives and some electric mobility policy packages have a positive and significant effect on PEV adoption. These effects are, however, notably weaker across the models in the analysis. Thus, while the study cannot conclusively come down on the side of infrastructure over personal incentives, it persuasively points to the crucial importance of charging infrastructures for the electrification of transportation.

Theoretically this makes sense. Personal incentives will increase the market shares of PEV, but only incrementally, running the risk of merely supplementing the old fossil-fuel based transportation system rather than replacing it. Charging infrastructure on the other hand creates the potential for structural change, implying that a more active and coordinated build-up of charging infrastructure is needed to ensure a rapid transition to low-emission mobility.

4.3 Article 3: A green maritime shift: Lessons from the electrification of ferries in Norway

In the dissertation's third article, co-authored with Espen Moe, we study the electrification of ferries in Norway as a case of a politically accelerated transition. Accelerated transitions are sorely understudied, as is the electrification of the maritime sector. We propose four main explanatory factors for what led to the rapid electrification of Norwegian ferries. First, what we label the Norwegian ferry innovation system played a major role in creating the conditions for—and an environment conducive to—electrification. Second, the Norwegian state acted entrepreneurially, moving beyond merely being a de-risker to playing an active and crucial role as market creator and transformer through various agencies and support schemes. We show that market mechanisms alone would never have yielded as fast a transition, and that what was also key to the state involving itself so heavily was the perception of electrification as ticking several boxes simultaneously, benefiting the climate and potentially creating a growth cluster/industry. Third, the absence of vested interest resistance in the maritime sector made it easy to pursue policies of structural change and find win-win solutions. In fact, to the extent that vested interests played a role, they were actively pushing the state to provide them with conditions that incentivized electrification. Instead of fearing losing out because of electrification, the sector saw the inevitability of change and tried to position itself to benefit from it. Fourth, the relative absence of vested interests interplayed with the occurrence of a strong oil shock, which created further incentives for a maritime sector overly dependent on orders from the petroleum sector to find new markets and products. In many ways, ferries became a new lifeline for the industry. While our findings are undoubtedly partially case-specific—there are several good reasons why Norway would be expected to be a frontrunner in exactly this area—we believe that the case holds important lessons in terms of the interaction between the public and the private sector, and ultimately in terms of how transitions— even in hard-to-decarbonize sectors—can be politically accelerated.

4.4 Article 4: Do Democratic Governance styles matter in the Energy Transition? An empirical inquiry into 46 developed and developing countries from 1990 to 2018

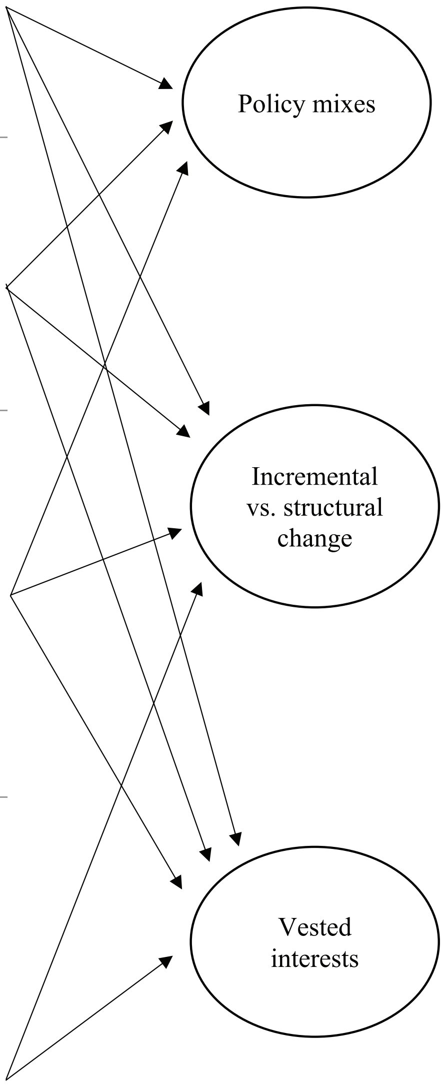
The fourth and final article takes us from studies of general and specific energy transition processes in different sectors to the question of the governance of energy transitions. The article is co-authored with Indra de Soysa and Espen Moe. We were interested in finding out if it was possible to detect whether different democratic styles of governance make a difference to the speed with which countries are transitioning. The existing literature is far from conclusive, but it is often argued that more egalitarian democracies are expected to be better in general at building broader consensus around important issues. Instead, we argue that there are theoretical reasons to believe that with respect to actually implementing climate policies and engaging in energy transitions, these advantages do not necessarily apply. Thus, this paper was in part triggered by a skepticism with parts of the established literature that egalitarian democracies are better at pursuing environmentally friendly policies and part triggered by a theoretically founded suspicion that egalitarian democracies may in fact have a distinctly hard time with processes of structural change. To explore this empirically, we used the Varieties of Democracy (V-Dem) framework to investigate the effect of egalitarian and liberal democratic governance styles on renewable energy production share, environmental related R&D expenditure and CO_2 intensity in 46 OECD, BRICS, and European countries from 1990 to 2018. Our main findings suggest that while there is no major difference between egalitarian and liberal democracies when it comes research funding or the share of renewables in the power mix, egalitarian democracies actually perform worse than liberal democracies with respect to CO_2 intensity. Thus, the suspicion that egalitarian democracies struggle with energy transitions, is supported by the data. Structural change may indeed be a bigger problem for egalitarian democracies. The magnitude of the effects however also suggest that the results are driven as much by consumption as by governance type, and that the greater opportunities for broad-based consumption in egalitarian democracies may be what tends them in the direction of higher CO_2 emissions.

4.5 Results and main findings across the articles

While the previous chapter summarized the findings of the individual articles, this section attempts to summarize the findings across the four articles. Figure 11 shows the findings in brief and the integration of the findings across all articles with the overarching questions the dissertation attempts to address. First, Article 1, 2, and 3 contribute to the question of policy mixes, and the questions surrounding market-based instruments versus technology policy. The articles tackle and shed light on these questions within three different segments of the energy transition, namely the power sector in Article 1, and within the transportation sector, road transport in Article 2, and the maritime segment in Article 3. The main findings across these first three articles are that the ongoing transition in each segment have not have happened by market-mechanisms alone. Rather, targeted well-specified technology- and support policies and governmental intervention have been essential to the transition. Interestingly, these policies tend to create virtuous cycles of deployment, where technology policies drive

Figure 11.. Integration of findings across the dissertation articles

Paper	Findings	Integration of findings
Article 1: *Climate policy choices: An empirical study of the effects on the OECD and BRICS power sector emission intensity*	• Market-based instruments have not been too effective at reducing CO_2 emission intensity • Deployment- and technological innovation supporting policies have been effective • Policy-makers should focus on a mix of policies that set up more cost-effective polices for success	
Article 2: *Mobility at a crossroads—electric mobility policy and charging infrastructure lessons from across Europe*	• Results strongly suggest that charging infrastructure increases PEV market share. • Fast charging in particular is a key enabler for higher PEV market shares. • Evidence for a positive effect of purchase incentives and some policy packages.	
Article 3: *A green maritime shift: Lessons from the electrification of ferries in Norway*	• Politically accelerated transition of the electrification of Norwegian ferry sector possible due to four factors • A system of innovation, labelled "the ferry innovation system", conducive to electrification • A Norwegian entrepreneurial state • Relative absence of vested interest resistance • Occurrence of a strong oil shock	
Article 4: *Do Democratic Governance styles matter in the Energy Transition? An empirical inquiry into 46 developed and developing countries from 1990 to 2018*	• No major difference found in research funding and share of renewable energy in the power mix between egalitarian and liberal democratic governance styles • Egalitarian democracies preform worse than liberal democracies in respects to CO_2 emission intensity • Structural change may be harder in egalitarian democracies • Results however suggest that the increase in CO_2 emission intensity may be driven as much by consumption as by governance type	



deployment, thus driving costs down, which again increases broader uptake, driving down costs further. Thus, over time, costs of transition technologies come down to a point where more cost-effective policies that have so far either been too low or not been implemented can start to make a meaningful contribution. In sum, I show with these contributions that policy-makers cannot rely on market-based instruments alone, and should rather pursue policy mixes that supplement each other's strengths and weaknesses.

Secondly, all four articles contribute either explicitly or implicitly to the question of incremental versus structural change. The first three articles all suggest that what is crucial in order to combat climate change are processes of structural change rather than incremental. The articles highlight both the importance and show examples of how some technology policies and commitment to transition-enabling infrastructure are better suited to yield structural change which can replace, rather than only supplement current fossil-based solutions. The fourth article builds on this suggestion by asking what type of governance is better for the energy transition and tentatively answers that structural change is something that egalitarian democracies may struggle with, possibly because they have a harder time going against major vested interests and phasing fossil fuels out than what liberal democracies do. At a yet early stage of the energy transition, any evidence can only be tentative. Yet, what I present here suggests quite clearly that energy transitions are more easily pursued in liberal democracies.

Finally, all four articles deal with the questions of vested interest, their impact and how to pursue policies and arrangements that lower resistance from vested interests, and in some cases even turns some would-be transition losers into transition convertibles. I show extensively that the impact of vested interest should not be taken lightly in the pursuit of effective climate policy. Rather, understanding how and when vested interest tend to influence policymaking can perceivably lead to policy design that tackles and reduces, rather than increases vested interest resistance. The articles also provide ample examples of under which conditions and policies vested interest resistance can be lowered and even in some cases turned around, making vested interests actively pushing for an accelerated transition.

5. Conclusions

5.1 Main findings of the dissertation

The world's climate goals suggest a rapid energy transition on a scale never witnessed before in history. The current transition is also unprecedented in the sense that much of the climate effort has been, and needs to remain, policy-induced. Up until now, much of the climate effort has only produced incremental change, supplementing, not replacing, the current fossil-based energy system. These incremental efforts fall short of the goals set by the Paris Agreement. Instead, what is in fact needed is structural change.

A crucial question then, becomes which policies policy-makers can pursue that lead to structural change. Additionally, it is important that these efforts are not diminished and outright delayed by incumbent vested interests, who would seek to prolong the current fossil paradigm, thereby extending the current carbon lock-in.

The dissertation provides insights on a range of topics that combined improve our understanding of the energy transition more broadly. It first looks at which climate policies and mixes of policies have been effective at reducing CO_2 emission intensity in the power sector, before moving onto the transportation sector, where it looks at lessons from both electric mobility in Europe and the electrification of the Norwegian ferry sector. Finally, the dissertation delivers some insights on what types of democratic governance styles matter for delivering on the energy transition.

The overall findings lend support to the view that market-based instruments have not so far been particularly effective in the power sector. In the transportation sector, the results suggest that while these market-based instruments and personal financial incentives have played a role in the adoption of electric solutions, they have so far only produced incremental change. The findings rather suggest that technology policy—that contribute to the rapid deployment and diffusion of low- and zero technologies and innovation- and technological development policies—have been more effective. Combining these policies with an active state that supports and facilitates energy transition-enabling infrastructure and extended use of public procurements aimed at supporting the transition is a potent mix of climate efforts more likely to produce structural change and create virtuous cycle of deployment of energy transition technologies.

To the cost-effective paradigm, it might seem like heresy to promote policy mixes and patchwork solutions, which undermine the effectiveness of market-based instruments, but from the perspective of evolutionary economics, the world of economics is really a world of political economy, where the effects of politics need to be taken seriously. And politics is not like the world of economic models, it is messy. Furthermore, from the perspective of evolutionary economy, shocks, disequilibria, and structural change are what pushes the world onto a new trajectory, whether it is a growth trajectory, industrial trajectory, or in the case of this dissertation a new energy trajectory. Thus, to evolutionary economists, cost-effectiveness is of precious little help if we want to understand the world. Patchwork solutions, while not as cost-effective, create solutions and drive down costs, and in doing so, set up market-based instruments and more cost-effective policies to win the day. In other words, structural change does not happen because of market-based, i.e., incremental policies that try to simply adjust their way through the energy transition. It happens because deployment- and technological innovation supporting policies create more level playing fields, drive down costs and make some of the most promising technologies in the present energy transition feasible substitutions for fossil fuel-based technologies. In other words, “an inefficient policy that gets us decarbonized is better than an efficient one that fails to do so. Simply put: carrots get you creative innovation; sticks don’t” (Patt, 2015 p. 280).

On the question of what types of democratic governance styles matter for the energy transition, the results are less obvious. While much of the literature suggests that egalitarian democracies are better for the environment than liberal democracies, we also theorize that egalitarian democracies might struggle with energy transition, as they are more likely to be caught in political carbon capture (e.g. Mildenberger, 2020), where policy-making on both the left and the right is more easily captured by incumbent vested interests. However, our study finds no major difference between egalitarian and liberal democracies when it comes to environmentally related research funding or the share of renewable energy in the power mix, whereas our results suggest that egalitarian democracies actually perform worse than liberal democracies on indicators related to CO_2 intensity. Thus, the suspicion that egalitarian democracies struggle with energy transitions, is supported by the data. Structural change may indeed be a bigger problem here, although the magnitude of the effects also suggest that the results are driven as much by consumption as by governance type. We conclude that the greater opportunities for broad-based consumption in egalitarian democracies may be one explanation for what moves them in the direction of higher CO_2 emissions.

The dissertation argues that up until now technology policy, not market-based policy, has been at the center of the energy transition. And while not as cost-effective as market-based instruments, the technology policies support and introduce crucial energy transition technologies, thereby reducing their costs to a point where they become competitive, leading to more deployment, and again further cost reductions. Structural change in the transportation sector also requires transition-enabling infrastructure, which is less likely to materialize at a sufficient level without a focus on both technology policy and infrastructure commitment.

The central conclusion of the dissertation is that policy-makers need to focus on policies that induce and set up structural change, where technology policy and a commitment to transition-enabling infrastructure set up more cost-effective policies for success. In such a scenario, the problems tormenting market-based policies would slowly get to a point where they would become more politically feasible as their effect has a less draconian effect on the overall economy. In this scenario, these more cost-effective market-based instruments would supplement technology policy, thereby accelerating the structural change needed to reach the world’s climate goals.

5.2 Limitations and calls for further research

Such a large body of work is, of course, not without limitations, as I have elaborated more in detail on the limitation of the qualitative approaches in 3.2.6 and generally in the methods chapters. Although the transition is not going fast enough to be in line with the world's climate goals, the rate of change is still tremendous. Trusting that the data in models are not outdated after the rigorous verification needed to do proper research is always something in the back of one's mind. Another limitation is that some of the climate policies that are clearly relevant, like renewable energy auctions, have not been in operation for long enough or are not available for study. These auctions are also tendered in advance on a project, so their tangible effect in, say, a regression model would have to be carefully managed, and methodology developed. This calls for further research when such data becomes available, verified, and useful for analysis.

On the question of transition-enabling infrastructure, the research frontier is seemingly endless. While the need for charging infrastructure seems obvious, how to best facilitate and support adequate buildout is still sorely understudied. Moreover, for harder-to-decarbonize segments of transportation, the largest heavy-duty segments, most of shipping and aviation, we are likely to see other solutions than pure electrification. Thus, here the challenge becomes one of how to facilitate and support both the commercialization and infrastructure of these new low- and zero-emission fuels, be it hydrogen, ammonia, advanced biofuels, syntenic fuels, or some new invention none of us could even imagine today. One thing is for certain; these solutions will not be commonplace overnight; they will likely rely on governmental support and active facilitation, thus further research on the policies, regulations, and support framework that can contribute to a structural change in these hard-to-decarbonize sectors of the economy is warranted.

On the question of governance in the energy transition, our findings in the fourth article are highly interesting and certainly set the stage for more granular analysis. First and foremost, further research should look at qualitative and comparative case studies of these dynamics of democratic governance of the energy transition. To continue where our study ended seems like a useful starting point for such an endeavor.

Appendix 1.

Appendix A1. Interview guide – ECHOES

Opening:

Hello, my name is *[Interviewer's Name]*, and I would like to welcome you on behalf of the ECHOES Project members, a H2020 project that aims to gain better insights into energy related decisions and decision making processes. Thank you for agreeing to take part in these interview series, as your point of view is very important for us to progress in the right direction.

I would like to remind that this interview session will be taped because we don't want to miss any of your comments. However, I would like to assure you that the discussion will be kept anonymous in accordance with research governance policies, information sheet and consent form.

I would also like to note that there are no right or wrong answers, and we care about your opinions. Therefore, please try to be as precise and detailed as possible, so that we do not miss any of your experiences, feelings, and opinions on the topics we will discuss.

Engagement:

- You can adjust and align the suggested engagement as appropriate for your context of the case you are inquiring.

Transition towards a decarbonized energy system of the future requires development of renewables - including wind, solar, geothermal etc., implementation of energy efficiency measures, new incentive mechanisms, the mobilization at all levels, shift to climate-resilient economy, fostering low-carbon innovations and adoption of new energy technologies.

Therefore, a significant system change is required in a number of areas, particularly through a technological change, and their implementation and acceptance. Especially, smart energy technologies, electric mobility and technological progress improvements to buildings address aforementioned high impact areas, representing the potential (1) to increase clean energy production and energy efficiency measures, (2) to reduce energy consumption and greenhouse gas emissions, (3) to implement system optimization and integration, and (4) electrification of energy system.

Accordingly, (1) smart energy technologies includes distributed, small-scale renewable energy production technologies (typically rooftop solar thermal and PV, micro wind, heat pumps and biomass), but also a range of technologies for the traditional “demand side” (e.g. In-home displays, home automation, smart home appliances, new tariffs etc.) and energy storage; (2) electric mobility includes electric engines (either as plug-in electric cars, hybrid cars or hydrogen cars), uptake of electric vehicles in the car fleet, optimization of transport systems; (3) technological progress improvements to buildings includes construction activities, insulation, energy efficiency upgrading, heating, cooling, illuminating, and energy use behaviour in buildings.

The following interview guide should be applied to each interview: **(Questions highlighted in bold are the key questions.)**

Questions:

1. Description of the Actual Problem/Idea/Case/Project:

    a) Please tell me briefly about your organization and your background.

    b) How long have you been with your current organization?

    c) What is your role in the organization?

    d) Is there anything in particular about the Actual Problem/Idea/Case/Project that you would like to state upfront?

    e) Please describe the Actual Problem/Idea/Case/Project briefly.

    f) Please provide us with an historical overview of the events and context that led to seek for a solution for the Actual Problem/Idea/Case/Project.

2. Analysis of the existing alternatives:

    a) Nowadays, there is a great deal of attention to the low-carbon energy transition. You as a top-level executive/mid-level managers/operational/field employees, how do you perceive low-carbon energy transition and how do you consider the importance of low-carbon energy transition with relevance to your Actual Problem/Idea/Case/Project?

    b) What alternatives were present regarding the Actual Problem/Idea/Case/Project?

    c) How did the organization select among alternative solutions? Briefly mention the top-down and bottom-up dynamics in decision-making process.

3. Development of the roadmap and the Solution Approach:

    a) How do you consider the rationale behind selecting a solution to the case considering the decision-making process?

    b) How was the case/project kick-off decided in the organization?

    c) How can you identify the planning steps that were followed?

    d) Please briefly describe the monitoring and tracking methods implemented for the roadmap.

4. Implementation phases:

a) You as a top-level executive/mid-level managers/ operational/field employees, how do you see your role-play in the implementation of the solution to the Actual Problem/Idea/Case/Project?

b) Please briefly describe how the solution to the case was implemented.

c) What were the challenges encountered during the implementation phase?

d) How would you identify the barriers and motivators that were effective during the implementation?

5. Results of the implementation:

a) You as a top-level executive/mid-level managers/ operational/field employees, how would you rate the success of the solution and why?

b) You as a top-level executive/mid-level managers/ operational/field employees, do you think the expected results were accomplished? Why/why not?

c) You as a top-level executive/mid-level managers/ operational/field employees, can you evaluate the results based on the key stakeholders' perspective?

d) How was the effectiveness of the solution measured?

e) What factors played a key role in the effectiveness of the solution?

6. Impact and Diffusion of Results:

a) You as a top-level executive/mid-level managers/ operational/field employees, how do you see the long term affects associated with the case including the impacts on the organization, its environment and stakeholders?

b) Where is the association headed in the future with the experience generated from Actual Problem/Idea/Case/Project?

Dismissal:

Provide a short summary of the things discussed and thank for taking part. Provide your card in case they might want to further get into contact with you.

Appendix A2. Interview guide—Electrification of ferries—translated

Interview guide - electric ferries – Connections

Hello and welcome to the interview. My name is Simen Rostad Sæther and I am a research fellow at NTNU and NTNU sustainability where I work with energy and climate-related issues on a daily basis. I have worked extensively with effects of various energy and climate policy on emission intensity in the power sector. I have also worked closely with ECHOES project, which is an EU-funded H2020 project that aims to gain better insight into energy-related decisions and decision-making processes at both the individual and societal level, within the three technological focus areas; smart energy technology, electric mobility and buildings.

I would like to talk to you in more detail about the ZZ connection (s), and go deeper into the decision-making processes, support schemes and political framework conditions that have led you to decide to go for an electric low-emission solution. So today I talk to you in XX and I look forward to hearing more about how this has been from your point of view. I would also like to remind you that I will record the conversation so that I do not miss important comments. At the same time, I want to assure you that our discussion will be kept anonymous in accordance with public guidelines, the information sheet and the consent form.

1. Description of the case and actor:

a) Tell me briefly about which relevant areas XX is responsible for/work with when it comes to the topic of electric ferries and preferably also briefly about your background, what you work with here and how long you have worked in XX?

b) Can you briefly describe the XX role in the ZZ project/s?

c) Please give me a brief historical overview of events and context that led to XX helping to create a more climate-friendly solution for the ZZ connection/s.

d) Can you tell us about whether the county or whether this particular ferry connection had any special conditions for such a solution to be chosen? For example, geography, distance, vessel size or departure frequency?

2. Analysis of existing alternatives:

a) Solutions are now being worked on for the transition to a low-emission society in most sectors and areas of society. How do you experience this in your job as a project manager / leader / advisor / actor, and how will you assess the importance of this focus in society when it came to the solution that was chosen for the ZZ connection/s?

b) Can you say something about what other alternatives were on the table for the ZZ connection(s)?

c) Tell me a little about how you chose among the alternative solutions? Feel free to tell us in detail how you proceed when you prepared a tender like this.

d) Would you say that the decision-making processes in the project can best be described as primarily top-down, or bottom-up driven? Feel free to tell us a little about how this has unfolded in this project.

3. Development of roadmaps and solution approach:

a) How would you consider the rationale behind the choice of the solution that was chosen, based on this decision-making process?

b) Can you describe any obstacles in the process before the tender process was completed and decided? For example, of a political, economic or technological nature.

c) After the solution was chosen, which processes were then started from XX side?

d) Can you identify which planning steps have been followed during the process and feel free to describe any methods you use to follow up the implementation.

4. Implementation phase:

a) Can you say which factors have been important after the tender process was concluded on your part?

b) What would you say has been challenging in the implementation phase? Have you encountered any obstacles or barriers that have been problematic during the implementation?

c) Can you identify any success criteria for successful implementation?

5. The results of the implementation:

a) As a project manager / manager / advisor / stakeholder, how will you assess the success of the solution that has been chosen and why? Comment if you consider that the expected results have been achieved.

b) As a project manager / manager / advisor / stakeholder, how would you evaluate the result, with the view of the key stakeholders?

c) How do you evaluate goal achievement?

d) What factors would you say you played a key role in making the solution as optimal as possible? Feel free to also comment on factors you consider to be essential for success.

6. The effect and dissemination of the results:

a) In the longer term, what ripple effects do you think this project will have for the organization, other and future tenders in the sector and other relevant actors? Feel free to tell us about what experiences you bring from the ZZ project into future projects.

Interview guide - electric ferries - Actors

Hello and welcome to the interview. My name is Simen Rostad Sæther and I am a research fellow at NTNU and NTNU sustainability where I work with energy and climate-related issues on a daily basis. I have worked extensively with effects of various energy and climate policy on emission intensity in the power sector. I have also worked closely with ECHOES project, which is an EU-funded H2020 project that aims to gain better insight into energy-related decisions and decision-making processes at both the individual and societal level, within the three technological focus areas; smart energy technology, electric mobility and buildings.

I would like to talk more about how you have worked with electric / low-emission ferries in Norway and to go deeper into the decision-making processes, support schemes and political framework conditions that have now led to Norway coming a long way on its way to lower emissions from the ferry sector and the road ahead for the Norwegian maritime sector.

So today I talk to you in XX and I look forward to hearing more about how this has been from your point of view. I would also like to remind you that I will record the conversation so that I do not miss important comments. At the same time, I want to assure you that our discussion will be kept anonymous in accordance with public guidelines, the information sheet and the consent form.

1. Description of actor:

a) Tell me briefly about which relevant areas XX is responsible for/work with when it comes to the topic of electric ferries and preferably also briefly about your background, what you work with here and how long you have worked in XX?

b) Which actors do you work most closely with in the ferry sector and how would you describe your collaboration with them?

c) What expertise/competence does XX have that makes you an important actor in the ferry sector and its development towards lower emissions?

2. Analysis of existing alternatives:

a) Can you say something about what alternatives the counties and the Norwegian Public Roads Administration have when they work with tenders? We know that electric/hybrid has come a long way in recent years, but that there are tenders/connections where other solutions may be relevant - if so, which are these? And feel free to tell us what you think about the technological development for electric ferries going forward? Are there any barriers on the on the technology side, say, on board the ferries? Or on the infrastructure side, such as grid capacity/getting enough charging effect etc. that are barriers holding back the development?

b) Tell us about how you work with the actors who contact you about assistance/assessment/competence.

3. Development of roadmaps and solution approach:

a) Do you know of any obstacles in the processes before the decision to go for electric/low emission solutions? For example, of an economic or technological nature, which was resolved/possibly not resolved?

b) Has XX had any role after the decisions have been made? In that case, feel free to tell us about the methods you use to follow up the actor.

4. Implementation phase:

a) Has XX been involved in any implementation phase?

b) Do you know if there have been any challenges in the implementation phase among the projects you have been involved in? Have you encountered any obstacles or barriers that have been problematic during the implementation?

c) Can you identify success criteria for projects that have been successful?

5. The results of the implementation:

There are more and more connections that are getting new ferries, and many more are on the way. of approx. 200 ferries in Norway will approx. 70 be low emissions by the end of 2021:

a) How would you like to assess the preliminary transitions we have witnessed in Norway, with a view of the key stakeholders?

b) What factors would you say have played a key role in making the solutions as optimal as possible?

c) How do you evaluate goal achievement in XX?

6. The effect and dissemination of the results:

The technological development within electric/low emission ferries is very rapid and many classify this as a new industrial adventure for Norway, where Norway can take a leading role internationally:

a) In the longer term, what ripple effects do you think this may have in the Norwegian maritime sector, such as high-speed ferries and more demanding ferry connections?

b) Also feel free to tell us about what experiences you in XX take with you from the projects you have been a part of into future projects.

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Article 1:

Climate policy choices: An empirical study of the effects on the OECD and BRICS power sector emission intensity

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Analyses of topical policy issues

Climate policy choices: An empirical study of the effects on the OECD and BRICS power sector emission intensity

Simen Rostad Sæther

Department of Sociology and Political Science, Norwegian University of Science and Technology, 7491 Trondheim, Norway

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ABSTRACT

A crucial and challenging part of the worldwide energy transition from fossil fuels to renewable energy is the decarbonization of the power sector. As governments struggle to pass politically feasible, emission-reducing policies that align with other national and international goals, empirical studies can provide insights for policymakers on the question of whether various approaches to combating climate change have effectively contributed to reducing CO_2 emissions. This paper investigates the effect of several key climate policies that governments have implemented in order to reduce CO_2 emission intensity in the power sector; used in this analysis are newly constructed panel data on 34 OECD countries and the 5 BRICS countries that range from 2000 to 2018. The main findings of this paper suggest that, despite a strong theoretical foundation, the market-based policy tested in this analysis does not display a significant negative effect on CO_2 emission intensity. Technological innovation support-policies and deployment-support policies such as feed-in tariffs for wind power production correlate negatively with CO_2 emission intensity. Feed-in tariffs for solar PV and public environmental R&D expenditure do not indicate a significant effect on emission intensity.

1. Introduction

The power sector is a crucial part of modern society and a significant source of global CO_2 emissions worldwide. Electricity and heat generation account for about 25% of global annual emissions. Electricity accounts for about 19% of final energy consumption; this is a share that is expected to rise considerably as more and more countries electrify their economies (IEA, 2018). Understanding how different climate policy choices support a shift towards cleaner technologies becomes an important insight for policymakers as governments plan and implement policies that are aligned with other policy objectives or goals related to energy, including energy demand increases, increases in efficiency and security, and so on, which are pursued concurrently to emission reductions. Given the power sector's position in the transition from fossil fuels to renewable energy (as being arguably the primary potential enabler of a low-carbon economy), interest from scholars in this sector has been rising fast. However, there is no consensus among scholars and experts on what policies might rapidly decarbonize the power sector. Some scholars argue that the most cost-effective way to decarbonize this sector is through market-based approaches such as a carbon tax or an emission cap-and-trade system. By contrast, other researchers propose a less strictly market-based approach where supportive policies, such as feed-in tariffs, R&D funding, and technology- and innovation-support grant enterprises more room to operate in the creation of new markets; furthermore, enterprises are assisted with deploying new capacity for renewable energy generation. This drives down the

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E-mail address: simen.r.sather@ntnu.no.

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costs for clean technologies through learning curves and economies of scale, which ultimately levels the playing field for renewable technologies.

Despite a strong theoretical foundation that market-based approaches produce the most effective way to reduce carbon emissions, Cullenward and Victor (2020) and Patt (2015) argue against placing the brunt of climate efforts solely on the promises of market-based approaches, as there are clear political, institutional, and enforcement constraints complicating the efforts of setting carbon prices high enough to be significant for environmental outcomes. Given this backdrop, this study presents a comprehensive empirical analysis of the effects of various climate policies on the outcome of CO_2 emission intensity in the OECD and BRICS power sector; I used the latest available data obtained from IEA, being also the first client to receive the data on CO_2 emission intensity that includes the year 2018 (IEA, 2020a). The rest of the data are collected from the World Bank, IRENA, and the OECD databases with new panel data for feed-in tariffs and cross-referenced data on the EU ETS and other emission trading systems around the OECD and BRICS; this is constructed for panel data analysis. Combining both the main market-based instruments and support policies in the power sector in an analysis of the OECD and BRICS countries, this paper covers the majority of the world's power sectors, and it can produce novel insights on the performance of different climate policies that countries in the analysis have implemented. The results of this analysis suggest that despite a strong theoretical foundation, the market-based instrument tested does not hold up to empirical scrutiny. Following those conclusions, the analysis shows that, although not as cost-effective and efficient, other policies (herein labeled deployment- and technological innovation support policies) seem to have contributed to a reduction in CO_2 emission intensity in the studied OECD and BRICS power sectors. This conclusion supports the view that the renewable energy revolution researchers have been witnessing over the last few decades were not enabled by market-based instruments but rather by targeted, generous, and technology-specific policies with substantial subsidies from an active state. Fortunately, now that these renewable energy technologies are competitive and a viable alternative to fossil fuels, the price level at which market-based policies can start to phase out CO_2-intensive power production has been reduced; this thereby sets up more cost-effective approaches for having a potentially greater impact.

The paper is organized in the following sections: Section 2 presents a brief summary of the relevant literature on various climate and energy-related policy choices, Section 3.1 presents the dataset and variables; Section 3.2 follows up with the model specification. Results and a discussion of them are presented in Section 4, which is followed by conclusions and policy implications in Section 5.

2. Literature review

2.1. Market-based approaches

In the OECD and increasingly in the BRICS block, the dominating paradigm in climate policy discussions is centered around market-based solutions. Instruments such as a carbon tax or an emission cap-and-trade system are the preferred solutions by policymakers as they wish to provide a market mechanism that will allocate resources and capital while reaching environmental goals at the lowest possible cost (Baumol and Oates, 1988; Hahn, 1989). By contrast, traditional environmental protection has taken the form of direct governmental regulations, which is often referred to as "command-and-control" regulation; this comes in the form of a technology requirement or emission standards. While standards have been a popular policy tool for policymakers, economists argue that these stringent regulatory approaches leave little flexibility for companies to reach both economic and environmental goals (Portney and Stavins, 2000). On the other hand, market-based instruments "harness market powers, because if they are well designed and implemented, they encourage firms (or individuals) to undertake pollution control efforts that both are in those firms' (or individuals') interests and collectively meet policy goals" (Portney and Stavins, 2000, pp. 31–32). Especially within the OECD, green tax reforms and other forms of carbon pricing are increasingly gaining popularity and support from relevant regulators (OECD, 2018). In the BRICS block, China experimented with eight pilot carbon markets in key jurisdictions and has fully implemented its national carbon-trading scheme as of the 1st of February 2021; the eight pilots have been integrated into the national emission trading system (ETS) (BNEF, 2017; World Bank, 2020a). Moreover, as climate-related issues are moving further up on the political agenda, researchers have witnessed an apparent shift in the handling of climate-related issues from the jurisdiction of the Ministries of Environment towards the Ministries of Finance, and consequently a change in the discussion of climate policy from traditional emission standards regulation towards a push for market-based solutions. Global financial institutions such as the World Bank and the International Monetary Fund (World Bank, 2014; IMF, 2015) are also actively promoting such policy prescriptions.

A contested effect of market-based approaches is that they tend to increase electricity prices, and researchers have studied the so-called CO_2 cost pass-through effect on the prices of wholesale electricity, although the evidence for the described effect is somewhat mixed (e.g., Fezzi and Bunn, 2009; O'Gorman and Jotzo, 2014; Patt, 2015; Wang and Zhou, 2017; Woo et al., 2018). Nevertheless, most scholars agree that this effect occurs in varying degrees in places with carbon pricing policies, and without adjustment, prices tend to be regressive in that they place a greater burden on those with lower incomes relative to those with higher income. However, it can be argued that while an increase in electricity prices stimulates energy savings and efficiency measures, it could also increase the risk of declining social acceptability among consumers, which produces opposition from energy-intensive industries, e.g., through a loss of competitive advantage and lower margins that result from higher electricity prices, as well as their pollution-related externalities (Tobin and Cho, 2010).

However, while market-based instruments have a strong theoretical foundation, the academic literature on their effects on emissions is mixed (to put it very favorably). Most published studies have understandably focused on the EU ETS, while the remaining studies have focused on various sub-national initiatives, including some in the US and the Chinese ETS pilot programs, as well as a few other Asian initiatives. Looking first at the research on the EU ETS, Martin et al. (2016) found in their ex-post analysis of the EU ETS an effect on emissions in regulated sectors in energy and industry in Phase I and the first two years of Phase II. Similar results are found in Anderson and Di Maria (2011) and Bayer and Aklin (2020). Of the studies that do not look at the EU ETS, Gao et al. (2020) uncovered some emission reduction effects when studying the impact of the Chinese pilot ETS programs; their conclusion was that the effect of CO_2 emission reduction is greater in production-based emissions than in consumption-based emissions. A study on the Korean ETS discovered a 2.5% emission reduction from the base case, but an electricity price increase of nearly 4% was associated with it (Choi et al., 2017). By contrast, other studies that form the majority of the literature indicates a far less convincing picture of this effect. Green (2021) provides an ex-post meta-analysis of carbon pricing policies worldwide, with data collected since 1990 and concludes that very few of these policies have actually contributed to significant emissions reductions. The analysis of this study also highlighted that carbon taxes, where applied, have generally been more successful than emission trading schemes (albeit both policies have not delivered the significant reductions promised by economic theorists). Of the studies that focus on the EU ETS, Bel and Joseph (2015) argued that EU emission reductions over the period studied are primarily attributable to the effect of the economic crisis rather than the ETS. Several studies have found a small effect of between around 1% to 2% in emission reduction in the EU ETS over the periods studied (Ellerman and Buchner, 2008; Egenhofer et al., 2011; Ellerman et al., 2016; Dechezleprêtre et al., 2018), while Gloaguen and Alberola (2013) discovered no statistically significant effects of the EU ETS on emissions in their panel data from 2005 to 2011. Outside of the EU ETS, Cullenward (2014) found that the California carbon market had severe carbon leakage, which delivered less of the emission reduction that was promised when accounting for the leakage. Fell and Maniloff (2018) concluded that when looking at the Regional Greenhouse Gas Initiative (RGGI) in the Northeastern US, CO_2 emissions were observed to be down 8.8M tons per year, but the RGGI states leaked about 4.5M tons per year, which puts the actual drop to about 4.3M tons per year. Both Tobin and Cho (2010) and Lin and Li (2011) discovered either no significant effect of environmental taxes and carbon taxes on CO_2 emissions, or that these policies were underperforming in countries that have implemented them; furthermore, Patt (2015) suggested that market-based instruments have been too weak to matter significantly in their outcomes. Lilliestam et al. (2021) went as far as to contend, in a recent paper, that there is no empirical evidence showing the effectiveness of carbon pricing as far as stimulating innovation and zero-carbon investment. Finally, Laing et al. (2013) suggested that enterprises with both top-down and sector-based, bottom-up evaluations could attribute savings in the range of 40 to 80 $MtCO_2$ per year in the EU ETS in all sectors that were covered by the scheme. Furthermore, Laing et al. (2013) concluded that EU ETS has only had a minor impact on investment decisions thus far. As European policymakers continue to affirm their commitment to the European trading system, decision-makers are likely planning for higher prices in the future. Regardless, it is important to underscore that there are large sectorial differences that affect outcomes, and that market-based instruments might work better or worse depending on sector-specific characteristics, e.g., the range of cost-competitive and viable substitutions and regulatory complexity. To pose a testable hypothesis, I relied on the theoretical foundations of market-based instruments, but I am well aware that previous studies suggest that we should not trust those foundations blindly.

2.2. Deployment- and technological innovation-supporting policies

In addition to studying market-based solutions, I evaluated policies focusing on technology support and deployment. The dominant policy promoting rapid deployment and cost reduction of renewable energy technology has been feed-in tariffs (FIT). For solar PV and wind power, in particular, FITs have created several strong domestic markets where both of these technologies have had considerable deployment: Germany is a prime example of this effect. Moreover, while FITs are sometimes defined as a market-based instrument, they operate according to a distinctly different mechanism from a emission cap-and-trade system, usually with a long price-purchasing agreement (PPA), which lasts typically for 15 to 20 years and includes sell-back priority back to the grid with premium pricing; therefore, FITs are better described as a support policy geared for scaling up renewable energy capacity (OECD, 2020). Thus, FITs' objective is to produce renewable energy technologies that support cost-competitive before regular market forces take over (Alizamir et al., 2016). According to a 2008 report by the European Commission, "well-adapted feed-in tariff regimes are generally the most efficient and effective support schemes for promoting renewable electricity" (European Commission, 2008). Studies by Alagappan et al. (2011), Dong (2012), Carley et al. (2017) support the notion that feed-in tariffs have been successful in promoting renewable energy and, thus, reducing emissions. Analyses of FIT schemes suggest that their success rate depends on the level at which tariffs are set and how well these tariffs are adjusted over time, particularly in light of new information and technological developments; in turn, this decides the profitability of investments. Aggressive tariffs are shown to increase investors' profitability, generally, but they can lead to less efficient projects that are subsidized at the taxpayers' expense. On the other hand, relatively more conservative tariffs could lead to limited technology deployment by making only the most efficient projects financially viable (Mendonca et al., 2009). A recent systematic review of the evidence of induced innovation in energy technologies by Grubb et al. (2021) discovered that deployment policies, such as feed-in tariffs, have been instrumental in driving down the costs of renewable technologies and that such policies (and their effects) are often overlooked in the policy debate and even more so by the modeling community. The results are what we might call the *vitreous cycle of deployment polices*: technology policies drive deployment which drives down costs; this increases broader uptake, which again drives down costs.

Technology and innovation policy has been another widely used approach in the goal of reducing CO_2 emissions. Newell (2009) argues that "a well-targeted set of climate policies, including those targeted directly at science and innovation, could help lower the overall costs of mitigation", but stresses that poorly designed technology policy could also potentially raise the cost of mitigation rather than lowering it. Newell continues stating that market-based prices on emissions, together with technological support policies, can be particularly effective in technology-areas where the private sector is least eager to invest. He concludes that "effective climate technology policy complements rather than substitutes for emissions pricing" (Newell, 2009, p.38). It is undoubtedly crucial that scientists innovate and develop more efficient climate mitigation technologies, including in renewable energy, storage, and smart grid technologies and systems; however, measuring the innovation or innovative performance of these technologies is notoriously difficult. One such evaluation approach that has been suggested is to look at research and development (R&D) expenditure. Tobin and Cho (2010) discovered a significant negative effect of environmental R&D expenditure on greenhouse gas emission in their study of 26 OECD countries, while Mazzucato (2015) concluded that public R&D expenditure is an important part of measuring the innovative performance of a country, but this is not adequate alone. Thus, another way to meet the goal of evaluation in this sector is to attempt to measure innovation through the study of patents, most commonly as practiced in econometrics (see, for instance Johnstone et al., 2010, 2012). According to Hall (2013), patent statistics are desirable because they are an objective measurement, but assuming that they constitute a stable measurement of innovation, does not follow. Mazzucato (2015) warned that patent statistics alone are an inadequate measurement for innovation or the rate of technological change, but patent statistics can be one part of the picture, together with the aforementioned public R&D expenditure. OECD researchers Haščič and Migotto (2015) suggested that OECD patent statistics such as the variable used in this analysis are analytical tools for assessing countries' innovative performance as these patents are a reliable, albeit far from a perfect, "measure of technological innovation because they focus on the outputs of the inventive process"' (Griliches, 1998 in Haščič and Migotto, 2015, p.15). The use of patent statistics as a measure of innovation has some clear advantages and some notable drawbacks: measures like these are commensurable, widely available, and quantitative in nature; furthermore, they can be disaggregated into sub-categories or domains, lending themselves useful for researchers across fields of study. The most notable drawbacks of patent statistics are that not all innovations are patentable, and not all patentable inventions are patented, and as such data can vary in quality (Haščič and Migotto, 2015).

From a theoretical perspective, it is extremely important to attempt to measure innovation. As I discussed, there are obvious advantages and disadvantages to using patents as an indicator. However, based on the above discussion, patent statistics are a quantitative measurement of innovation outputs, which is arguably the main reason that patents are a good indicator. I can thus propose a testable hypothesis that technological innovation support-policies which are proxied by patent statistics have contributed to a significant reduction in emission intensity, and that despite its shortcomings, it is fairly straight-forward to make a credible argument on why this is the best indicator that researchers currently have to measure innovative performance.

Based on the literature review I have presented above, I propose three main hypotheses to be tested empirically:

H1: *Market-based policy instruments such as emission trading systems have resulted in a decrease in* CO_2*intensity from electricity generation.*

H2: *Deployment supporting policies such as feed-in tariffs for solar PV and wind have resulted in a decrease in* CO_2*intensity from electricity generation.*

H3: *Technological innovation support policies have contributed to a decrease in* CO_2*intensity from electricity generation.*

Increases in consumption, along with industrial development, have traditionally implied an increase in fossil-based electricity generation, and while renewables dominate markets today (2020), this was not always the case for the whole time period used in the analysis. According to Asane-Otoo (2016), increases in consumption will mainly depend on the electricity used in a given country; however, as it is a general control variable that covers all 39 countries, I expect an increase in electricity generation to correlate positively with an increase in CO_2 emission intensity. Thus, I expect that increases in GDP per capita, energy consumption from industry, and residential electricity consumption will all correlate positively with CO_2 emission intensity. Furthermore, I expect the last control variable, installed renewable energy capacity, to correlate negatively with intensity of CO_2 emissions.

3. Data and methodological approach

3.1. Data and variables

The analysis investigates collected, processed, and formatted data that ranges from 2000 to 2018, and that covers 34 OECD countries and the 5 BRICS countries (Sæther, 2021). To make a note, the years after the Fukushima Daiichi nuclear disaster in Japan are removed because of the shock it caused to the Japanese power sector (EIA, 2017); this is unfortunate, but it is difficult to control for otherwise. Data on CO_2 emission intensity (CO_2 *emission intensity per* KWh) were purchased

Table 1
CO_2 emission intensity change in percent and changes in grams per KWh.

Country	CO_2 emission intensity change % 2000–2009	Change in grams per KWh 2000–2009	CO_2 emission intensity change % 2010–2018	Change in grams per KWh 2000–2018
OECD:				
Australia	5,1	43,3	−15,0	−125,0
Austria	−4,7	−8,2	−25,2	−50,0
Belgium	−28,2	−84,2	−10,1	−22,5
Canada	−19,9	−43,7	−28,1	−51,3
Chile	10,0	34,3	−3,7	−15,3
Czech Republic	−18,3	−133,9	−15,5	−90,6
Denmark	−10,6	−47,7	−53,5	−193,8
Estonia	1,2	13,1	−17,4	−177,9
Finland	8,6	15,3	−50,0	−117,0
France	3,5	2,7	−31,3	−25,0
Germany	−11,5	−62,3	−15,8	−75,2
Greece	−11,8	−98,5	−25,4	−185,1
Hungary	−33,2	−157,0	−20,9	−66,8
Iceland	−50,0	−0,2	−50,0	−0,1
Ireland	−30,0	−195,0	−29,2	−136,3
Israel	−9,4	−72,9	−29,3	−204,8
Italy	−17,4	−87,7	−25,2	−103,1
Japan	4,9	19,5	16,5	70,9
Korea	−1,6	−9,0	−2,5	−13,5
Luxembourg	−27,2	−128,6	−55,0	−187,6
Mexico	−13,5	−79,7	−9,4	−47,3
Netherlands	−14,5	−72,7	−1,1	−4,5
New Zealand	1,9	3,2	−29,7	−45,7
Norway	841,7	10,1	−62,6	−14,4
Poland	−7,6	−67,0	−11,7	−93,2
Portugal	−22,3	−109,7	14,6	37,6
Slovak Republic	−14,5	−36,4	−21,0	−42,3
Slovenia	−7,3	−25,5	−23,6	−78,1
Spain	−32,1	−141,5	7,7	18,4
Sweden	−17,0	−3,8	−49,6	−13,1
Switzerland	2,6	0,6	4,0	1,0
Turkey	−6,1	−32,6	−0,7	−3,3
United Kingdom	−6,6	−31,6	−49,7	−224,7
United States	−15,9	−99,7	−22,5	−119,4
BRICS:				
Brazil	−27,6	−24,9	13,2	11,6
Russia	1,9	7,7	−15,0	−62,7
India	2,2	17,7	−7,3	−58,8
China	−14,2	−127,8	−18,2	−136,7
South Africa	1,4	12,7	−5,8	−54,5

and obtained from the IEA Emissions Factors database.[1] The decision to focus on CO_2 intensity rather than CO_2 emission is first-and-foremost a question of how to most effectively measure the performance of the power sectors' ability to reduce CO_2 emissions while at the same time attempting to eliminate the underlying growth in electricity demand. According to Ang and Su (2016), a variable measuring CO_2 intensity is a good performance indicator since "a decrease in its value indicates a lower level of CO_2 emissions for each unit of electricity produced than otherwise. This can be taken as a desirable outcome from the environmental and climate change viewpoints" (Ang and Su, 2016, p.57). The measure of intensity is a ratio expressed in grams of CO_2 per KWh. The ratio is based on total emissions from fossil fuels consumed for electricity generation, in both electricity-only and combined heat and power plants (CHP), which is divided by the output of electricity generated from all fossil and non-fossil sources (IEA, 2020b). As a ratio of two physical measurements, CO_2 intensity per KWh is a transparent and unambiguous variable that can be compared across countries and over time (Ang and Su, 2016). Table 1 indicates that power sectors' emission intensity around the world is trending downward. The variable is log transformed in the analysis.

Data on emission trading system quota prices (*Emission Trading System Price*) are cross-referenced from several sources[2] using the mean annual value for the quota price in US$ per ton of CO_2 equivalent. Furthermore, the price was deflated

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[1] For full calculation see page 35 in http://wds.iea.org/wds/pdf/CO2KWH_Methodology.pdf (IEA, 2020b).

[2] Weekly data from April 2008 is sourced and calculated to annual data from the EU ETS dashboard that is provided by Sandbag (2020), while prior data is sourced from a range of official EU sources which estimate an annual price for 2005–2007. The rest of the emission trading system data is collected from the World Bank Carbon Pricing Dashboard (World Bank, 2020a).

in order to adjust to inflation in the allowance price by using the CPI index (2010 = 100) that was collected from the World Bank, which is itself based on IMF data (World Bank, 2021). Several previous studies have used a simple dummy variable to measure whether or not a country is connected to an ETS, and this in most instances have been the EU ETS. However, since the effectiveness of the ETS is primarily determined by the price at which emission quotas are traded, it makes more sense to use the actual price of a quota as the annual mean price to measure whether or not it has been effective at reducing emission intensity in the sample countries. In addition to the EU ETS, which covers 23 countries, Australia implemented their own emissions trading scheme called the ERF Safeguard Mechanism — which has been in effect since 1 of July 2016 and at 17 US$. South Korea launched its national ETS in 2015, New Zealand in 2008 (with operations in 2010), and finally Switzerland had their own ETS outside of the EU ETS, with trading beginning in 2011; since January 1. 2020, the Swiss ETS have been linked with the EU ETS. Of the various sub-national ETS around the world, China has introduced 7, and then 8, pilot carbon markets from December 2013 with the eighth coming into operation in late 2016, and California introduced its California Cap and Trade (CaT) system in 2012. The province of Quebec in Canada introduced an ETS in 2013, and while the trading system covers the power sector, it is dominated by hydroelectric power production and is thus excluded outright. In order to include these sub-national emission trading schemes, I coded them by the following formula: the yearly price divided by the number of sub national schemes in a given year, multiplied by the share of the countries power sector emissions in ETS jurisdiction. For China, I have used a mean coverage of 25% (based on a calculation provided in Jotzo and Löschel (2014). The real number is somewhere between 20 and 30% over the time-period since the pilot projects were implemented. For California, I have used a 7% share, as the Californian power sector accounts for about 5%–7% of the total US power sector (DOE, 2015). As a precaution, I ran one stricter model, without the inclusion of modified sub-national ETS (*ETS price (national only)*), and one model without the inflation adjusted ETS price (*ETS price (non-inflation adjusted*); both tests showed no significantly different results and the outcomes can be found in the appendix.

Another market-based instrument that is often proposed as a cost-effective measure to reduce CO_2 emissions is a pure carbon tax. However, with very few exceptions, like the UK carbon price support (CPS) system, every country that has a carbon tax in the analysis exempted its power sector from it, because these countries, with few exceptions,[3] are also connected to the EU ETS and have decided not to double-tax their power producers; thus, a pure carbon tax variable is omitted from the analysis. Finally, another variable that is sometimes used when studying the effect on emissions in the power sector is a broadly defined energy tax. These measurements are mainly tallied as a percentage of state revenues from energy production. The problem with using such a variable to investigate whether various types of policies affect CO_2 emission intensity, in the power sector, is that renewable and other lower-emission energy production technologies are also taxed and, indeed in some countries, taxed at the same rate as their fossil-based counterparts. Therefore, this analysis only uses the ETS price variable, as it is the only variable measuring this form of intervention, i.e., how a market-based instrument affects CO_2 emission intensity is what I am interested in. Fig. 1 shows the evolution of the ETS quota prices (non-inflation adjusted) in the various countries that have implemented the policy.

The indicator of renewable energy feed-in tariffs (*FIT solar PV*, *FIT wind*) is collected from OECD's Environmental Policy database. The indicator measures mean feed-in tariff for a.) Solar PV, and b.) Wind. The data are comprised of country-level values on the tariff in US$/KWh. There exist data on small hydro, biomass, waste, geothermal, and marine energies, but the focus for this analysis is on solar PV and wind (OECD.stat., 2020a). Figs. 2 and 3 display the feed-in tariffs for solar PV and wind.[4]

Governmental R&D expenditure is an important indicator for technology development and innovation. This analysis uses an indicator measuring the share of public environmental R&D expenditure of total public R&D expenditure (*Public environmental R&D expenditure*). There are several other useful indicators for measuring R&D as it is related to the power sector, such as energy-related R&D, and renewable energy R&D, but these data are incomplete and lack consistent measurement that is suitable for panel data analysis; therefore, the broader environmentally-related R&D indicator is the best available measure, although it lacks data for Brazil, China, India, and South Africa. The variable was collected from the OECD Green Growth dataset (OECD.stat., 2020b).

All patent statistics that are used in this analysis were collected from OECD's Innovation in environmental-related technologies database. The data were compiled by the OECD Environment Directorate, in collaboration with the Directorate for Science, Technology, and Innovation, which used additional data from the Worldwide Patent Statistical Database (PATSTAT). The indicator used in this paper is Technology Diffusion (*Technological innovation support policies*), which is defined as the number of inventions that seek protection through national, regional, or international routes in a given jurisdiction as restricted to the sub-category: *Climate change mitigation technologies related to energy generation, transmission or distribution* (OECD.stat., 2021). This variable is log-transformed.

Finally, the indicators for GDP per capita (*ln(Income)*) have been log-transformed and together with the indicator for residential electric power consumption in MWh (*Residential electricity consumption*), and the variable for related to industry (*Industry share of GDP*), measuring industry (including construction), and value-add as a percentage of GDP, were

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[3] The Australian carbon tax experiment from 2012–2014 is an example.

[4] The dataset classifies the various feed-in tariff equivalent schemes in the US as feed-in tariffs; more information can be found here: https://www.eia.gov/todayinenergy/detail.php?id=11471# (EIA, 2013).

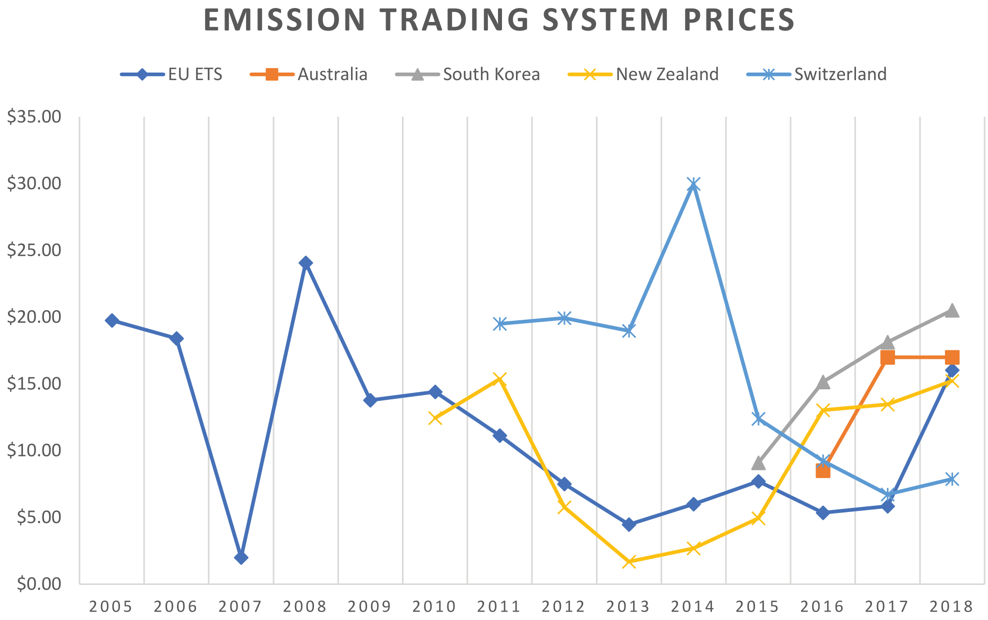

Fig. 1. Annual CO_2 quota price in Emission Trading Systems.
Source: Constructed based on Sandbag EU ETS dashboard and World Bank Carbon Pricing dashboard.

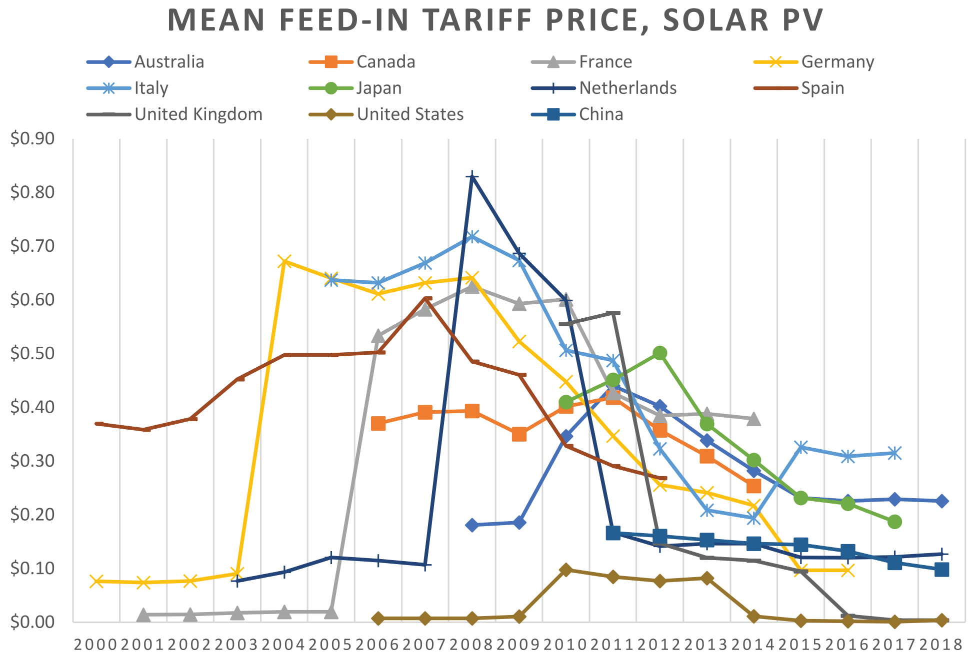

Fig. 2. Feed-in tariffs solar PV in US dollars/KWh.
Source: Constructed based on the OECD Environmental Policy database.

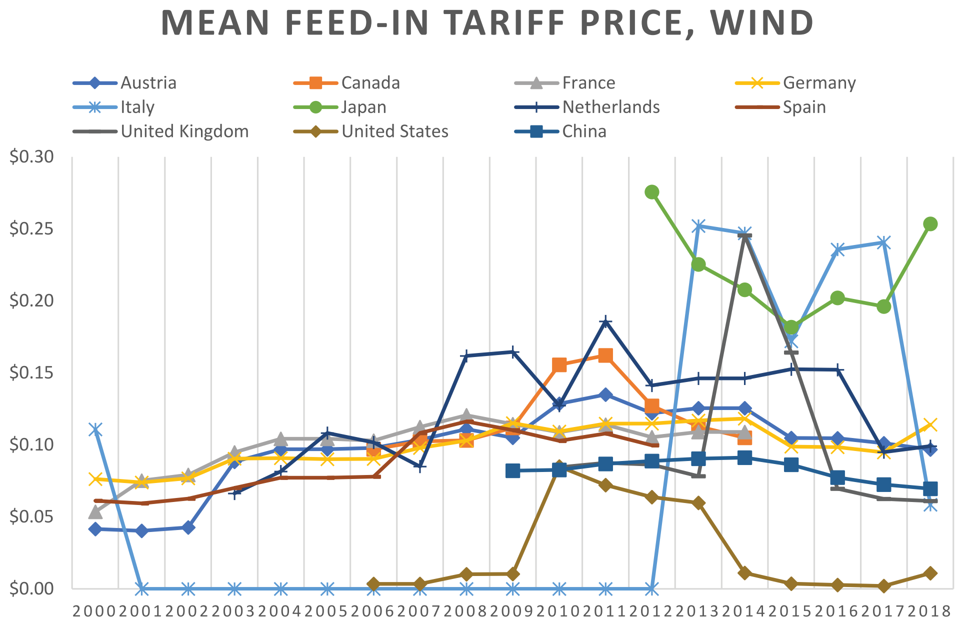

Fig. 3. Feed-in tariffs wind in US dollars/KWh.
Source: Constructed based on the OECD Environmental Policy database.

Table 2
Descriptive statistics.

Variables	N	Mean	St. dev	Min	Max	Unit
CO_2 emission intensity	733	413.75	267.65	0.10	1,096.10	Gram of CO_2 emission per KWh
Emission trading system price (inflation adjusted)	741	5.31	7.44	0	30.21	US$ per tonne of CO_2 equivalent
Feed-in tariff Solar PV	741	0.12	0.20	0	0.83	Mean feed-in tariff in US$/KWh
Feed-in tariff Wind	741	0.05	0.09	0	0.73	Mean feed-in tariff in US$/KWh
Public environmental R&D expenditure	595	2.61	2.09	0	17.66	% of total R&D budget
Technological innovation support policies	741	1,765.26	5,080.44	0	53,501	Number of patents
Income	741	31,405.90	22,621.67	443.31	1,18,823.6	US$ constant
Industry GDP	738	25.91	6.13	10.52	47.56	Value added, % of GDP
Industrial energy consumption	740	27.66	8.31	9.45	56.18	% of total energy consumption
Residential electricity consumption	741	8.38	7.57	0.40	55.10	MWh per capita
Installed renewable energy capacity	741	28.23	59.20	0.01	695.48	Installed GW

all obtained through the World Bank Open Data database (2020b).[5] The alternative indicator used to control for industry energy consumption (*Industrial energy consumption*) measures the share of industrial energy consumption of total energy consumption, and has been collected from the OECD Green Growth dataset (OECD, 2020). Finally, the data on installed renewable energy capacity (*ln(Installed renewable energy capacity)*) have been collected from the IRENA database and measures the cumulative renewable installed capacity from all renewable sources (excl. nuclear power). The variable is log-transformed (IRENA, 2020). Table 2 provides summary statistics for every variable used in the regression analysis.

Table A.1 (with variables included in Table 3) and Table A.2 (with variables included in Table 4) in the Appendix provide pairwise correlation tables for the variables included in the analysis. As policy instruments like ETS can affect energy prices (thus affecting consumption), I have run separate models with and without consumption variables. Furthermore, policies like feed-in tariffs have likely influenced renewables' installed capacity, and can thus lead to some over control in the model and is therefore only included in some model specifications.

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[5] GDP per capita and industry share of GDP is collected from World Bank national accounts data, while residential electricity consumption in MWh per capita is based on IEA statistics.

3.2. Model specifications

To investigate the effects of climate policy choices on CO_2 emission intensity in the OECD and BRICS power sector, this study used panel data regression with the fixed-effects estimator with Driscoll–Kraay standard errors. The Driscoll–Kraay method estimates standard errors are robust to spatial correlation and heteroscedasticity when using ordinary least squares (OLS) regression (Driscoll and Kraay, 1998; Hoechle, 2007). By using the fixed-effects estimator, equivalent to the unit centering all observation, researchers can investigate deviations in the mean in each unit over time (Petersen, 2004). Another advantage of using such a model, according to Asane-Otoo (2016), that used a similar regression design to investigate the effect of liberalization of electricity markets on emissions intensity in the OECD, is that the fixed effects model controls for unobserved heterogeneity or time-invariant omitted variables and can provide unbiased estimates even if these variables correlate with explanatory variables. One clear downside to using the fixed-effects model is that it only estimates within-country variation, hence comparisons between countries are not possible. Moreover, a fixed effects model does not allow for time-invariant variables in the analysis (Petersen, 2004; Beck, 2008). In order to investigate whether or not to use a fixed-effects estimator over a random-effects (RE) estimator, the main model has been run with both estimators followed up by a Hausman test. The result of the Hausman test suggests evidently that fixed effects are the proper estimator for the model. Furthermore, the dependent variable in the panel data analysis may suffer from the problem of non-stationarity, or unit-root. After running appropriate tests for this method, the results indicate that there is not a significant problem with the unit-root in the dependent variable in the analysis. The model thus employs a fixed effects estimator, with the general fixed effects equation:

$$Y_{it} = \beta_0 + \beta_{(1,2,\ldots,n)it} X_{(1,2,\ldots,n)it} + (\alpha_i + \varepsilon_{it})$$

4. Results and discussion

The main models in Table 3 contain the dependent variable; logged CO_2 intensity (l*nCOI*) and three independent variables; emission trading system (*ETS*), Feed-in tariffs for solar PV ((FiT_{PV}) and wind (FiT_W) and controls (*Controls*).

Main fixed effects model Table 3:

$$lnCOI_{it} = \beta_0 + \beta_1 ETS + \beta_2 FiT_{PV} + \beta_3 FiT_W + \beta_{(4,5,6,7)} Controls + \beta_8 YearsDummy + \varepsilon_{it}$$

The main models in Table 4 contain the dependent variable; logged CO_2 intensity (l*nCOI*) and five independent variables; emission trading system (*ETS*), feed-in tariffs for solar PV (FiT_{PV}) and wind (FiT_W), public environmental R&D expenditure (*R&D*), and technological innovation support policies (*TISP*), and controls (*Controls*).

Main fixed effects model in Table 4:

$$lnCOI_{it} = \beta_0 + \beta_1 ETS + \beta_2 FiT_{PV} + \beta_3 FiT_W + \beta_4 R\&D + \beta_5 TISP + \beta_{(6,7,8,9)} Controls + \beta_{10} YearsDummy + \varepsilon_{it}$$

Finally, the analysis deploys temporal control by adding year dummies as time fixed-effects in all models.

Table 3 presents the regression results for the fixed-effect models. The table below displays six models with estimated fixed-effect coefficients with Driscoll–Kraay standard errors. To test the presence of collinearity in the models, I have used variance inflation factors (VIF). All of the VIF values are below threshold levels, which suggests that the explanatory variables are independent of one another. Furthermore, all F-statistics are significant.

Looking at the market-based variable emission trading system price, the estimated coefficients suggest there is a negative correlation with CO_2 emission intensity, but the relationship is not significant in any model. The impact of deployment- and technological innovation support policies is more mixed. The results indicate that feed-in tariffs for wind power have a negative and significant relationship with CO_2 emission intensity across nearly all models in the study at the 0.05 and at the 0.01 significance levels. Feed-in tariffs for solar PV, on the other hand, show no such significant relationship.

Finally, the control variable, income, which measures GDP per capita, displayed a significant positive effect on CO_2 emission intensity, which is robust at the 0.01 significance level across all model specifications, while industrial GPD indicator was not significant in any models. Residential electricity consumption is positively correlated with higher CO_2 power sector emission intensity at the 0.05 significance level in Models 5 and 6. Installed renewable energy capacity displays a negative and significant effect at the 0.01 significance level. Table 4 shows results of the technology innovation support policies. The results from Table 3 stay generally the same with the inclusion of these policy indicators. As for the public environmental R&D expenditure, the results are not significant, while technological innovation support policies show a negative significant effect at the 0.01 significance level across all models. The control variable, Income, stayed positive and significant while residential electricity consumption and installed renewable energy capacity were not significant.

Table 3
Effect of climate policy choices on power sector CO_2 emission intensity.

CO_2 emission intensity per KWh	(1) FE	(2) FE	(3) FE	(4) FE	(5) FE	(6) FE
Emission trading system price	−0.00259		−0.00121	−0.00147	−0.00129	−0.00158
	(0.00340)		(0.00174)	(0.00115)	(0.00114)	(0.00125)
Feed-in tariff Solar PV		0.0417	0.0449	0.0286	0.0268	0.0256
		(0.0324)	(0.0315)	(0.0271)	(0.0279)	(0.0271)
Feed-in tariff Wind		-0.193^{**}	-0.200^{**}	-0.186^{**}	-0.186^{***}	-0.195^{***}
		(0.0790)	(0.0753)	(0.0740)	(0.0673)	(0.0599)
ln(Income)				0.161^{***}	0.164^{***}	0.175^{***}
				(0.0339)	(0.0354)	(0.0395)
Industry GDP				0.00290	0.00346	
				(0.00818)	(0.00825)	
Industrial energy consumption						−0.00213
						(0.00329)
Residential electricity consumption					0.00524^{**}	0.00683^{**}
					(0.00197)	(0.00291)
ln(Installed renewable energy capacity)					-0.0882^{***}	-0.0798^{***}
					(0.0286)	(0.0259)
Constant	5.574^{***}	5.652^{***}	5.652^{***}	4.061^{***}	4.146^{***}	4.176^{***}
	(0.0375)	(0.000996)	(0.000945)	(0.378)	(0.388)	(0.362)
R-squared (within)	0.0067	0.2430	0.2436	0.2573	0.2688	0.2745
Observations	733	733	733	730	730	733
Countries	39	39	39	39	39	39
Time period	2000–2018	2000–2018	2000–2018	2000–2018	2000–2018	2000–2018
Country fixed effects	YES	YES	YES	YES	YES	YES
Time fixed effects	NO	YES	YES	YES	YES	YES

Note: Driscoll–Kraay standard errors in parentheses, all columns include year fixed effects.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.1. Robustness tests

Several robustness tests have been performed. First and foremost, having both OECD countries, which are mostly developed economies together with BRICS, which are primarily developing countries, might suggest we are dealing with different stages of climate policy implementation, and, as such, different policy effects. Since I incorporated the per capita (*ln(income)*) and industrial control variable in the models, I captured some of differences in the development stages and industrial structure. Nevertheless, for robustness purposes, I ran the main models with an OECD-only sample found in Table A.3. Interestingly, the ETS variable is barely significant at the 0.1 significance level in the two models with ETS and feed-in tariffs for solar PV and wind in the OECD-only sample. When including the R&D and technological innovation support policies indicators, the significant results of the ETS disappear. By and large, the rest of the model stays the same as in the OECD and BRICS sample. The results are nevertheless surprising and might suggest that the ETS policies have been more effective in the more developed countries of the OECD, compared to the less-developed countries of BRICS; further research is warranted.

Table A.4 displays the results of the regressions using the more conservative emission trading variables that exclude the adjusted sub-national emission trading systems; Tables A.5 and A.6 shows models with non-inflation adjusted ETS, and the results are nearly identical with the results in Tables 3 and 4. Additionally, I have estimated all models using Cook's distance (Cook, 1977), which looks for influential observations or outliers. I found no significant outliers, further strengthening the robustness of the results.

4.2. Discussion

Considering policies aimed at scaling up renewable energy deployment, the significant negative effect of feed-in tariffs for wind energy generation on the power sector's CO_2 emission intensity is not surprising. Many countries included in this analysis have generous feed-in tariffs for wind power that have likely contributed significantly to cost-reduction, and this explains the accumulated capacity observers see for wind power around the world. The results are robust across all model specifications tested. The finding that feed-in tariffs for solar PV do not seem to display the same significant negative effect as wind power is somewhat surprising, but not entirely unexpected as solar PV electricity production has, until recently, been fairly marginal, even if solar power will have an even greater role for energy production and CO_2 emission reduction in the decades to come. This is partly due to their enormous cost reductions and small areal footprint, not to mention the fact that they can be placed on existing buildings. Areal and visibility disputes surrounding onshore wind power are likely to increase in the coming decades as land becomes scarce, which could inevitably force most new wind power offshore, and even further down the line, into floating offshore wind installations. As onshore wind power is

Table 4
Effect of climate policy choices and technology support policies on power sector CO_2 emission intensity.

CO_2 emission intensity per KWh	(7) FE	(8) FE	(9) FE	(10) FE	(11) FE
Emission trading system price		0.000276	−0.000606	−0.000351	−0.000547
		(0.00118)	(0.00107)	(0.00115)	(0.00116)
Feed-in tariff Solar PV		0.0240	0.00697	0.00498	0.00739
		(0.0320)	(0.0336)	(0.0338)	(0.0327)
Feed-in tariff Wind		-0.289^{***}	-0.260^{**}	-0.263^{***}	-0.284^{***}
		(0.0751)	(0.0953)	(0.0882)	(0.0739)
Public environmental R&D expenditure	0.00599	0.00630	0.00721	0.00813	0.00866
	(0.00629)	(0.00624)	(0.00746)	(0.00758)	(0.00645)
Technological innovation support policies	-0.0544^{***}	-0.0546^{***}	-0.0520^{***}	-0.0448^{***}	-0.0460^{***}
	(0.0102)	(0.0102)	(0.00955)	(0.0101)	(0.0104)
ln(Income)			0.140^{**}	0.129^{*}	0.148^{***}
			(0.0582)	(0.0686)	(0.0482)
Industry GDP			0.00388	0.00502	
			(0.0104)	(0.0110)	
Industrial energy consumption					−0.00177
					(0.00342)
Residential electricity consumption				0.00219	0.00354
				(0.00309)	(0.00342)
ln(Installed renewable energy capacity)				−0.0561	−0.0503
				(0.0366)	(0.0316)
Constant	5.822^{***}	5.829^{***}	4.342^{***}	4.459^{***}	4.444^{***}
	(0.0567)	(0.0575)	(0.441)	(0.555)	(0.476)
R-squared (within)					
Observations	587	587	587	587	587
Countries	35	35	35	35	35
Time period	2000–2018	2000–2018	2000–2018	2000–2018	2000–2018
Country fixed effects	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES

Note: Driscoll–Kraay standard errors in parentheses, all columns include year fixed effects.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

now one of the cheapest sources of new electricity generation in most places around the world, the results of the empirical analysis suggest that feed-in tariffs for wind power have, while being expensive, significantly contributed to reducing CO_2 emission intensity in the OECD and BRICS countries (with the added benefit of driving down the technological cost for current and future installments: a trend that is likely to, and frankly must, continue, if the world is to have any chance of reaching its climate goals). As policy innovations continue to surround goals to ensure environmental sustainability, new and interesting policies have emerged as the costs of solar PV and wind power have reached more competitive prices. One of these is renewable energy auctions or tenders: this allows governments to tender new capacity in a competitive market of bidders, thus securing competitive prices (IRENA, 2019). This helps alleviate feed-in tariffs' greatest downside, namely its limited price flexibility and long-term "locked-in" prices.

Furthermore, as technological innovation support-policies have a significant negative effect on CO_2 emissions, the results indicate that policies that have stimulated overall innovation in climate change-mitigating technologies (i.e. in electricity generation, transmission, and distribution, and for renewable energy technologies specifically) have contributed to CO_2 emission intensity reductions. The finding is in line with the research of, amongst others, Patt (2015), Mazzucato (2015) and Grubb et al. (2021). This suggests that policies aimed at technological innovation support could be an effective way for governments to assist in climate change mitigation efforts. Not all patented innovations will lead to emissions reductions, but the cumulative effort of a country's innovation efforts will surely increase the chance of technological innovations that may have significant emission reduction potential, not only regarding renewable energy technologies but in terms of innovations in transmission and distribution as well.

Finally, the emission trading system variables tested correlated negatively with CO_2 emission intensity, but this is statistically insignificant across all models. This finding is more surprising, and the results are harder to explain, but they are somewhat in line with several other studies that have looked at the effect of market-based instruments on CO_2 emissions, emission intensity, and environmental performance (for instance Green, 2021). These studies, however, have evaluated everything from cross-sectoral taxes to the effect of environmental taxes for emissions in all sectors, and some of them are arguably difficult to compare with the results from this study. This observation also underscores the importance of studies like mine that look at policies that target the power sector in particular, and combine both market-based instruments and deployment- and technological innovation-support policies in the same analysis.

There are two plausible explanations for these results. The first likely explanation for the lack of effect is that the quota prices in the emission trading systems studied are simply too low to have a significant impact. While few observers would argue against an emission trading system with a sufficiently high price on carbon, policymakers have to consider the short-to-medium feasibility of reaching these prices. Because, as Patt (2015) points out, unless prices are high enough to really matter, at least in the short-term, they are only an instrument for more efficient fossil-based electricity production. At the same time, policymakers could also increase electricity prices, which tend to have regressive effects, in addition to its impact on energy-intensive industries (which in turn makes it even harder to pass more strict climate policy measures as these industries ramp up lobbyism; this is combined with a fear of layoffs and loss of national competitiveness). On the other hand, due to coal's high carbon intensity, even a moderate quota price increase should, in theory, result in serious reductions in the use of coal-fired power production. European policymakers have already taken some steps towards strengthening the EU ETS by introducing a Market Stability Reserve (MSR) that attempts to address the current problem of surplus allowances and improve the resilience to shocks by adjusting the supply of allowances that can be auctioned, but this has been introduced too late to have had any effect on my study (European Commission, 2019). Furthermore, while it would make sense to look at the different temporal dimensions of policies as they take time to come into full force, the effect of the price signal should, in theory, be fairly immediate as a higher quota price that should lead to changes in the merit-order by increasing the price of CO_2 intensive sources.

Going forward, as policymakers attempt to find the right mix between political feasibility and cost-effectiveness, some key lessons can be drawn from the discussion of the empirical results of this study. The fact that renewable energy technologies such as solar and wind have already dropped significantly in price and are expected to continue to do so, provides power producers with reliable and cost-competitive substitutes for fossil-based generation. This, in turn, increase the likelihood of the feasibility of passing adequate market-based instruments that will assist in keeping new fossil-based capacities uneconomical and, in the longer term, also to help phase out existing, uneconomical fossil-based generation. Thus, the policy implications presented here suggests that market-based approaches have not been effective enough to decarbonize the power sector and will likely not be able to do so alone going forward. On the contrary, the reason some observers suggest that the power sector is one of the easiest sectors to decarbonize is precisely because generous governmental support policies and long-term commitment to renewable energy development have made them cost-competitive substitutions to coal, gas, and nuclear electricity generation.

4.3. Limitations

Although this study considers many of the prominent climate policy choices policymakers have implemented in an effort to reduce emissions in their power sectors, the analysis does not cover all of them. Green certificates, tax credits, net metering, and the aforementioned competitive bidding auctions/tendering are policies that are not included or investigated in the study. Part of the reason is that some of these policies have only become prominent in recent years due to innovations and due to the falling costs of renewable energy, and therefore they are less relevant for the time period studied (especially as many successful tenders are still in construction). These are nevertheless important policies one should keep in mind when interpreting the results. Thus, the possibility that these policies would have impacted the results if the data were available cannot be discarded.

5. Conclusion and policy implications

This study investigates the effect of several prominent climate policy choices that have been implemented with the aim of reducing CO_2 emissions and emission intensity in the power sector. By analyzing panel data of 34 OECD and 5 BRICS countries taken from 2000 to 2018, the study set out to test the effect of climate policies on CO_2 emission intensity using empirical methods. For the market-based policy tested, the effect of the emission trading systems indicated no significant effect on CO_2 emission intensity. Using an OECD-only sample, the results showed a significant negative effect of emission trading systems at the 0.1 significance level in the OECD sample. This finding is interesting but, considering the weak statistical effect, suggests further research is needed.

Looking at deployment-supporting policies for renewable energy, the results from this analysis suggest that feed-in tariffs for wind have contributed to a reduction in CO_2 emission intensity, while this analysis finds no significant relationship with feed-in tariffs for solar PV. Finally, technological innovation to support policies correlates negatively with CO_2 emission intensity while public environmental R&D expenditure does not.

The results of this study contain some policy implications. While market-based instruments have strong theoretical foundations and are important policies to pursue for policymakers, there is limited evidence to suggest that the renewable energy revolution researchers have witnessed in the last decades has come from the deployment of market-based instruments. Rather, there is more evidence to suggest that deployment and technology-specific policies have been more significant: a result which is much in line with findings of a recent review by Grubb et al. (2021).

Theory suggests that market-based policies can help get governments and people 'over the line' in combating climate change, but research indicates that this will happen only after market-based policies become politically feasible enough to a point where they can really have an effect — these efforts will likely only deliver on their promises if policymakers decide to implement them in conjunction with other policies that support renewable technology deployment (i.e. with an eye to stimulating technological innovation, development, and cost reductions). In conclusion, the results of this study indicate that policymakers are benefited by advocating for a 'mix' of policies where deployment supporting- and technological innovation-supporting policies drive the costs of renewable technologies down, and thereby set up more cost-effective market-based policies for success.

Table A.1
Correlation table (N = 730)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1. **COI**	–							
2. **ETS**	−0.1596	–						
3. **FitPV**	0.1210	0.2537	–					
4. **FITW**	0.0748	0.0698	0.3936	–				
5. **inc**	−0.4053	0.3538	0.1858	0.0791	–			
6. **IGDP**	0.1054	−0.1785	−0.1537	−0.1447	−0.4442	–		
7. **IEC**	−0.2759	−0.1667	−0.2037	−0.1768	−0.3317	0.4722	–	
8. **REC**	−0.7460	0.1369	−0.0812	−0.1299	0.5005	−0.1540	0.2859	–
9. **IRC**	−0.1051	−0.1755	0.0080	0.0074	−0.1053	0.1841	0.2266	−0.0550

Table A.2
Correlation table (N = 587)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1. **COI**	–									
2. **ETS**	−0.1126	–								
3. **FitPV**	0.1687	0.2107	–							
4. **FITW**	0.1334	0.0477	0.4079	–						
5. **R&D**	0.0938	0.0701	0.0001	−0.0863	–					
6. **TISP**	0.2337	−0.2099	0.1322	−0.0486	−0.0567	–				
7. **inc**	−0.3939	0.2196	0.0918	0.0307	−0.1215	0.0434	–			
8. **IGDP**	−0.0095	−0.1091	−0.1359	−0.1682	−0.0147	0.1206	−0.3898	–		
9. **IEC**	−0.4871	−0.0343	−0.1679	−0.2052	0.0286	−0.1723	−0.0688	0.3590	–	
10. **REC**	−0.7722	0.0375	−0.1506	−0.1726	−0.0403	−0.1843	0.4603	−0.0633	0.5380	–
11. **IRC**	−0.1513	−0.1189	0.0636	0.0074	−0.0946	0.6577	0.1956	0.0381	0.0299	0.0535

Table A.3
Robustness analysis with OECD countries only.

CO$_2$ emission intensity per KWh	(12)	(13)	(14)	(15)
	FE	FE	FE	FE
Emission trading system price	−0.00208*	−0.00222*	−0.000359	−0.000615
	(0.000948)	(0.00115)	(0.00121)	(0.00122)
Feed-in tariff Solar PV	−0.00427	−0.00761	0.00447	0.00588
	(0.0317)	(0.0316)	(0.0340)	(0.0332)
Feed-in tariff Wind	−0.138**	−0.132***	−0.263***	−0.284***
	(0.0538)	(0.0467)	(0.0892)	(0.0741)
Public environmental R&D expenditure			0.00810	0.00859
			(0.00755)	(0.00650)
Technological innovation support policies			−0.0447***	−0.0458***
			(0.0100)	(0.0103)
ln(Income)	0.233**	0.249***	0.131	0.154**
	(0.0872)	(0.0697)	(0.0813)	(0.0539)
Industry GDP	0.00325		0.00496	
	(0.0106)		(0.0113)	
Industrial energy consumption		0.00397		−0.00172
		(0.00390)		(0.00341)
Residential electricity consumption	0.00642**	0.00476	0.00220	0.00356
	(0.00264)	(0.00340)	(0.00313)	(0.00342)
ln(Installed renewable energy capacity)	−0.0654	−0.0541	−0.0561	−0.0504
	(0.0425)	(0.0335)	(0.0369)	(0.0316)
Constant	3.293***	3.102***	4.435***	4.378***
	(0.786)	(0.690)	(0.665)	(0.527)
R-squared (within)	0.3130	0.3200	0.3491	0.3484
Observations	635	638	582	582
Countries	34	34	34	34
Time period	2000–2018	2000–2018	2000–2018	2000–2018
Country fixed effects	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES

Note: Driscoll–Kraay standard errors in parentheses, all columns include year fixed effects.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A.4
Robustness analysis with ETS price national only.

CO_2 emission intensity per KWh	(16) FE	(17) FE	(18) FE	(19) FE	(20) FE
ETS (national only)	−0.00393	−0.00161	−0.00170	−0.00160	−0.00193
	(0.00361)	(0.00185)	(0.00123)	(0.00119)	(0.00129)
Feed-in tariff Solar PV		0.0456	0.0289	0.0274	0.0263
		(0.0314)	(0.0270)	(0.0279)	(0.0270)
Feed-in tariff Wind		-0.202^{**}	-0.187^{**}	-0.188^{**}	-0.196^{***}
		(0.0748)	(0.0735)	(0.0671)	(0.0596)
ln(Income)			0.160^{***}	0.164^{***}	0.174^{***}
			(0.0336)	(0.0351)	(0.0390)
Industry GDP			0.00288	0.00340	
			(0.00817)	(0.00823)	
Industrial energy consumption					−0.00226
					(0.00328)
Residential electricity consumption				0.00535^{**}	0.00704^{**}
				(0.00199)	(0.00292)
ln(Installed renewable energy capacity)				-0.0881^{***}	-0.0796^{***}
				(0.0284)	(0.0257)
Constant	5.581^{***}	5.652^{***}	4.071^{***}	4.153^{***}	4.184^{***}
	(0.0357)	(0.000940)	(0.373)	(0.383)	(0.357)
R-squared (within)	0.014	0.244	0.257	0.269	0.275
Observations	733	733	730	730	733
Countries	39	39	39	39	39
Time period	2000–2018	2000–2018	2000–2018	2000–2018	2000–2018
Country fixed effects	YES	YES	YES	YES	YES
Time fixed effects	NO	YES	YES	YES	YES

Note: Driscoll–Kraay standard errors in parentheses, all columns include year fixed effects.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A.5
Robustness test of models in Table 3, with ETS price non-inflation adjusted.

CO_2 emission intensity per KWh	(21) FE	(22) FE	(23) FE	(24) FE	(25) FE	(26) FE
Emission trading system price (n-inf. adj.)	−0.00400		−0.00164	−0.00177	−0.00166	−0.00199
	(0.00362)		(0.00185)	(0.00123)	(0.00119)	(0.00129)
Feed-in tariff Solar PV		0.0417	0.0458	0.0291	0.0276	0.0265
		(0.0324)	(0.0314)	(0.0270)	(0.0279)	(0.0271)
Feed-in tariff Wind		-0.193^{**}	-0.202^{**}	-0.187^{**}	-0.188^{**}	-0.196^{***}
		(0.0790)	(0.0749)	(0.0736)	(0.0672)	(0.0596)
ln(Income)				0.161^{***}	0.164^{***}	0.175^{***}
				(0.0336)	(0.0352)	(0.0390)
Industry GDP				0.00284	0.00337	
				(0.00816)	(0.00823)	
Industrial energy consumption						−0.00228
						(0.00328)
Residential electricity consumption					0.00536^{**}	0.00705^{**}
					(0.00199)	(0.00292)
ln(Installed renewable energy capacity)					-0.0879^{***}	-0.0793^{***}
					(0.0285)	(0.0258)
Constant	5.581^{***}	5.652^{***}	5.652^{***}	4.068^{***}	4.151^{***}	4.180^{***}
	(0.0356)	(0.0001)	(0.0009)	(0.3730)	(0.3830)	(0.3570)
R-squared (within)	0.0145	0.2430	0.2441	0.2576	0.2692	0.2749
Observations	733	733	733	730	730	733
Countries	39	39	39	39	39	39
Time period	2000–2018	2000–2018	2000–2018	2000–2018	2000–2018	2000–2018
Country fixed effects	YES	YES	YES	YES	YES	YES
Time fixed effects	NO	YES	YES	YES	YES	YES

Note: Driscoll–Kraay standard errors in parentheses, all columns include year fixed effects.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A.6
Robustness test of models in Table 4, with ETS price non-inflation adjusted.

CO_2 emission intensity per KWh	(27) FE	(28) FE	(29) FE	(30) FE	(31) FE
Emission trading system price (n-inf. adj.)		−0.000479	−0.000401	−0.000135	−0.000386
		(0.00136)	(0.00121)	(0.00128)	(0.00131)
Feed-in tariff Solar PV		0.0237	0.00689	0.00485	0.00734
		(0.0320)	(0.0336)	(0.0339)	(0.0328)
Feed-in tariff Wind		−0.288***	−0.259**	−0.261***	−0.283***
		(0.0744)	(0.0945)	(0.0877)	(0.0734)
Public environmental R&D expenditure	0.00599	0.00636	0.00718	0.00812	0.00864
	(0.00629)	(0.00627)	(0.00745)	(0.00755)	(0.00646)
Technological innovation support policies	−0.0544***	−0.0546***	−0.0521***	−0.0448***	−0.0460***
	(0.0102)	(0.0102)	(0.00951)	(0.0101)	(0.0104)
ln(Income)			0.138**	0.127*	0.147***
			(0.0578)	(0.0686)	(0.0488)
Industry GDP			0.00393	0.00509	
			(0.0104)	(0.0110)	
Industrial energy consumption					−0.00178
					(0.00343)
Residential electricity consumption				0.00219	0.00358
				(0.00310)	(0.00342)
ln(Installed renewable energy capacity)				−0.0565	−0.0505
				(0.0367)	(0.0316)
Constant	5.822***	5.829***	4.360***	4.478***	4.458***
	(0.0567)	(0.0575)	(0.442)	(0.558)	(0.481)
R-squared (within)	0.331	0.338	0.346	0.349	0.348
Observations	587	587	587	587	587
Countries	35	35	35	35	35
Time period	2000–2018	2000–2018	2000–2018	2000–2018	2000–2018
Country fixed effects	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES

Note: Driscoll–Kraay standard errors in parentheses, all columns include year fixed effects.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Disclaimer

This work is partially based on the data from the Emissions Factors database developed by the International Energy Agency, © OECD/IEA 2021, but the resulting work has been prepared by the author, *Simen Rostad Sæther* and does not necessarily reflect the views of the International Energy Agency.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The dataset in the article can be found at: http://dx.doi.org/10.17632/vs899t86tv.1, *an open-source online data repository hosted at Mendeley Data (*Sæther, 2021*)*

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Appendix. Supplementary material

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Article 2:

Mobility at a crossroads—electric mobility policy and charging infrastructure lessons from across Europe

Mobility at a crossroads – electric mobility policy and charging infrastructure lessons from across Europe

Simen Rostad Sæther
simen.r.sather@ntnu.no

Department of Sociology and Political Science, Norwegian University of Science and Technology, 7491 Trondheim, Norway

Highlights

- Study of electric mobility policy and charging infrastructure effect on PEV uptake.
- Panel data on 30 European countries from 2009–2019 are used.
- Results strongly suggest that charging infrastructure increases PEV market share.
- Fast charging in particular is a key enabler for higher PEV market shares.
- Evidence for a positive effect of purchase incentives and some policy packages.

Abstract

The transportation sector accounts for a significant part of European emissions and is one of the few sectors with rising emissions. Thus, one crucial part of the European strategy to reduce overall emissions is a shift to low-emission mobility and electric mobility in particular, in the transportation sector. As European governments and policymakers consider feasible ways of supporting the transition, one central question is whether the policies and actions they enact should aim for creating incremental or structural change, here operationalized as personal incentives vs. charging infrastructure. Therefore, this analysis investigates the effects of electric mobility policies and charging infrastructure on plug-in electric vehicle (PEV) market shares in Europe from 2009 to 2019. Charging infrastructure, and fast charging infrastructure in particular, exhibit by far the strongest and most robust results of the analysis, having a significant positive effect on PEV market shares in all models. The analysis also suggests that purchase incentives and some electric mobility policy packages tested have a positive and significant effect on PEV adoption. These effects are however notably weaker across the models in the analysis. Thus, while the study cannot conclusively come down on the side of infrastructure over personal incentives, it persuasively points to the crucial importance of charging infrastructures for the electrification of transportation. Theoretically this makes sense. Personal incentives will increase the market shares of PEV, but only incrementally, running the risk of merely supplementing the old fossil-fuel based transportation system rather than replacing it. Charging infrastructure on the other hand creates the potential for structural change, implying that a more active and coordinated build-out of charging infrastructure is needed to ensure a rapid transition to low-emission mobility.

Keywords

Electric mobility; PEV; electric mobility policy; charging infrastructure.

1. Introduction

Worldwide, the transportation sector accounts for around ¼ of greenhouse gas emissions and is one of the few sectors that continues to increase its emissions. In the EU28 countries in 2017, 25% of emissions came from transportation (including international aviation), which is a 10 percent increase from 1990 levels, and passenger cars alone stand for 12 percent of EU's total CO2 emissions (European Commission, 2020). Member countries have adopted the European Commission's strategic vision of an irreversible shift to low-emission mobility through several regulations and directives (European Commission, 2009; 2013; 2014; 2017). The EU member countries have signed the 2030 target of 40% greenhouse gas emission cuts by 2030 from 1990 levels (European Commission, 2018), a target which EU members now have agreed to increase to 55% by 2030, as part of the new European Green Deal proposal (European Commission, 2021).

A shift towards a cleaner and more efficient transportation system has several additional benefits such as less air and noise pollution, and less fossil fuel import dependency for Europe (Biresselioglu, Kaplan, & Yilmaz, 2018). What is less clear, and very difficult to predict is how Europe and the rest of the world will get there. Great transitions, and the energy transition in particular, is a subject of great debate and scholarly interest. Their length, reach, and impact on society and the natural world have been studied in great detail (e.g. Smil, 2010, 2017), but have to a lesser extent been studied by social scientists (one example is: Sovacool, 2016). Given its importance, the energy sector has been the centerpiece of much of this literature while research on the transportation sector has, at least comparatively in relation to its emission share, until quite recently been vastly understudied. The rate of change in the energy sector has been incredible and energy-related emissions are decreasing fast due to the rapid uptake of ever cheaper renewable energy sources like wind and solar PV. However, IEA (2019) estimates that transport-related emissions, at 32 percent of total final energy consumption (TFEC), were almost twice as large as energy sector emissions, 17 percent, in 2018, yet most of the focus has been on the energy sector.

From the transition literature, there is an emphasis on structural change, and much of the debate around transitions and structural change evolves around its pace and their drivers; do energy transitions move gradually, incrementally and seamlessly towards a new paradigm as new technologies become better and cheaper than old and obsolete ones, or do they happen as a result of abrupt shocks or by disruptions through a process more akin to Schumpeter's (1942) waves of creative destruction? And finally, what role does the state, institutions, and vested interests play in these structural changes (Moe, 2010; 2015; Patt, 2015)? Or is our transportation system mired in what Unruh (2000) calls a techno-institutional complex (TIC), where strong fossil fuel and legacy automobile companies have created powerful feedback loops between the technological infrastructure and institutions, thereby creating lock-ins that are very difficult to replace? While it has been more common to talk about such a complex in the energy sector, in many ways it is even more reasonable to assume that something that resembles a TIC is present in the transport sector. With only 0.3% of final energy consumption for all transport coming from renewable electricity and a mere 3% from biofuel (which are by no means unproblematic) (REN21, 2020 p.33), and hosting some of the world's largest companies, both car manufactures and oil companies (Fortune, 2020), the presence of a transport techno-institutional complex is more than plausible. With this in mind, one central cleavage within the transportation sector policy revolves around the divide between infrastructure and personal incentives. On one side, there is the economic-centered notion of pricing externalities, price signals, and tax exemptions. Here, financial incentives, deductibles, and exemptions create favorable market conditions for consumers waiting to purchase a cleaner vehicle. Or by levying increased taxes on vehicles with an internal combustion engine or increased taxes on fossil fuel at the gas pump. The underlying notion is that by simply getting the "price right" or making the "polluter pay" the informed consumer will opt for the cleaner option (Hardman, Chandan, Tal, & Turrentine, 2017). Eventually, electric cars will replace gasoline ones simply because they are better and cheaper. However, the fact that emissions from the transportation sector is actually rising (IPCC, 2014; IEA, 2021), an alternative view says that policymakers cannot sit idly by while market forces incrementally move us towards low-emission vehicles. The argument here is that getting the price right and making polluters pay will lead to structural change is at best grossly simplified, and at worst downright wrong. Incremental change does not necessarily lead to structural change, it follows a very different logic. Thus, these transitions do not happen by themselves in an orderly manner and personal economic incentives will only get us so far. Instead, these transitions require the state and institutions to play an active role in coordinating and facilitating changes in areas where markets act too slowly, or are even incapable of acting, such as infrastructure. In sum, this view advocates that structural change, in these contexts, implies building infrastructure and systems that replace rather than incrementally supplement the old fossil fuel-based transportation system.

This study represents a comprehensive empirical analysis of the effects of electric mobility policy, charging infrastructure on the share of PEV of total passenger car sales and new PEV registrations in 30 European countries from 2009 to 2019. The analysis is based on a new state-of-the-art dataset manually collected, formatted and sorted from several sources, including the European Alternative Fuels Observatory (EAFO), OECD.stat Database, Eurostat, and the World Bank Open Data and then constructed for panel data analysis on electric mobility. Increasing amounts of literature have been devoted to studying the effect of traditional electric vehicle incentives and by which means governments can increase PEV adoption among its citizens. A large state-of-the-art literature review, conducted by ECHOES, a Horizon2020 project this author between 2017 and 2019 was part of, found that the vast majority of studies on electric mobility were focused on the national level, clearly suggesting a lack of international and large sample regional country studies for electric mobility. Most of these studies have focused on one or a few specific, and usually large countries, such as Germany and the UK, or success stories like Norway, which is famous for its very generous PEV policies (Biresselioglu et al., 2017; Biresselioglu, Demir, Kaplan, & Solak, 2020). This study is, therefore, improving and adding to the lack of literature on more extensive regional cross-country studies, focusing on Europe.

Large sample empirical studies such as this one, should complement case studies and smaller comparative studies (e.g. Nordic country comparative studies) because they provide overarching analysis of trends and effects that are not captured by case studies, simply because they are too case- or national specific. Another argument is that the few countries that are most studied are rich, developed countries and PEV markets, while this sample is non-discriminatory in regard to GDP or other measures. To date, to my knowledge, only two papers have conducted a systematic large-scale cross-country study of factors affecting PEV sales; Sierzchula, Bakker, Maat & Van Wee (2014) looking at 30 countries spread across the world in a single year, 2012, and Münzel, Plötz, Sprei & Gnann (2019) which look at financial incentives and PEV adoption in 32 European countries from 2010 to 2017. By contrast, this empirical analysis spans from 2009 to 2019 covering 30 European countries in one analysis and looks at both charging infrastructure and personal incentives.

The paper is organized in the following order: Section 1.1 presents a brief overview of definitions and trends in electric mobility in Europe, followed by Section 2, with a summary of relevant literature on electric mobility policy and charging infrastructure. Section 3.1 presents the dataset and variables, with Section 3.2 following up with the model specification. Results and a discussion of these are presented in Section 4, followed by conclusions and policy implications in Section 5.

1.1 Electric mobility terminology, developments and trends in Europe

EU regulation uses the term zero- and low-emission vehicles (ZLEV), where a ZLEV is defined in the Regulation as a passenger car or van with CO_2 emissions between 0 and 50 g/km (European Commission, 2019). Appendix Table A1 shows that modern plug-in hybrid models comply with the EU regulation limits[1]. Another common term for this type of vehicles are battery electric vehicle (BEV), or all-electric vehicle, that gets all its power from its onboard battery pack, and plug-in hybrid vehicle (PHEV), that have both an electric motor and an internal combustion engine together with a plug to connect it to the grid for charging (EAFO, 2020).

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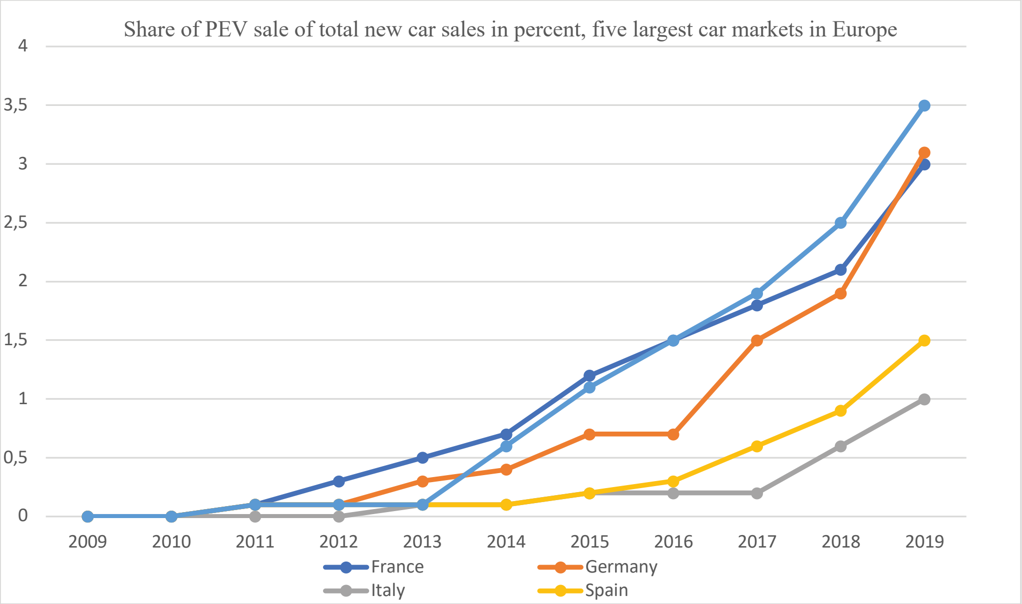
[1] CO_2 emission as gram/km based on NEDC standard. The NEDC standard has now been replaced with the WLTP standard, which aim to represent real and modern driving conditions more accurately.

Following this, a plug-in electric vehicle (PEV) is a classification that includes both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEV) (Hardman et al, 2017). Since EAFO (PEV) and EU Regulation (ZLEV) classifications offer considerable overlap, the following analysis will adopt the term plug-in electric vehicles (PEV). Vehicles with an internal combustion engine will be referred to as ICE. The benefits of vehicles with battery technologies is first and foremost lower emissions and pure battery-electric vehicles have no tailpipe emissions, which contributes to lower climate emissions and air pollution and less noise. An electric engine is also far more efficient than an internal combustion engine (IEA, 2020), so the energy consumption is favorable. Anecdotal evidence from Norway, which has the highest share of PEV in the world, at over 50% in 2020, shows that the electricity consumption from charging has so far been marginal. The Norwegian electricity supplier Statkraft has calculated that the consumption of charging all PEVs in Norway was just 703 GWh in 2020, a mere 0.53% of the total Norwegian electricity generation, at 153.3 TWh (TU, 2021). Looking at battery production and cost development, the picture is even more optimistic. A recent paper by Ziegler and Trancik (2021) find estimated annual cost declines of 13% for lithium-ion cells from 1992-2016, constituting a 97% cost decline since its commercial introduction in 1991, and find 20% cost declines for all cell types and 24% for cylindrical cells for every doubling of the cumulative market. The declining battery costs and other improvements indicate that PEVs will start to approach price parity with ICE vehicles (see for instances: Nykvist, 2019; UBS, 2019; DNV GL, 2020; BNEF, 2020; EVO, 2020; IEA, 2020; Lander, 2021).

Figure A shows that several key European markets have seen slow adaption rates, but that sales are growing, and this is generally true in all European countries. The COVID-19 situation has, by summer 2020, seen significant drops in all new car sales. Although electric and plug-in hybrid (PEV) car sales are holding up better than new internal combustion engine (ICE) vehicle sales, Bloomberg New Energy Finance Electric vehicle outlook (EVO) 2019 projects that PEV sales will drop for the first time in 2020, and automobile sales, in general, will not recover until 2023 (EVO, 2020).

Figure A: Plug-in electric sales in selected European markets (share of total new car sales from 2009 to 2019)



2. Literature review and hypotheses

Research on PEV adoption and uptake can be divided roughly into four main categories; 1. fiscal or economic factors, e.g., purchase price, taxes, fees, and the total cost of ownership. 2. technological factors, such as range, charging time, charging networks and infrastructure, 3. local policies or incentives, such as free toll crossings, free parking, access to bus lanes, and finally, 4. individual or behavioral factors, such as identity, environmental consciousness, customer awareness. The other massive literature relevant for the electrification and decarbonization of transport is the one on total life cycle emissions, material use, and costs of PEVs. Here, topics such as life-cycle analysis (LCA), analysis of various stages of "well-to-wheel"[2] and integrated energy models (IEMs) are discussed, covering topics surrounding national and global energy-

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[2] The stages of "Well-to-wheel" (WTW) are "well-to-tank" (WTT) and "tank-to-wheel" (TTW) (see for instance: EU, 2016).

and electricity mixes, emissions, and critical materials use. In this literature review, I mainly focus on the first two, i.e. primarily economic and infrastructural factors, or to put it differently, personal incentives versus infrastructure, which represent deeper theoretical discussions in the literature on energy transitions, namely, incremental versus structural change.

Legitimate concerns over mass PEV adoptions tend to focus on the vehicle's life cycle assessment, with secondary questions related to the electricity mix used to both produce the batteries and the vehicle and the mix that is charging the vehicle. The potential of increased pressure on national grids caused by mass PEV adoption, especially in nations and regions that lack sufficient grid infrastructure is another issue of concern. To this point, we should be reminded when applying broad generalizations and policy recommendations that countries are on different development paths. For instance, Onn et al. (2018) find that the introduction of a massive uptick in electric vehicle charging would, in fact, increase greenhouse gas emissions due to its fossil fuel-dependent grid infrastructure. However, while not all countries and regions have the capacity and financing to decarbonize their power sector rapidly, it is generally agreed that to reach the Paris climate agreement goals, the world needs to decarbonize both the transportation sector and the energy system as fast as possible. The promise of cost reductions, innovation, and technological development can alleviate some of the of these problems, and promising developments, such as vehicle-to-grid (V2G) technologies, while no panacea, show that additional CO_2 reductions can be achieved vis-à-vis simply replacing ICE vehicles with PEVs (Tomić & Kempton, 2007; Xu et al., 2020) as well as perform valuable grid management responses (see for instance: Guille & Gross, 2009; Tan et al., 2016; Garcia, Freire & Clift, 2018; Alirezazadeh et al., 2021).

Reports comparing electric vehicles and PEV vs. ICE vehicles are becoming commonplace. While not all efforts have the scientific rigor one might expect, more or less every serious analysis find electric vehicles to be more climate-friendly than their fossil-fuel counterparts, even if charged by fossil-heavy grids (see for instance: Hoekstra, 2019; Knobloch et al., 2020), and as grids decarbonize, the environmental impact decreases rapidly (see for instance Burchart-Korol et al. (2020) for LCA analysis of EV charging in European countries towards 2050). LCA analyses by Ellingsen et al. (2014) and Ellingsen, Hung & Strømman (2017) also find considerable emission savings from electric vehicles, even with the manufacturing process taken into account. Material use and efficiency are also topics of considerable research, and several studies look at the effect of material use, ranging from increased use of lighter-weight materials and improved recyclability (see for instance: Hottle et al., 2017; Hertwich et al., 2019; Milovanoff et al., 2019).

Another approach that concerns the energy use and greenhouse gas emissions from automotive fuels and powertrains options is well-to-wheels (WTW) analysis. The main aim of WTW is to investigate and usually compare fuels and vehicle options, in other words looking at the "in-use" emissions. WTW thus differs from LCA as it does not usually include emissions and energy from the manufacturing of the vehicle or end-of-life aspects (EU, 2016). There is also a range of stages researchers can investigate, such as well-to-station, station-to-tank, and tank-to-wheel. In the literature, there is a well-known dilemma around whether energy production should be considered throughout its lifespan, i.e., from well-to-wheel or only during the last phase of the process; tank-to-wheel. As the same vehicle using the same amount of energy in two different countries may have a significantly different environmental impact due to the differences in the national and local production and transport of energy. For instance, for vehicle categories such as buses, more emphasis has been on the operational phase (i.e., tank-to-wheel). For instance, Dreier et al. (2018) find significant WTW Greenhouse gas emissions from hybrid buses (30%) and plug-in electric hybrid buses (75%) compared with conventional buses in the Bus Rapid Transit (BRT) system in Curitiba, Brazil.

Cavallaro et al. (2018) use WTW analysis of BEV and non-BEV at the European level and find large variations across European countries and segments and make a point that we should distinguish according to vehicle classes (e.g., comparing small BEVs with smaller ICE vehicles) and country profiles. They still find some general considerations and conclude that firstly, ICE vehicles emit more carbon than other vehicles in all European countries in the study. Secondly, as the energy mix is the crucial determinant for finding the carbon efficiency of alternative fuel vehicles, the authors find that PHEVs produce less carbon than BEVs in counties with a high amount of fossil fuels in their energy mix (e.g., a large share of coal), especially for vehicles characterized by high fuel/energy consumption such as SUVs. Another study by Yazdanie et al.

(2016) finds that compressed natural gas (CNG) and biogas (BNG) vehicles deliver the best overall performance from a WTW analysis of Switzerland. The analysis highlights that energy carriers and batteries contribute considerably to the overall emission profiles. Similar results are found in Kosai, Nakanishi & Yamasue (2018), which show that including material structures in the manufacturing phase and fuel consumption at the operation phase leads to significantly higher WTW emissions estimations. The authors state that the inclusion of the energy consumption for the material structure (e.g., from the battery) has considerable impacts on the vehicle energy efficiency, especially for the new generation of vehicles (e.g., PEVs). Two takeaways can be highlighted; the results suggest that as energy production and energy used in battery production are cleaned up, significant improvements of battery-electric and hybrid powertrain options should be seen. Secondly, while CNG and BNG options might continue to play an interim role in the European light-duty fleet, there is little evidence that carmakers are deploying any significant resources towards these powertrain options.

Another common method to explore pathways for transportation is integrated energy models (IEMs). Wolfram and Hertwich (2019) investigate assumptions in 14 state-of-the-art integrated energy models for light-duty vehicles (LDV) and show that decarbonization efforts in the LDV sector might be more cost-effective than previous estimates. For instance, updating cost estimates for electric vehicle batteries, in line with current technological development, would more accurately represent mitigation scenarios, which again would have considerable implications for policymakers using IEM output to guide climate policy action.

The bottom line for most of these studies is that electrification of transport, while no perfect solution, is better for the climate than fossil cars and will only continue to be so as Europe adds more renewable energy to their electricity mixes. Technological developments and efficiencies will presumably also lower the footprint of both manufacturing and battery production, both of which will benefit tremendously from being produced with electricity from ever cleaner sources. Another key takeaway is that while PEVs (and especially BEVs) can progressively become less emission-intensive over time as CO_2 intensity in the European grids that are charging them are decarbonized – the same cannot be said for an ICE vehicle. One should, therefore, arguably think more dynamically rather than statically about these questions. With the EU proposing its new European Green Deal, thereby raising greenhouse gas emission reduction ambitions from 40% to

55% in 2030, we would expect increased efforts in deploying more renewable energy, increased promotion of PEVs, and an increased focus on European battery supply chain.

With this backdrop, where this article contributes to the literature, is in investigating the effects of PEV policies and charging infrastructure factors. Economic incentives and other market-based policies, such as purchase incentives, tax and VAT deductions or exemptions, and general reductions in fees and taxes of ownership are the subjects of many studies over the last decade, and most of these suggest more or less that financial incentives do work (Sierzchula et al., 2014; Aasness & Odeck, 2015; Zhou et al., 2015; Rudolph, 2016; Zhou, Levin & Plotkin, 2016; Slowik & Lutsey, 2016; Kester, Noel, de Rubens & Sovacool, 2018; Fluchs, 2020; Gong, Ardeshiri & Rashidi, 2020). Hardman et al. (2017) has systematically reviewed the effectiveness of financial incentives for BEV and PHEV promotion and find that incentives should 1.) be applied at the point of the sale, not afterward, 2.) incentives should promote BEV with higher electric ranges, and prioritize PHEVs with longer ranges rather than applying the same subsidy for all vehicles, 3.) VAT and purchase tax exemptions are most effective, and finally, 4.) incentives should not be applied on high-end BEVs. The authors also raise the point that premature removal or uncertainly surrounding the policy could negatively affect PEV sales, and therefore policymakers need to design incentive structures with longevity in mind. Sierzchula et al. (2014), Mock & Yang (2014), Mersky, Sprei Samaras & Qian (2016), and Axsen, Plötz & Wolinetz (2020) also find significant positive effects of financial incentives on PEV adoptions, while all studies clearly underline the importance of policy mixes and that financial incentives alone are not enough to increase PEV adoptions significantly. These results are confirmed by Münzel et al. (2019) in one of the few empirical studies outside the US. Finally, Gallagher & Muehlegger (2011) find that rising fuel prices were associated with higher PHEV sales in the US, while they could not find any association between consumers' income and education.

The literature has, to a lesser extent, investigated the effects of infrastructure for the transition to low-emission mobility, but there is an increasingly building evidence for the importance of charging infrastructure for PEV adoption (see for instance: Lieven, 2015; Javid & Rejat, 2017; Kester et al., 2018; Wei et al., 2021). Additionally, beyond finding a significant effect of financial incentives, Sierzchula et al. (2014) find that charging infrastructures were a significant factor for electric vehicle adoption. The model results suggest that the charging infrastructure effect was even more substantial than the financial incentives' effect. Further research by Bakker & Trip (2013) suggests that the build-up of charging infrastructure is a key enabler for PEV adoption rates and rests on favorable and consistent governmental support and regulation, emphasizing the role of private-public partnerships as one favorable route to go. A recent study by Haustein, Jensen & Cherchi (2021) also finds that new fast-charging increased BEV adoption in Denmark but finds no such effect in Sweden but still suggests that better infrastructure and clear policy signals, as well as marketing, tailored explicitly for electric mobility to increase the adoption of BEVs. Contrastingly, Miele et al. (2020) only find limited effects of additional charging and refueling infrastructure in their simulation of zero-emission vehicle sales in Canada to 2030. The simulation suggests that other strong policies are needed to stimulate sales of zero-emission vehicles. Funke et al. (2019) find that public charging infrastructure is still a barrier to PEV adoption, especially where home charging is not an alternative, such as in some densely populated areas, but highlight that framework conditions vary significantly from country to county, so it is hard to determine the optimal level of public charging infrastructure equally for all countries. Considering that Hardman et al. (2018) find that between 50-80% of charging happens at home, with the workplace as the second most common charging place, and public charging, both fast and slow only accounting for less than 10% makes it important to pose questions surrounding levels of charging infrastructure needed.

Anecdotal evidence from Norway suggests that once a country reaches a certain market share of PEV, having an adequate charging infrastructure with sufficient charging speeds and inconvenience of long charging queues along highway corridors are issues that are taking over from the more classic issue of range anxiety (TØI, 2019). As deep-rooted industrial lock-ins and vested interests make transitions slower, innovation and technological development are also regarded as essential transition-enablers as technical and economic hurdles are overcome, therein making the choosing and economic rationale of purchasing a PEV more appealing for more consumers (see for instance: Newell, 2009; Patt, 2015 and Mazzucato, 2015). Finally, Fritz, Plötz & Funke (2019) find that ambitious fuel standards are a powerful instrument for CO2 emission reduction and PEV market diffusion. Interestingly, they find that current fuel standards are lower than the automaker's own targets when their PEV targets are taken into account.

With a structural change lens, the interesting question is not how to get to ten percent market share, but how a structural change to low-emission mobility happens, i.e., how to get to fifty percent and higher PEV market shares, and this view finds it is doubtful that this will happen through personal incentives alone. The story of incremental change can quickly lead to a plateau in market shares simply because the surrounding transportation system has not coordinated and transformed sufficiently to accommodate the changes. The story of structural change then, clearly advocates building infrastructure and systems that replace, rather than just supplement the current transportation system.

As a final note, there is a lot of literature on psychological and behavioral factors at the individual level connected to the energy transition in general and within electric mobility and PEV adoption specifically. The literature on this is looking at factors such as information and user acceptance about and of new technology (see for instance: Graham-Rowe et al., 2012; Plötz et al., 2014; Esslen et al., 2016; Plötz & Dütschke, 2020), trust in PEVs environmentally friendliness, social desirability and symbolism among other factors (e.g., Axsen & Sovacool, 2019; Long et al., 2019), and while it is outside of the scope of this article, it is nevertheless recognized as a crucial research area in order to understand motivations and challenges for the energy transition.

Summed up, based on the literature, I propose the following hypotheses to be tested empirically:

H1: PEV incentives and electric mobility policies

Having electric mobility incentives and policies have contributed to an increase in PEV market share of new car registrations.

H2: Electric mobility packages

Having policy packages of several electric mobility incentives have contributed to an increase in PEV market share of new car registrations.

H3: Charging infrastructure

An increase in charging infrastructure has contributed to an increase in PEV market share of new car registrations.

H4: Fast charging infrastructure

An increase in fast-charging infrastructure has contributed to an increase in PEV market share of new car registrations.

3. Data and methodological approach

3.1 Data and variables

The dataset used in this analysis has been collected, formatted, and sorted manually by the author and provides unique, updated and state-of-the art data for electric mobility data analysis (Sæther, 2020). The analysis investigates an 11-year period from 2009 to 2019. The raw data is primarily obtained from the European Alternative Fuels Observatory (EAFO), a database and online portal funded by the European Commission in order to support Member States with the implementation of EU Directive 2014/94 on the deployment of alternative fuels infrastructure (European Commission, 2014). In addition, several variables are obtained from the OECD.Stat Database, Eurostat and the World Bank Open Data database. The dataset covers 33 European countries, including Turkey, while the analysis excludes Latvia, Lichtenstein, and Malta[3]. Summary statistics for the variables are shown in Table A.

Table A. Summary statistics: PEV indicators, charging variables and control variables

Variables	N	Mean	St.dev	Min	Max
Share of PEV of total new registrations (*logged)*	330	0,50	0,73	0	4,12
Total new PEV registrations (*logged)**	330	5,46	3,22	0	11,56
Share of BEV of total new registrations (*logged)**	330	0,34	0,57	0	3,85

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[3] Latvia and Malta lack data on fast charging infrastructure, while Lichtenstein lacks data on several key variables and is thus excluded from the analysis.

Vehicle per charging points (*logged)*	323	1,20	1,04	0	4,39
Charging point per PEV (*logged)**	279	0,22	0,25	0	1,67
Fast public charging points (*logged)*	330	1,34	1,54	0	6,49
GDP per capita (*logged*)	330	10,32	0,67	8,81	11,62
Urban population	330	73,43	12,28	52,43	98,04
Residential electricity price	330	0,17	0,05	0,08	0,31
Pump price petrol and diesel	330	2,11	0,82	0,99	5,88
Total population (*logged*)*	330	15.98	1.40	12.67	18.24
Share of renewable energy of total generation**	296	34.47	25.75	0.59	99.99

* : Used in the robustness model

** : Used in the instrumental variable (iv) regression model to test reverse causality

Data for the PEV market share of new registrations of total car sales, all categories (*Share of PEV of total new registrations*) and new registrations for PEVs (*Total New PEV registrations*), which is used for robustness testing, are both collected from EAFO (EAFO, 2020a) and are defined as newly registered passenger vehicle category M1; used for the carriage of passengers, with no more than eight seats in addition to the driver seat, also known as passengers cars, following UNECE standards (EAFO, 2020b). Both variables are logarithmically transformed as both are heavily skewed and have high kurtosis.

Two variables for electric mobility infrastructure are included in the analysis, the first measures vehicles per charging points (*Vehicle per charging point*) and is calculated by dividing the number of PEV by the number of public charging points in a given year. The second variable for fast charging infrastructure (*Fast public charging point per 100 km highway*) is defined as fast (>22kW) public charging points per 100 km of highway. Charging infrastructure is here defined as public chargers that have "non-discriminatory" access, but also includes chargers that are sometimes referred to as "semi-public" chargers, such as public chargers at supermarkets or parking lots. Data on both charging variables are obtained from the EAFO database (EAFO, 2020a) and both are logarithmically transformed in the analysis. In the robustness tests I include an alternative charging specification called charging point per PEV (*Charging point per vehicle*).

In order to test the effect of various low-emission mobility incentives, I have constructed several dichotomous variables. In addition, I test bundles of policy incentive packages to investigate the effect of sets of multiple incentives (i.e. Purchase subsidies and ownership benefits) versus single policies, shown in Table B. The dichotomous variables are operationalized as 0 = The country does not have the incentive in a given year, and 1 = The country has the incentive in a given year. Data for all low-emission mobility incentives are collected from the EAFO database (EAFO, 2020a) and cross-referenced from country-by-country official and semi-official sources[4]. Purchase subsidies (*Purchase subsidies, Ps*) is classified as a state subsidy that is granted to a private customer, and/or businesses and/or municipalities for the purchase of a PEV. VAT benefits (*VAT benefits, Vb*) covers lower or exemptions from value added taxes. Following the classification of Hardman et al. (2017), *purchase subsidies* and *VAT benefits* have been combined to create the variable purchase incentives (*Purchase incentives, Pi).* Tax reduction or exemption for registration taxes (*Registration tax benefits, Rtb*) are classified as exemption or significant reduction in taxes or fees related to registration of a PEV. Ownership benefits (*Ownership tax benefits, Otb*) are defined as benefits such as exemption or significant reduction of annual circulation/road taxes and other federal taxes related to ownership of a vehicle. Company benefits (*Company tax benefits, Ctb*) are operationalized as benefits such as deduction on company taxes for PEVs operating as company car. And finally, local incentives (*Local incentives, Li*) are defined as free or beneficial parking, exemptions or significant reductions for toll crossing, and allowance to use bus lanes.

Table B. Summary statistics: Low emission mobility policies

Variables	N	Min	Max	N=0	N=1
Purchase incentives (*Pi*)	330	0	1	214	116
Purchase subsidies (*Ps*)	330	0	1	237	93
Registration tax benefits (*Rtb*)	330	0	1	212	118
Ownership tax benefits (*Otb*)	330	0	1	204	126
Company tax benefits (*Ctb*)	330	0	1	238	92
VAT benefits (*VATb*)	330	0	1	302	28
Local incentives (*Li*)	330	0	1	264	66

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[4] National electric mobility organizations etc.

Policy package 1	330	0	1	304	26
Policy package 2	330	0	1	267	63
Policy package 3	330	0	1	298	32
Policy package 4	330	0	1	268	62

In addition, I test several policy packages; Policy incentive package 1 (*Policy package 1 (Pi + Rtb + Otb +Ctb + Li*)) covers a package of incentive policies that includes all incentives tested. Policy incentive package 2 (*Policy package 2* (*Pi + Rtb + Otb*)) covers incentives related to purchase and ownership costs, policy incentive package 3 (*Policy package 3* (*Pi + Rtb + Otb + Li*)) covers incentives related to purchase and ownership costs, as well as any local incentives, and lastly, policy incentive package 4 (*Policy package 4* (*Pi + Ctb*)) covers the incentives aimed at private and company purchases, where there are some overlap.

The indicators measuring urban population (*Urban population*), measuring the percentage of the total population that live in urban areas as defined by national statistical offices, and GDP per capita (*GDP per capita*), measuring GDP per capita, where gross domestic product divided by midyear population in constant 2010 US dollars are both obtained through the World Bank Open Data database (2020a; 2020b) and the variable has been logarithmically transformed in the analysis. Residential electricity prices (*Residential electricity prices*) are measured in Euro per kWh and have been collected from Eurostat (Eurostat, 2020) with data on Switzerland is collected from The Swiss Federal Office of Energy (SFOE, 2020). Finally, to estimate an indicator for the fuel costs of ICE vehicles, two indicators of the fuel user price of petrol and diesel in 2010 US dollars per liter are combined into variable measuring the mean pump price for fuel (*Mean pump price petrol and diesel)* and have been collected from the OECD Green Growth database (OECD.stat, 2020).

3.2 Model specifications

Panel data or time-series cross-sectional data suffer from two main problems that needs to be controlled for. The first is temporal dependence, or autocorrelation, where the error term correlates across the panel over time and can inflate the standard errors thus leading to biased results. The second problem is spatial dependence or cross-sectional dependence. Here, the units, in this case the countries, correlate systematically with each other across space. Both problems need to be controlled for in order to produce unbiased estimates. Therefore, this study deploys panel data regression with the fixed-effects estimator with Driscoll-Kraay standard errors to investigate the effects of electric mobility incentives and charging infrastructure on the share of PEV registrations. Using the fixed-effects estimator, equivalent to the unit centering all observation, we can investigate deviations in the mean in each unit over time (Petersen, 2004). One downside of fixed-effect models is that it only estimates within-country variation, making comparison between countries impossible. Moreover, a fixed effects model does not allow for time-invariant variables in the analysis (Petersen, 2004; Beck, 2008). The Driscoll-Kraay method estimates standard errors that are robust to spatial correlation and heteroscedasticity using ordinary least squares (OLS) regression (Discroll & Kraay, 1998; Hoechle, 2007). The analysis also deploys temporal control by adding year dummies as time fixed-effects in all models.

In this study we are interested in whether or not increases in charging infrastructures significantly increase PEV shares and whether or not implementation of electric mobility incentives and packages of incentives yield significant increases in PEV shares of new car registrations, and secondly, if significant, can we say something about the size of their contributions, relative to each other. Finally, in order to test reverse causality for the charging infrastructure indicators I employ an instrumental variable regression model based on Baum, Schaffer & Stillman (2007). The iv-regression model runs share of renewable energy of total electricity generation as the instrumental variable.

4. Results and discussion

Table 1 presents the regression results for the fixed-effect models. Table 1 shows the results for PEV market share of new registrations, while Table A2, A3 and A4 show the robustness test estimates.

All tables report the estimated coefficients and Driscoll-Kraay standard errors. Using the variance inflation factors (VIF), we can establish whether there is a presence of collinearity in the model. All VIF values are below threshold levels except for the variable to test the curvilinear effect of fast charging, which we should expect, suggesting that the explanatory variables are independent of one another. Furthermore, all F-statistics are significant. As the fixed-effects estimator with time control and the Driscoll-Kraay standard errors are robust to both heteroscedasticity and serial correlation, this ensures reasonably unbiased model estimations.

Table 1. Effects of charging infrastructure and electric mobility policies on PEV market share of new registrations in Europe

Variables	(1) Share of PEV	(2) Share of PEV	(3) Share of PEV	(4) Share of PEV	(5) Share of PEV	(6) Share of PEV	(7) Share of PEV
Vehicle per charging points (*logged*)	0.212**	0.197**	0.191**	0.197**	0.192**	0.194**	0.202**
	(0.0773)	(0.0713)	(0.0661)	(0.0714)	(0.0681)	(0.0704)	(0.0712)
Fast public charging points (*logged*)	0.316***	0.0997***	0.0814**	0.0993***	0.106***	0.103***	0.0741**
	(0.0302)	(0.0325)	(0.0367)	(0.0315)	(0.0304)	(0.0313)	(0.0281)
Fast public charging points (*cubed*)		0.0445***	0.0484***	0.0443***	0.0435***	0.0427***	0.0483***
		(0.00267)	(0.00263)	(0.00256)	(0.00261)	(0.00267)	(0.00233)
Purchase incentives (*pi*)			0.217***				
			(0.0695)				
Registration tax benefits (*Rtb*)			-0.0586				
			(0.0482)				
Ownership tax benefits (*otb*)			0.0583				
			(0.0430)				
Local incentives (*li*)			-0.0674				
			(0.0544)				
Policy package 1				0.0779*			
				(0.0401)			
Policy package 2					0.177**		
					(0.0563)		
Policy package 3						0.172***	
						(0.0449)	
Policy package 4							0.224***
							(0.0325)
Urban population	0.123***	0.115***	0.120***	0.110***	0.118***	0.106***	0.104***
	(0.0149)	(0.0167)	(0.0178)	(0.0155)	(0.0178)	(0.0158)	(0.0184)
GDP per capita (*logged*)	-1.087***	-0.982***	-0.897***	-1.032***	-1.107***	-1.095***	-0.970***
	(0.215)	(0.210)	(0.261)	(0.203)	(0.203)	(0.191)	(0.225)
Residential electricity price	-0.885	-0.663	-1.132	-0.793	-1.427	-1.102	-1.474
	(1.178)	(1.066)	(1.037)	(1.094)	(1.226)	(1.105)	(0.886)
Mean pump price petrol & diesel	0.467***	0.344*	0.375*	0.334*	0.337*	0.322*	0.308*
	(0.147)	(0.163)	(0.202)	(0.162)	(0.166)	(0.164)	(0.164)

Constant	1.505 (2.613)	1.212 (2.429)	0.0296 (3.526)	2.117 (2.128)	2.391 (2.500)	3.101 (1.969)	2.096 (2.499)
Observations	323	323	323	323	323	323	323
Number of countries	30	30	30	30	30	30	30
Time FE	YES	YES	YES	YES	YES	YES	YES

Driscoll-Kraay standard errors robust to temporal and spatial autocorrelation in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Looking first at the control variables in Table 1 that display the results on PEV market share of new registrations, we can see that the estimated coefficients for urban population show a positive and significant effect on PEV market share of new registrations at the 1% level across all six models. These results are in line with the findings of Lane & Potter (2007) and Gallagher & Muehlegger (2011) showing that urbanization increases PEV market shares, despite limited charging opportunities in dense urban centers, which could suggest that greater urbanization would allow also PEVs with limited range higher utilization and convenience. The effect of mean pump prices for petrol and diesel are also positive and significant at the 10% level across all models and in line with previous research on the price effects on consumer choices. Interestingly, the converse effect on cheaper electricity prices cannot be shown to have any impact on the PEV market share, one explanation for this non-finding is that the mean price of a liter of petrol and diesel in the sample is around 2.1 US dollars, while in contrast the mean price of a kWh of electricity is 0.17 euro, and while these are not fully comparable prices, charging an electric car is considerably cheaper than using petrol or diesel. Therefore, it is possible to argue that an increase in pump prices might matter, while an increase or decrease in electricity prices makes little difference for consumer choices. As European countries deal with increased electricity demand from electrification, ways to regulate price signals and reduce peak demand will be an interesting development and will likely have a larger impact than the mean price itself. The effect of GDP per capita is negative and significant at the 1% level across all models, suggesting that increases in GDP does not result in higher PEV shares. At first glance, the negative GDP effect seems surprising, but given the fixed-effects estimation it suggests that higher changes in income do not matter much for PEV market shares, and given the negative effect it rather suggests that some of the richest units (countries) in Europe are laggards (e.g. Switzerland and Luxembourg). We could however expect income *level* to matter for PEV share. Running the model with random effects (Model 9 Table A2) shows that this is indeed the case.

Sierzchula et al. (2014) found no significant relationship between EV market share and electricity prices on their 2012 sample but did not find any positive correlation with neither urban density, fuel prices or GDP indicators either.

Observing the effect of charging infrastructure we can see that both vehicle per charging point and fast charging point per 100 km highway is positive and significant at the 5% level and 1% level across all six models in Table 1, in line with previous research reviewed in this paper. Substantively, a standard deviation increase the PEV per charging point ratio increases the (logged) PEV market share of new registrations by 36% of a standard deviation of the (logged) PEV market share of new registrations. The effect is even stronger for fast charging infrastructure where a standard deviation increase in fast charging point per 100 km highway increase the (logged) PEV market share of new registrations by 73% of a standard deviation of the (logged) PEV market share of new registrations. In the following I present two graphical representations of the effects of increased charging infrastructure. Regarding the effects of electric mobility incentives, there is a positive effect of purchase incentives, in line with the findings of Harding et al, 2017, at the 1% level. Here a standard deviation increase in purchase incentives (i.e. from 0 to 1) increases the (logged) PEV market share of new registrations by 12% of a standard deviation of the (logged) PEV market share of new registrations[5]. The models show no significant effect for neither registration nor ownership benefits and no significant effect of local incentives. The results for the electric mobility policy packages are interesting and display a positive effect, with varying significance. The effect of policy package 3, covering incentives related to purchase and ownership costs, as well as any local incentives (*Pi* + *Rtb* + *Otb* + *Li*) and 4, covering the incentives aimed at private and company purchases (*Pi* + *Ctb*) are both significant at the 1% level, but the effect is less or almost equal to the effect of purchase incentives alone displayed in model 2. The same is true for policy package 2 that covers incentives related to purchase and ownership costs (*Pi* + *Rtb* + *Otb*) which displays a weaker but significant effect on the 5% level than purchase incentives alone. Finally, policy package 1, which covers all the incentives (*Pi* + *Rtb* + *Otb* +*Ctb* + *Li*) tested is significant at the 10% level but displays a considerably smaller effect than purchase incentives alone.

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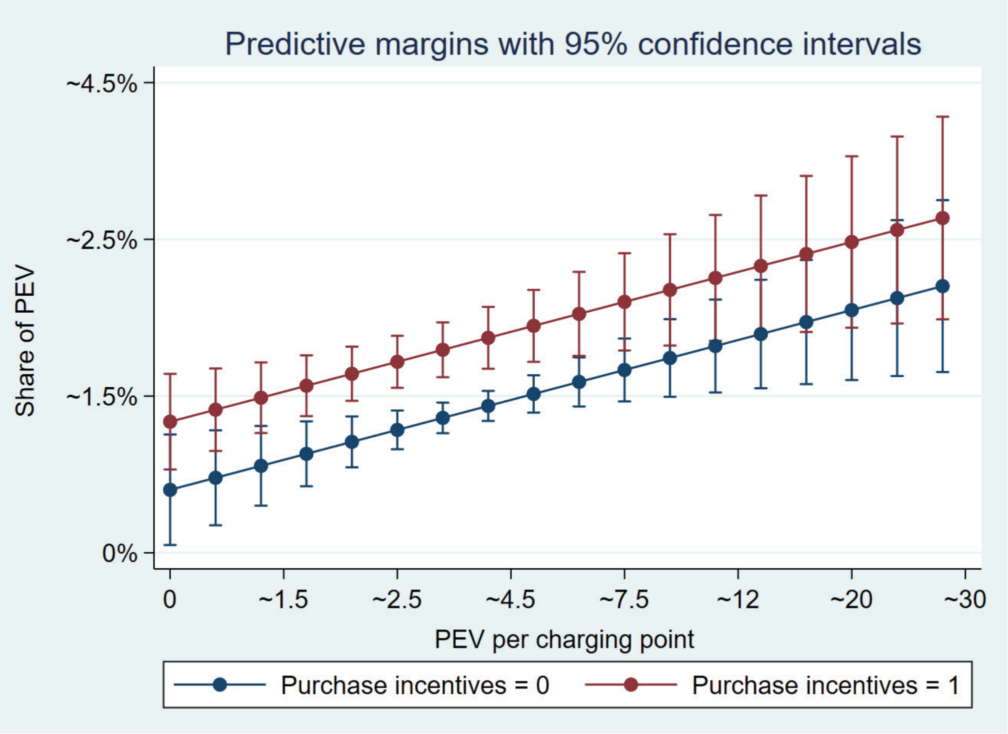
[5] Calculations for the standardized coefficients can be found in Table A5 in the appendix.

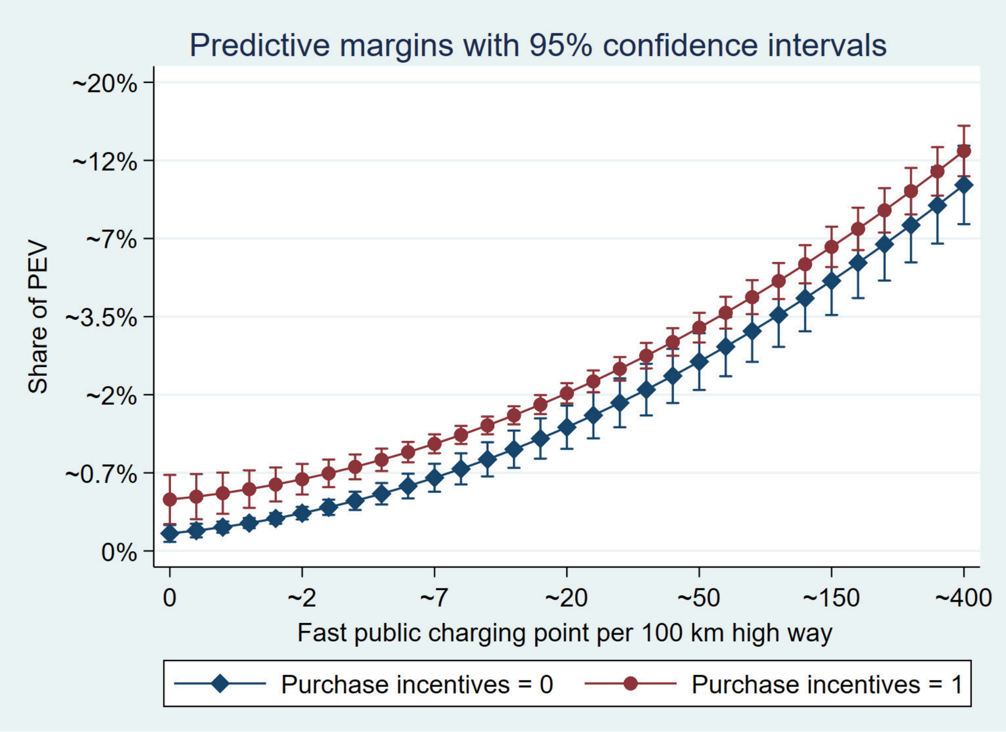
Looking graphically at the effects, Figure 2 presents the predicted PEV market share of new registrations if the PEV per charging point ratio changes, with and without a purchase incentive policy. The prediction is based on model 3 in Table 1. The model predicts that if the ratio of PEVs per public charging point is increased, for example approximately from 5 to 20, equivalent to the ratio that Norway had in 2018, we would observe increases in the market share of PEVs. Using Norway as an example, the ratio between PEVs per charging point from the earliest stages of the transition (from 2009 to 2013 Norway has ratios from 1 to 3) points to the fact that Norway built a lot of infrastructure, thereby making PEVs a more feasible options for consumers, as the observed ratio of PEVs per public charging point has been stable around 20 since 2014. Bottom line, it is good to observe an increasing ratio in the beginning of the transition, as it suggest that PEV numbers are growing (expect in the extreme cases, e.g. way too many PEVs per charging point), while in the longer term, the market will ideally find the right balance or ratio: a very low ratio could signal inefficiencies and an overbuilt infrastructure, while a very high ratio could suggest that the infrastructure is underdeveloped relative to the amount of PEVs on European roads. Early in the transition, one such balance point for sufficient infrastructure coverage, could be the EU target ratio of 10 PEVs per public charging point, with the ratio slowly stabilizing around some level based on market signals as the transition progresses.

Figure 2. Predicted PEV market share of new registrations with an increase in the PEV per charging point ratio and with or without a purchase incentives policy



Looking further at Figure 3, it displays the predicted PEV market share of new car registrations to increase quite dramatically with an expansion of fast charging capability per 100 km highway, and the effect is stronger at the right end of the curve, and the difference with or without a purchase incentive policy is very small. This prediction is also based on model 3 in Table 1. The model thus predicts that if European countries build around 125 fast chargers per 100 km highway (for reference, Norway had 655 fast charging stations per 100 km highway in 2019), they will see PEV market shares over ten percent of new registrations. The results related to charging infrastructure are in line with Bakker & Trip (2013), Sierzchula et al. (2014), and Wei et al. (2021), and strongly suggest that policy-makers need to focus on providing the necessary regulation, funding, and political conditions for private companies and relevant public entities to upgrade essential local, regional, and continental charging networks and infrastructure to enable a shift toward low-emission mobility.

Figure 3. Predicted PEV market share of new registrations with increases in fast charging points per 100 km highway and with or without a purchase incentives policy



Additionally, as battery and PEV prices continue to go down, it is just a matter of time before PEVs will be price competitive without incentives (e.g. DNV GL, 2020; BNEF, 2020; EVO, 2020), which again creates an incentive for governments to roll back on lucrative financial incentives. If then, as the results of the analysis seem to suggest, charging infrastructure availability and convenience is as important, or even more, so for consumers as the upfront financial cost, it might be more cost-effective to provide support for infrastructure of charging, which can be used by everyone with a PEV, rather than subsidizing the vehicles as they approach cost parity with ICE cars.

Robustness checks

A model with an alternative charging infrastructure variable is tested in Table A2, model 8, and is significant and, as expected, negatively correlated with share of PEV, as a decrease in the ratio of charging points to PEV is associated with higher PEV market shares. Additionally, models without outliers are estimated in Table A2 (models 10-14) using Cook's distance (Cook, 1977). These models display remarkably similar results to the main models in Table 1, implying robustness of the results. Furthermore, Table A3 shows the robustness tests with market share of battery electric vehicles only as the dependent variable. Model 15 (with 2009 included, miniscule BEV share in the sample) and 16-21 (2010-2019) show that by and large the results are similar to Table 1. Finally, in Table A4 the results for total new PEV registrations with an additional control for total population, show that the same significant effect for urban population and mean pump prices for petrol and diesel and GDP cannot be observed. In model 23, higher electricity prices display a negative effect on new car registrations at the 10 % level. While Vehicle per charger and fast charging display significant and positive effects on PEV market share, the curvilinear fast charging variable displays a negative sign in the robustness tests with total new registrations of PEV. However, looked at graphically, it fattens out at higher values while slightly tipping down at very high values. The positive significant effect of purchase incentives is confirmed in this robustness test, and in addition, ownership tax benefits display a positive significant effect on new PEV registrations on the 5 % level. The rest of the individual electric mobility incentives show no significant effect. For the policy packages, only policy package 3 (*Pi* + *Rtb* + *Otb*) is positive and significant at the 10 % level.

In sum, the results are remarkably stable across nearly all 27 models in the analysis. Arguably the most noteworthy and stable result across all models is the effect of charging infrastructure, and fast charging in particular on PEV market developments. Similarly, the positive effect of purchase incentives and several policy packages, across both PEV market specifications suggests another robust empirical finding, in line with the previous research.

Limitations

Despite having the latest available data and reasonably sophisticated models covering key electric mobility policies and charging infrastructure variables, this analysis is not without drawbacks. One key question related to the effect of charging infrastructure is related to the issue of reverse causality. One way to establish the arrow of causality in these situations is to employ an instrumental variable (IV) regression. It is notoriously hard to find a sufficient variable for this purpose. The choice made here is renewable energy share of total electricity generation, the argument being that countries with high renewable shares in their power generation have pursued charging infrastructure buildout, and that those with lower renewable energy shares might be slower to adopt strategies and support for charging buildout as their power mix is more emission intensive. We then attempt to prove that charging infrastructure does indeed increase PEV shares, and not the other way around. However, for the model to be valid, establishing the arrow of causality for these particular variables is clearly important. The IV regression show that the parameters and test results are adequate and in line with that provided by Baum, Schaffer & Stillman (2007). We can with reasonable certainty establish that increases in charging infrastructure does lead to higher PEV shares. Following this, we should be wary of untethered belief in the predictive power of econometric models based on historical data (see for instance the Lucas critique (Lucas, 1976)), especially early in a world-wide transition.

The data used in the analysis only distinguish between whether or not a country has a specific electric mobility policy in place in a given year. Ideally it would be best to have access to concrete monetary values on the incentives in each country in a given year, and the lack of more calibrated indicators differentiating between high and low financial incentives has to be kept in mind when interpreting the results. Finally, the analysis lacks an indicator measuring home- or privately-owned charging points. The conclusions should not be influenced to a large extent by this, but it is nevertheless a key indicator to keep an eye on going forward. If anything, it makes the infrastructure story more rather than less credible, as it is reasonable to assume that especially in big cities, with difficult and crowded parking situations, charging infrastructure will remain a problem. According to the latest projections by Bloomberg New Energy Finance – EVO 2019, about 290 million charging points will be needed globally by 2040, and while home chargers will be by far the largest category, it is estimated that around 12 million public charging points will be needed as home options are either saturated or unavailable (e.g. in dense cities) (EVO, 2020). The importance of charging networks is arguably even more critical at the start of the low-emission mobility transition, to dispel range anxiety and increase the convenience for PEV owners and those deciding whether or not to become PEV owners. This type of data will inevitably become available at some point in the future as the low-emission mobility transition goes forward, but does not exist today. This should be kept in mind while interpreting the results. Another variable that would be interesting to include is the price of the vehicles. PEVs are still more expensive than ICE vehicles in most markets and although the gap is rapidly closing, together with lower costs of total ownership, they are still not price competitive. For future research, comparative price data for PEV to ICE counterparts would be interesting for further investigation.

5. Conclusions and policy implications

The results of the empirical analysis show that increasing charging infrastructure, especially fast charging infrastructure, leads to higher shares of PEV market shares. Secondly, purchase incentives and some policy packages are significant, but do not display a convincing additional effect over purchase incentives alone. Furthermore, the empirical evidence from this European analysis suggests that increased urbanization and higher fuel prices for petrol and diesel correlate with higher shares of PEV of new car sales, but these findings do not replicate for total new PEV registrations. The results and the following discussion provide some support for the view of the energy transition as a process of structural rather than incremental change, where infrastructure can be seen as more enabling and more important than personal incentives: there is strong evidence for the importance of public charging points and an even stronger effect of fast public chargers for PEV adoption. Purchase incentives also have a positive and significant effect across model specifications but as the preceding discussion has shown, although it is an important tool for policymakers, it is not necessarily sufficient to lead to structural change. These conclusions suggest that to enable wider PEV adoption policymakers should focus as much attention on charging infrastructure, especially fast charging infrastructure, as they so far have done on personal incentives. The implications of these conclusions are in line with the notion that personal incentives and price signals are certainly important, but they will only get us so far. In order to massively reduce emissions in the transportation sector, governments around Europe, and the world for that matter, need to create the frameworks and regulatory conditions, and likely in some cases and areas, a sufficient support system for relevant actors to upgrade charging infrastructure with sufficient charging speeds to make it convenient for consumers to own a PEV. These conclusions are also timely, as governments around the world are attempting to reboot their economies after lockdowns and global economic slowdowns following their attempts to slow down the spread of COVID-19. As wise as it might seem, attempting to green the economy while rebooting it, policymakers should make note of the empirical effects of increasing charging infrastructure on PEV adoption in the European sample. Whereas renewable energy was the recipient of major stimulus packages around the world after the 2008 financial crisis, electric mobility and infrastructure could and seems to be part of many of the post-2020 stimulus packages. Infrastructure requires more governmental involvement, coordination, and regulatory consistency than implementing personal incentive schemes, but is clearly no less important. Given how short the world has come in transforming the transportation sector, massive reductions in emissions and increased efficiency of the transportation system are at stake.

Acknowledgements

Data Availability

The dataset related to this article can be found at doi: 10.17632/kszst8ssd2.1l*, an open-source online data repository hosted at Mendeley Data (*Sæther, 2020*).*

APPENDIX A

Table A1: Selected modern plug-in hybrids from auto manufacturers

Car model	**CO_2 emissions in g/km - NEDC (collected from manufacturer)**
Audi A3 Sportback e-tron 2018	37
Audi Q7 e-tron 2018	48
Hyundai IONIQ Plug-in Hybrid 2018	26
Volkswagen Golf GTE 2020	38
Mercedes-Benz C 350 2018	49
Mercedes-Benz E 350e 2018	49
Mitsubishi Outlander Plug-in Hybrid 2018	46
Volvo V60 Plug-in Hybrid 2018	48
Volvo XC60 T8 Twin Engine 2018	49
Volvo XC90 T8 Twin Engine 2018	49

Table A2. Robustness testing for the effect of charging infrastructure and electric mobility policies on the share of PEV registrations in Europe

Variables	(8) Share of PEV – Charging point per PEV	(9) Share of PEV - Random effects	(10) Share of PEV using Cook`s distance	(11) Share of PEV using Cook`s distance	(12) Share of PEV using Cook`s distance	(13) Share of PEV using Cook`s distance	(14) Share of PEV using Cook`s distance
Vehicle per charging points (*logged*)		0.192*	0.181***	0.201***	0.194***	0.198***	0.197***
		(0.0882)	(0.0477)	(0.0563)	(0.0569)	(0.0552)	(0.0539)
Charging point per PEV (*logged*)	-0.427***						
	(0.0947)						
Fast public charging points (*logged*)	0.297***	0.310***	0.125**	0.122*	0.129*	0.124*	0.118*
	(0.0375)	(0.0277)	(0.0541)	(0.0592)	(0.0599)	(0.0576)	(0.0603)
Fast public charging points (*cubed*)			0.0450***	0.0428***	0.0415***	0.0423***	0.0446***
			(0.00757)	(0.00842)	(0.00783)	(0.00810)	(0.00872)
Purchase incentives (*pi*)	0.178***	0.148**	0.206***				
	(0.0555)	(0.0577)	(0.0525)				
Registration tax benefits (*rb*)	-0.0962	-0.0277	-0.0850				
	(0.0516)	(0.0524)	(0.0708)				
Ownership tax benefits (*ob*)	0.0248	0.0988*	0.0149				
	(0.0399)	(0.0462)	(0.0501)				
Local incentives (*li*)	-0.185***	-0.113*	-0.207**				
	(0.0463)	(0.0563)	(0.0514)				
Policy package 1				-0.101			
				(0.0757)			
Policy package 2					0.0713		
					(0.0963)		
Policy package 3						0.0145	
						(0.0612)	
Policy package 4							0.108*
							(0.0551)
Urban population	0.102***	0.0124**	0.154***	0.142***	0.138***	0.131***	0.129***
	(0.0299)	(0.00444)	(0.0242)	(0.0277)	(0.0338)	(0.0285)	(0.0310)
GDP per capita (*logged*)	-0.708**	0.112	-0.105	-0.262	-0.458*	-0.402	-0.371
	(0.298)	(0.239)	(0.294)	(0.299)	(0.242)	(0.273)	(0.255)
Residential electricity price	-1.110	-0.465	0.393	-0.190	-0.557	-0.388	-0.744
	(1.482)	(0.653)	(1.477)	(1.473)	(1.730)	(1.531)	(1.423)
Mean fuel user price petrol & diesel	0.646***	0.109	0.546**	0.532**	0.571**	0.555**	0.524*
	(0.203)	(0.0892)	(0.238)	(0.228)	(0.236)	(0.236)	(0.244)
Constant	-1.357	-2.176	-11.63**	-8.970*	-6.664	-6.761	-6.772
	(4.344)	(2.830)	(4.400)	(4.581)	(4.030)	(4.175)	(4.163)
Observations	279	323	237	237	237	237	237
Number of countries	30	30	30	30	30	30	30
Time FE	NO	NO	YES	YES	YES	YES	YES

Driscoll-Kraay standard errors robust to temporal and spatial autocorrelation in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table A3. Effect of charging infrastructure and electric mobility policies on the share of BEV registrations in Europe

Variables	(15) Share of BEV – with 2009	(16) Share of BEV – 2010-2019	(17) Share of BEV – 2010-2019	(18) Share of BEV – 2010-2019	(19) Share of BEV – 2010-2019	(20) Share of BEV – 2010-2019	(21) Share of BEV – 2010-2019
Vehicle per charging points (*logged*)	0.0972**	0.0921**	0.0367*	0.0921**	0.0871**	0.0893**	0.0944**
	(0.0374)	(0.0359)	(0.0178)	(0.0362)	(0.0330)	(0.0356)	(0.0355)
Fast public charging points (*logged*)	0.252***	0.231***	0.229***	0.229***	0.231***	0.227***	0.229***
	(0.0319)	(0.0289)	(0.0289)	(0.0288)	(0.0274)	(0.0285)	(0.0292)
Purchase incentives (*pi*)	0.0900*		0.107**				
	(0.0503)		(0.0471)				
Registration tax benefits (*rb*)	-0.0477		-0.0748				
	(0.0473)		(0.0533)				
Ownership tax benefits (*ob*)	-0.0245		0.00263				
	(0.0189)		(0.0336)				
Local incentives (*li*)	-0.101***		-0.108***				
	(0.0194)		(0.0215)				
Policy package 1				0.0907**			
				(0.0392)			
Policy package 2					0.167***		
					(0.0442)		
Policy package 3						0.128**	
						(0.0396)	
Policy package 4							0.0758**
							(0.0305)
Urban population	0.119***	0.138***	0.134***	0.131***	0.145***	0.130***	0.134***
	(0.0293)	(0.0291)	(0.0382)	(0.0274)	(0.0283)	(0.0277)	(0.0288)
GDP per capita (*logged*)	-0.645**	-0.539**	-0.156	-0.608***	-0.686***	-0.638***	-0.534**
	(0.209)	(0.175)	(0.297)	(0.173)	(0.160)	(0.165)	(0.168)
Residential electricity price	-1.629	-1.831	-1.731	-1.975	-2.496*	-2.148	-2.119*
	(0.947)	(1.140)	(1.475)	(1.165)	(1.259)	(1.197)	(1.074)
Mean fuel user price petrol & diesel	0.288	0.381**	0.393***	0.366**	0.371**	0.357**	0.367**
	(0.160)	(0.150)	(0.120)	(0.150)	(0.159)	(0.152)	(0.154)
Constant	-2.269	-4.960	-8.743	-3.679	-3.864	-3.242	-4.661
	(3.757)	(3.091)	(5.735)	(3.015)	(3.314)	(3.074)	(3.166)
Observations	323	293	293	293	293	293	293
Number of countries	30	30	30	30	30	30	30
Time FE	YES	YES	YES	YES	YES	YES	YES

Driscoll-Kraay standard errors robust to temporal and spatial autocorrelation in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table A4. Effect of charging infrastructure and electric mobility policies on new PEV registrations in Europe

Variables	(22) New PEV registrations	(23) New PEV registrations	(24) New PEV registrations	(25) New PEV registrations	(26) New PEV registrations	(27) New PEV registrations
Vehicle per charging points (*logged*)	0.508***	0.483***	0.507***	0.496***	0.507***	0.512***
	(0.114)	(0.0933)	(0.113)	(0.107)	(0.114)	(0.114)
Fast public charging points (*logged*)	0.442**	0.358*	0.444**	0.455**	0.443**	0.429**
	(0.172)	(0.169)	(0.174)	(0.169)	(0.171)	(0.167)
Fast public charging points (*cubed*)	-0.0901**	-0.0652*	-0.0901**	-0.0918**	-0.0909**	-0.0877**
	(0.0314)	(0.0326)	(0.0316)	(0.0306)	(0.0312)	(0.0304)
Purchase incentives (*pi*)		0.514***				
		(0.128)				
Registration tax benefits (*rb*)		0.160				
		(0.116)				
Ownership tax benefits (*ob*)		0.347**				
		(0.123)				
Local incentives (*li*)		-0.229				
		(0.141)				
Policy package 1			-0.160			
			(0.157)			
Policy package 2				0.489*		
				(0.238)		
Policy package 3					0.119	
					(0.118)	
Policy package 4						0.0912
						(0.0973)
Urban population	0.0361	0.0599	0.0460	0.0446	0.0301	0.0315
	(0.0416)	(0.0359)	(0.0430)	(0.0393)	(0.0449)	(0.0429)
GDP per capita (*logged*)	0.0299	0.259	0.145	-0.356	-0.0640	0.00418
	(0.898)	(1.151)	(0.910)	(0.900)	(0.894)	(0.915)
Residential electricity price	-3.882	-6.105*	-3.596	-6.058	-4.208	-4.255
	(3.461)	(3.057)	(3.500)	(3.642)	(3.439)	(3.279)
Mean fuel user price petrol & diesel	-0.510	-0.575	-0.485	-0.546	-0.531	-0.537
	(0.376)	(0.450)	(0.382)	(0.387)	(0.383)	(0.394)
Total population (*logged*)	1.701	-0.366	1.819	1.304	1.553	1.403
	(1.272)	(1.693)	(1.305)	(1.300)	(1.305)	(1.189)
Constant	-27.43	1.923	-31.30	-17.37	-23.58	-21.97
	(18.88)	(21.48)	(20.05)	(19.02)	(19.96)	(18.74)
Observations	323	323	323	323	323	323
Number of countries	30	30	30	30	30	30
Time FE	YES	YES	YES	YES	YES	YES

Driscoll-Kraay standard errors robust to temporal and spatial autocorrelation in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table A5. Standardized coefficient calculation

Coefficient of x-variable multiplied by the (within) Std. deviation of x-variable -

Product divided by the (within) Std. deviation of the y variable.

	Coefficient	Standard deviation (within)	Standardized coefficient	Percentage
Log share of PEV		0,560		
Log PEV per charging point	0,210	0,971	0,36	36 %
Log Fast charging points	0,316	1,292	0,73	73 %
Purchase incentives	0,190	0,347	0,12	12 %

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Article 3:

A green maritime shift: Lessons from the electrification of ferries in Norway

A green maritime shift: Lessons from the electrification of ferries in Norway.

Simen Rostad Sæther
simen.r.sather@ntnu.no

Espen Moe
espen.moe@ntnu.no

Department of Sociology and Political Science, Norwegian University of Science and Technology, 7491 Trondheim, Norway

Abstract

Norway is at the forefront of a transition toward cleaner solutions in the maritime sector. In 2015, the first fully electric ferry, the MF Ampere, started operating in Western Norway. Since then, 60 electric or hybrid-electric ferries are in operation or scheduled to be by the end of 2021. With a few exceptions the literature on energy transitions sees transitions as disjointed and slow. Through this case study—based on 13 semi-structured interviews, two focus groups, as well as seminars, conferences and workshops with industry experts, public sector stakeholders, and project managers—we show how the Norwegian ferry case is an example showing that, under the right circumstances, energy transitions can however be politically accelerated, even in what is widely deemed a hard-to-decarbonize sector. This is one of the first attempts at analyzing the politics of accelerated transitions within the maritime sector. It is also one of few studies of the electrification of ferries, and at the end of which we suggest a set of success criteria for accelerated transitions. We propose four main explanatory factors: First, what we label the Norwegian ferry innovation system was instrumental in providing an environment conducive to electrification. Second, the Norwegian state acted entrepreneurially, by moving beyond merely being a de-risker through playing an active role in market creation and transformation through public agencies and support schemes. Third and fourth, we argue that the relative lack of strong opposing vested interests combined with an oil shock to create favorable conditions for structural change.

Keywords

Electric ferries, accelerated transitions, maritime sector, climate policy

1. Introduction

Energy transitions are slow. Smil [1] states that they take decades to materialize, and that the current renewable energy transition will be no different. Human-induced climate change makes this an uncomfortable statement. The need to accelerate the current transition is obvious. Indeed, Sovacool [2] argues that under certain conditions, some regional and national transitions have been quite fast. The politics of accelerating transitions is however poorly understood and sorely understudied (e.g. [3,4]).

In this article, we study the electrification of ferries in Norway as a case of accelerated transitions. Norway is at the forefront of a maritime energy transition (e.g. [5,6]), with the first fully electric ferry, MF Ampere, commencing operations in 2015 [7]. As of 2021, 60 electric or hybrid-electric ferries are in operation. Norway recently specified that by 2023 ferry tenders will only be awarded to low- or zero-carbon emission ferries [8]. Energy transition studies often focus on the power sector. By comparison, with the exception of electric vehicles, the transportation sector is understudied, despite being significantly larger in terms of energy consumption (e.g. [9]).[1] Within transportation, the focus has primarily been on road transport, with far less attention given to maritime emissions. However, globally the maritime sector accounts for 10% of transportation emissions [12] and 2.9% of total emissions [13]. According to the International Maritime Organization (IMO), which is the UN body tasked with regulating and monitoring emissions from international shipping, greenhouse gas (GHG) emissions from shipping are expected to increase from 90% of 2008 emissions in 2018 to 90-130% of 2008 emissions by 2050 [13]. Instead, they need to fall by 50% [14], underlining the massive challenge ahead. Shipping is also considered a hard-to-decarbonize sector, as long-term decarbonization options such as ammonia and liquid hydrogen are not yet commercialized at a scale needed for massive utilization [15]. Even in smaller-size shipping segments, such as ferries, battery developments have only recently materialized as a probable path forward.

This case study shows that energy transitions can indeed be accelerated, even in hard-to-decarbonize sectors. We argue that this requires considerable coordination efforts between the state and the market actors and that it is inconceivable that market mechanisms alone

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[1] The power sector accounts for 17% of total final energy consumption, the transportation sector 32% [10,11].

would have produced a similar result. More specifically, we show that it was possible because of a mix of features: First, Norway has a ferry innovation system characterized by a culture of close collaboration, mutual trust, and information-sharing. This made it possible to overcome potential initial resistance to electrification and for the maritime sector to pull in one direction.

Second, crucial to success was the state actively intervening to remove first-mover risks and costs associated with new and unproven technology. The two public entities responsible for ferry tenders, the Norwegian Public Road Administration (NPRA) and the Norwegian counties, deliberately sought to bring actors from different fields together to create credible solutions. The involvement of the state was also a case of identifying co-benefits. Stakeholders who engage in energy transitions do it for many reasons, with mitigation of climate change often lower on the preference list than, for instance, energy security or business opportunities [16,17]. For the state, involvement was made attractive by electrification being neither climate policy nor industrial policy, but a combination of the two, whereas for the industrial actors it represented a business opportunity. Thus, while the emphasis on reducing emissions is sincere, what made the ferry sector an alluring case for decarbonization was the potential for exploiting existing competitive advantages and creating an industrial cluster within battery production and green maritime shipping—both potential growth sectors. Thus, the state went further than simply de-risking. Instead, in the words of Mazzucato ([18] p.9), the state acted entrepreneurially, serving as a key partner of the private sector.

Third, also important was the lack of resistance from vested interests. The maritime sector constitutes a politically influential potential brake on electrification. Instead it was possible to create win-win solutions. Thus, Schumpeterian creative destruction [19] proved easy because the parties were able to focus on the creation part, without having to worry about the destruction of jobs and industries. In addition, fourth, transition was accelerated by a shock, namely the 2014 oil price crash, which inflicted empty order books on a maritime sector overly dependent on orders from the petroleum sector, providing an incentive to find new markets. Electric ferries became a welcome potential opportunity.

While there are undoubtedly case-specific factors making Norway a more obvious choice for the decarbonization of shipping than most nations, the policy implications are potentially great. There are lessons that can be transferred from the Norwegian maritime sector to the maritime sectors of other countries regarding transfers of technologies, institutional frameworks, and interactions between industry and state. This is also an example of the energy transition pursuits of a small state meaningfully contributing to accelerating energy transitions on a larger scale.

The article contributes in several ways. First, it contributes to the literature on accelerated energy transitions. The Norwegian case, exemplifying an accelerated transition within a hard-to-decarbonize sector, is a crucial case for theory development on accelerated energy transitions. Second, this is one of very few studies on the electrification of ferries, and one of the first attempts at analyzing the politics of the maritime energy transition. Third, it provides success criteria for accelerated energy transitions.

2. Literature and theory

Energy transitions can be defined as fundamental, long-term, structural changes in the energy system [10], affecting all its parts. Thus, previous energy transitions have typically led both to transportation revolutions and revolutions in the fuel source for energy production (e.g. [20,21]). Smil [1] however asserts that what they all have in common is their long duration. Energy transitions take generations, some even go beyond a century [22]. All predictions about a rapid renewable energy transition have failed because their promoters thought the present transition, unlike previous ones, could be rapidly accelerated ([1] p.136). The literature on the political dynamics of energy transitions suggests that transitions are difficult and protracted— "messy, conflictual and highly disjointed" ([23] p.323).

Against the view of transitions as slow and tenuous, Schmitz [17,24] stresses that there are indeed examples of rapid transformations, where green policies have been politically fast-tracked. Sovacool [2] provides 10 short case studies, suggesting that under certain circumstances transitions can be rapid, namely when there are "synergistic advances in multiple domains at once" ([2] p.211), domains such as energy, materials science, computing, etc. Both however stress that there is no magic formula and no overarching theory. Transitions are complex, context-specific, and dependent on timing, and states have different institutions, political systems, resource abundances and energy-security situations. The focus on *political* accelerations however suggests a focus on the actors instrumental in accelerating change. Here, the literature is scarcer. Already in 2012 Markard et al. [25] argued that how to promote and govern sustainability transitions would become a prominent topic. Yet, at the end of the decade Stokes and Breetz [4] lamented that while many studies examine technical, economic and policy drivers, little attention is paid to the political dynamics of transitions. True, there *are* examples of articles looking at political dynamics. Kotilainen et al. [26] focus on the combating of multiple lock-ins in their explanation of accelerated transport transitions in the Nordic countries. However, Hess [27] highlights that, as a rule, research on the policy failures behind slow energy transitions has been context-specific rather than looking for general conditions, whereas Roberts et al. ([3] p.305) emphasizes that while the renewable transition is actively pushed by policymakers, "the crucial issue of the *politics surrounding their deliberate acceleration*, remains under-examined".

The literature on the deliberate acceleration of the maritime sector is still in its infancy, and much existing work focuses on the technical. Gagatsi et al. [28] analyzes the potential for E-ferries in Europe, Reddy et al. [29] discusses the technologies of zero-emission ferries (using Norway as a case), whereas Ančić et al. [30] analyzes power options for ro-ro passenger ships. Of scholarly work with a social science content, the number of recent publications looking at maritime sustainability transitions using Norway as a case underline our claim of Norway being at the forefront of a maritime transition. Bergek et al. [9] argues that maritime transport has been neglected within sustainability transitions research. Several articles focus on procurements. Bergek et al. [9] and Sjøtun [7] highlight the role of the ferry Ampere in contributing to green public procurements in Norway, and Bjerkan et al. [31] argues that public procurement was used by policymakers for market creation and transformation, pushing suppliers to develop and offer greener solutions for the public sector. Berntsen et al. [32] focuses on human judgment and dialogue in ferry procurement processes. Sjøtun and Njøs [33] discusses Norwegian cluster policy and the green reorientation of clusters, the maritime sector being one of these. Hessevik [34] analyzes how Norwegian maritime clusters have used networking and lobbying to influence a green shipping transformation. Bjerkan and Seter [35] and Bjerkan et al. [36] both focus on technological challenges and their political solutions with respect to port infrastructures (providing power from land to vessels, on-board battery packs and the regulation of emission limits for docking in ports, etc.). Yet, despite this rapid and welcome growth in maritime transition literature, this article is one of very few to focus directly on the deliberate acceleration of such transitions.

We suggest four theoretical avenues that might help us understand how it may be possible to accelerate decarbonization processes.

First, we turn to the national system of innovation literature. Introduced by Freeman [37] ,[2] there is no single definition, but innovation and learning, and the diffusion of new technologies through webs of interactions between public and private sector actors, are central. A well-functioning innovation system consists of organizations, institutions, and linkages that generate, diffuse, and apply scientific and technological knowledge. Most definitions share a focus on interactivity—actors communicate, co-operate, and establish relationships that lead to the creation of knowledge and the exploitation of existing knowledge, domestically and abroad ([38] p.5). Patterns of interaction are stable over time, with distinct national features [39]. The main components are organizations (primarily firms) and institutions, the latter thought of as habits, norms, routines, rules, and laws, i.e., the rules of the game. Edquist ([40] p.196) characterizes the patterns of interaction as ones of either competition, transaction, or networking. Networking involves knowledge transfer through collaboration, cooperation, and long-term network arrangements. There is ample empirical support that networking, i.e., the interactive learning among organizations, has been crucial for innovation (e.g. [41]). Thus, we can expect that structural change is more easily pursued in systems characterized by networking, cooperation, and openness, the different industrial actors sharing knowledge when possible and acting together, rather than constantly engaging in cut-throat competition.

Second, Mazzucato [18] suggests a need to go beyond innovation systems. She emphasizes how the notion of the state as merely a facilitator belongs to the past. The onus on actively bringing actors together—state, industry, finance, research—can also be found in the systems of innovation literature (e.g. [37,42]), the historical literature (e.g. [43,44]), as well as scholarship on, for instance, energy security (e.g. [45]). Mazzucato ([18] p.74) stresses that the state must move beyond the clichés of either merely supplying research funding or actively picking winners. Instead, the state is a key partner of the private sector. It coordinates intra-industrial exchange, inter-sectoral linkages, inter-company linkages and the private-public space. It inserts low-carbon requirements in public procurements, and it "takes on

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[2] Freeman's definition ([37] p.1): The network of institutions in the public and private sectors whose activities and interactions initiate, import and diffuse new technologies.

risks, shaping and creating new markets" ([18] p.9). Prontera [45], in his description of the catalytic state, mirrors this. The catalytic state does not resolve the tensions between market and state, but combines them, forging coalitions between public and private actors. The state is not passive. In fact, the most successful states are those that have "collaborative power", i.e. the ability to creative cooperative agreements and consortia for action [46]. This is important in a field like the decarbonization of ferries, where easy market-based solutions are hard to identify. Thus, the entrepreneurial state goes further than just *de-risking* the private sector, "but envisions risk space and operates boldly and effectively within it to make things happen" ([18] p.6).

Third, historically, political resistance has been widespread (e.g. [43,47]), as transitions create both winners and losers, the losers typically being old energy incumbents with ample time to organize, influence regulations and institutions, lobby politicians, etc. Thus, transitions routinely meet with vested interest resistance. Mildenberger [48] suggests that climate politics is particularly difficult, as the dispersion of carbon polluters across the political spectrum means that labor actors and business actors have captured policymaking on the left and the right, leading to incremental change at best. For politicians, going against major vested interests comes at a cost. Decisions with large redistributive consequences are politically risky. Instead, the safe bet is to back established carbon interests and eschew major structural change, pushing energy transition into the distant future (e.g. [49,50]).

This derives from Joseph Schumpeter's [19] emphasis on creative destruction and structural change—electric ferries constituting a significant maritime structural change and a potential process of creation. However, often structural change is delayed or blocked by actors with a stake in the perpetuation of the existing system. Kivimaa and Kern [51] points out that energy transitions consist of both creation and destruction. This means policies aimed both at creating the new and destabilizing the old. The creation part is comparatively easy, i.e. niche support (e.g. [52]). But without destabilizing policies to phase out the old, which is always politically more difficult, transition is unlikely.

A potential answer comes from Kelsey [53], who divides industrial actors into winners, losers, convertibles, and management. Winners and losers are the actors that gain from change or indisputably lose. (The management category is not particularly relevant here.) The interesting category – directly relevant to the ferry case – is *convertibles*: "[c]onvertible industries are industries that make polluting products but do have the capability to switch to non-polluting products" ([53] p.620). First, we cannot take for granted that the ferry sector would automatically electrify, regardless of the energy alternatives. Second, this is an attempt at *accelerating* change, in a situation where it is not obvious that electrification represents any short-term economic gain over existing solutions. (It *does* for climate reasons but that is a different matter). There is also economic risk associated with several technological and infrastructural solutions necessary for electric ferries to be viable. This all suggests a sector where vested interests might resist change rather than embrace creative destruction. At the same time, in the ferry sector, the key requirement is not a specific source of propulsion but that the ferries run reliably, efficiently and turn a profit, conceivably making them convertibles rather than losers. If so, this is a sector where creation might happen without destruction being necessary.

Many argue that the world's energy situation is best described as one of carbon lock-in (e.g. [54]). Thus, a fourth and final suggestion comes from Aklin and Urpelainen [55], who theorizes that carbon lock-in is so prevalent that no change will happen unless there is a prior exogenous shock that re-politicizes the field. Change is not automatic, but shocks bring a potential for change by creating a window of opportunity for policymakers to regain autonomy over vested interests and stake out a new course. History has given us many examples of shocks that have led to the acceleration of change, e.g. the 1970s' oil crises, Chernobyl, or the 2011 tsunami in Fukushima (e.g. [2,56,57]). For a major petroleum exporter with a huge offshore industry like Norway, the 2014 oil price drop was a serious shock.[3]

3. Methodology

Data was gathered from 13 semi-structured interviews, two focus group interviews,[4] and high-profile workshops and conferences. Interview guides can be found in Appendix A3. Additionally, official documents, white papers, sector strategies, national and regional sector strategies, and media statements from stakeholders are part of the case material, contributing

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[3] At the most, the oil price fell from $115/barrel (June 2014) to 26$ (January 2016) [58].

[4] The topic of some interviews and focus groups was not exclusively on electric ferries, but ferries were either explicitly discussed, or related issues were discussed.

to cross-referencing and to our understanding of the transition dynamics from a broad range of stakeholder perspectives.

Our respondents constitute a wide range of actors and stakeholders, including county project managers and representatives from governmental agencies and the private sector. Some interviews were conducted between 2018 and 2020 as part of data collection for the Horizon2020 project ECHOES[5], including a best-practice case study of the implementation and decision-making process of the electrification of a Norwegian ferry crossing presented to the European Commission [59]. Additional interviews were carried out in 2020 specifically for this paper. The respondents were chosen for their expertise and viewpoints, with an aim to cover relevant aspects of the political and technological aspects of the electrification of Norwegian ferries. The respondents' names and identifiable positions are anonymized. Because of sensitivity issues surrounding contracts, support schemes, and opinions provided in the interview setting, we have not used direct citations. One should be cautious about drawing strong conclusions from single interviews, thus unless specified the data we present represents the views of a clear majority of the respondents. For a list of respondents and their approximate titles and positions (e.g. project manager, county), see Appendix A1. Stakeholder interviews provided valuable insights that are hard to obtain by assessing official documents and statements. The interview data thus uncover and highlight aspects of this transition that are not well-known and that provide relevant insights as well as revealing success criteria and pitfalls that others can learn from.

We attended six conferences and workshops: in 2018 the Zero Conference (annual climate conference in Oslo, Norway) and a workshop on the electrification of the maritime sector in Bergen, hosted by Zero; in 2019, Ocean Week in Trondheim, Norway, a workshop on green growth in Trøndelag county, and the Zero Conference; finally, in 2020 the Enova Conference in Trondheim. The attendance and presented materials obtained provided us with cross-referencing data, allowing us to adjust, support, or question statements from interviews. The complete list of conferences and seminars is provided in Appendix A2.

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[5] Webpage: https://echoes-project.eu/

4. Norwegian climate policy and the state of the Norwegian ferry sector

Norway recently increased its GHG emissions reduction target from 40% in 2030 to 50-55%, with an ambition of 90-95% reduction by 2050 (compared with 1990 levels), in accordance with the Paris Agreement and improved EU ambitions [60]. Substantial reductions must be made in areas that are not covered by the EU ETS, like the road and maritime sectors. Additionally, the Norwegian counties have ambitious climate targets as well as a national and partly regional ambition to drive new and greener growth in the maritime sector [5]. The responsibility for ferries is split between the counties and the NPRA.[6] This creates interesting possibilities related to procurement practices and the economic opportunity space in the ferry tenders, as for instance with the tender for the first electric ferry, Ampere, and is one of the few segments of the county economy where it is possible to cut emissions[7] (e.g. [7]). In 2017, Norway had 203 ferries, with an average age of 26 years, accounting for 12.7% of total domestic shipping emissions and 1.4% of Norwegian CO_2 emissions, as well as being a considerable source of local air pollution in ports [61]. With an old and polluting fleet, an upcoming replacement phase created a window of opportunity for the electrification of ferries, thus reducing the average age of the fleet while significantly cutting emissions and air pollution.

In 2015, after considerable political debate and involvement from environmental NGOs, maritime clusters and industry lobby groups, the Norwegian Parliament passed a ruling that all new ferry tenders must require low-emission technologies if possible/feasible [62]. The push was partly driven by a broad coalition across party lines and lobby organizations as the effect of the oil price drop in 2014 heavily affecting the petroleum sector and Norwegian shipyards, both industries with considerable political influence [63]. The government's goal was to electrify or provide low- and zero emission solutions to all ferries by 2025, which has since been pushed forward to 2023 [8].

As of early 2021, Norway has 34 ferry crossings that are fully electric or hybrid-electric with a considerable electrification rate (and one hydrogen ferry), and 57 crossings scheduled for

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[6] The NPRA is responsible for 16 ferry crossings and the counties 102 (including very short crossings). Additionally, five crossings will be replaced by bridges/tunnels.

[7] For many Norwegian counties a considerable amount of emissions under their responsibility comes from public transport like buses, ferries and high-speed ferries.

electrification.[8] Annually a standard electric ferry saves over 2,500 tons of CO_2 and 800,000 liters of diesel [65]. The most trafficked ferry crossing in Norway, Horten-Moss, which transports 1.8 million vehicles and 3.7 million passengers annually across the Oslo fjord, is scheduled to be fully electric by summer 2022.[9] For most new tenders, the winning contract has been awarded to ferry designs with battery-electric systems on-board with back-up diesel or gas-electrical propulsion systems that use second generation HVO biodiesel or biogas providing redundancy and securing regularity of operations. There are also examples of tenders for retrofits of existing ferries to battery-electric systems. Apart from contractual emission limits and reductions put in tenders, which have been crucial for the development toward electric ferries (e.g. [5,66], electricity is cheaper than (bio)diesel and LNG in Norway. Thus, there are incentives to maximize the rate of electrification.

The NPRA has contracted with ferry operator Norled to provide the world's first hydrogen-electric ferry, scheduled to start operating in Rogaland County from fall 2021.[10] The Norwegian government also wants to tender a hydrogen solution for Vestfjorden, a three-hour ferry crossing from Bodø to Lofoten, by 2024 [68]. Figure 1 shows a county-by-county overview of the ongoing electrification of ferry crossings in Norway, with operational ferry crossings, and scheduled year of electrification (or hydrogen). For details, see Appendix B1.

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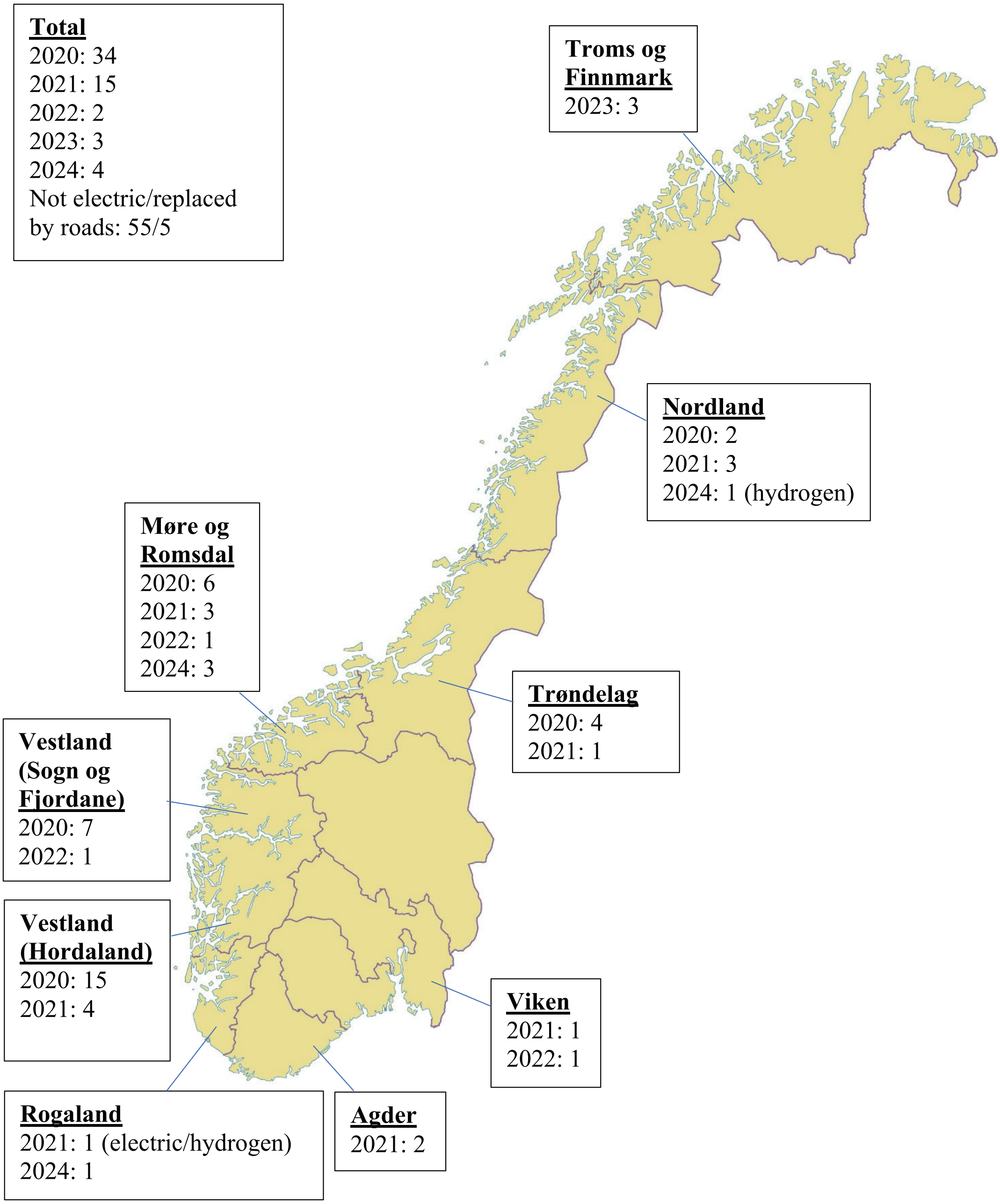
[8] For a graphical overview of electrification of ferry crossings, see https://energiogklima.no/nyhet/gronn-skipsfart/gronnskipsfart-naermere-60-elektriske-bilferger-innen-2021/ [64].

[9] One newbuilt electric ferry started operating in March 2021, two are to be electrified by 2022.

[10] MF Hydra is the first ferry in the world to use a liquefied hydrogen fuel cell [67].

Figure 1: Progression of electrification of Norwegian ferries



Sources: [64,69,70]

5. The electrification of Norwegian ferries

Norway's swift transition toward electric ferries is an example of an accelerated transition within a hard-to-decarbonize sector. We suggest that four main explanatory factors were crucial for electrification developments in the Norwegian ferry sector. First, what we label the "Norwegian ferry innovation system" played a major role in creating the conditions and environment where electrification of ferries could happen. Second, the Norwegian state acted entrepreneurially, moving beyond merely being a de-risker and playing an active and crucial role as market creator and transformer through various agencies and support schemes. Finally, we argue that the relative lack of strong opposing vested interests in combination with an oil shock created favorable conditions for structural change.

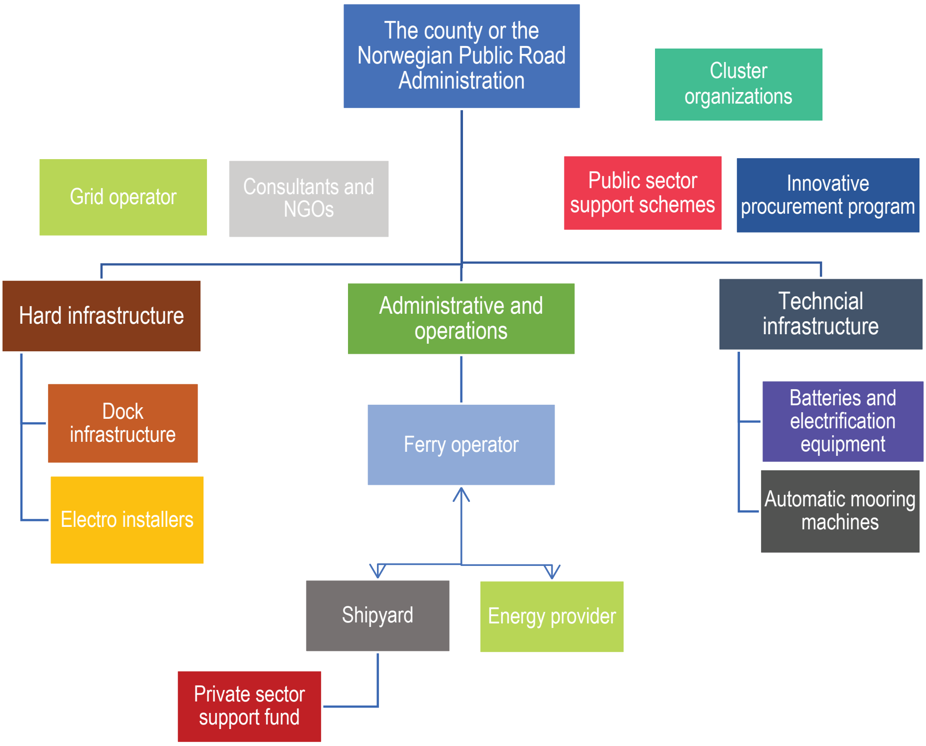
5.1 The Norwegian ferry innovation system

While a system of innovation is to some extent always a theoretical abstraction imposed on the empirical material by the authors, the empirical research made it clear that the Norwegian ferry actors are close-knit and collaborative to an extent that justifies the label system of innovation. We find ample evidence that the Norwegian ferry innovation system acted as a cluster characterized by close collaborations, transparency, trust, and knowledge sharing. These conditions and distinct features of the system have been crucial for the transition to electric ferries. The Norwegian system conforms to what Edquist [40] labels a networking innovation system, characterized by knowledge transfer through cooperation and collaboration and by long-term network arrangements.

5.1.1 Main actors and interactions in the ferry innovation system

To highlight the stakeholder linkages within this transportation segment, in Figure 2, below we have graphically mapped out the key stakeholders, displaying how they are linked and how they operate. In the following, we highlight why some of these interactions were vital in enabling the accelerated transition toward electric ferries in Norway.

Figure 2: The Norwegian ferry innovation system



The NPRA handles the operation of the ferry crossings that are part of the national roads system, while the counties have responsibility for ferry operations affiliated with county roads. Their responsibilities vary slightly but involve setting public tenders for new ferry contracts, while some also own and run dock infrastructure. The management of public transport varies slightly but generally the counties have created public transport administrative companies that run the day-to-day operations. These can be either fully-owned or co-owned companies with neighboring counties, which in turn procure ferry operators to operate the ferry crossings. Appendix C shows the ownership structure of these companies. The counties and the NPRA also make use of consultants to map energy needs to evaluate whether grid upgrades will be needed. Especially for remote ferry crossings, which do not necessarily have the grid infrastructure and capacity needed to sufficiently charge the ferry batteries, this is a challenge. Operators bid on contracts that usually last 10 years through tenders set by the county or the NPRA. The biggest operators are Fjord1, Norled, Boreal, Torghatten, FosenNamsos Sjø, and Bastø Fosen. As the transition toward electric ferries has progressed, fewer ferry operators own dock side infrastructure. Therefore, it is becoming more common that operators only pay for fuel/electricity of their operations. Operators calculate substantial fuel cost savings from electric propulsion, even if the ferry itself is currently more expensive to purchase. This however is slowly changing as battery costs are coming down and shipyards build more electric ferries.

5.1.2 A unique Norwegian culture

The close relationships between the actors within the Norwegian maritime networks are thoroughly documented by Hessevik [34]. While Hessevik's study is more about the lobbying influence of these networks than their collaboration, she leaves little doubt that they work closely together as a cluster whenever this is beneficial.

The line that sums up the network the best, and one repeated in different versions by several respondents, is that the maritime actors collaborate when they can (through clusters and private-public partnerships) and compete only when they have to. Several respondents referred to this as a distinctly unique and specifically Norwegian culture.

The respondents close to the decision-making processes have been very clear about the transparency between stakeholders, which has contributed to process-learning and sharing of best-practices. The county and public transport administrative company respondents told us that the electrification of ferries completely changed the process and the amount of involvement from the procuring side, from everything to do with new charging infrastructures to the fact that they needed updated knowledge and capacity to understand and feel competent enough about the new technologies compared to a traditional ferry. The general sentiment is that although there have been bumps in the road and numerous challenges, it has been a rewarding and continuous learning process for everyone involved. The respondents are clear that the stakeholders have been interested more in learning, dialogue and sharing, than secrecy and competition. There is a lot of interaction between large and small industrial actors, and information and experiences are being shared. The ferry actors explicitly confirmed that one thing they think is unique about Norway is how the whole value chain cooperates.

Thus, the value chain is central to the system. The ferry value chain is mostly local and linked together, including battery production and system integration. This has made the whole sector more willing to embrace electrification and technology development. One of the respondents added that this also applies to the state, including its support agency Enova. There is enormous value-added from the fact that the entire value chain is within Norway, making it far easier to create market change. Thus, the closer knit the cluster is, the more attractive it is also for the state to be involved, among other factors because of the potential for Norwegian technology development and job creation. One respondent added that not only is it easier and faster to relate to partners that speak the same language and come from the same business culture, but in many cases the distance between the actors is so short that they can physically see each other. This greatly improves the speed with which actors can coordinate and jointly move in new directions, such as building battery ferries with state-of-the-art dock-side charging infrastructure. Another respondent was clear that the physical proximity between Siemens' battery factory in Trondheim and the technological knowledge cluster constituted by The Norwegian University of Science and Technology and SINTEF (one of Scandinavia's largest applied research institutes) has been essential.

Finally, several environmental NGOs play a central role in the innovation system. Zero especially, has been invaluable, through its persistence in pushing policymakers to take action on climate solutions and through the facilitation of dialogue at forums and conferences, such as the annual Zero conference where policymakers, industry, NGOs, and academia meet and engage in networking, knowledge sharing and showcasing of best-practices. This represents a core feature of the Norwegian innovation system.

In sum, close collaboration, knowledge sharing, and high levels of trust between the actors, combined with the early market dialogue between the NPRA, the counties, ferry operators and their supply chains, was reiterated time and again by our respondents as important mediators of success. The ferry innovation system thus created conditions that allowed for an accelerated transition to electric ferries.

5.2 Beyond the innovation system: A Norwegian entrepreneurial state

5.2.1 Active market creation and transformation through public procurements

To fully understand the Norwegian transition to electric ferries, it makes sense to start with the technology-neutral development contract that yielded the world's first electric ferry. The contract was issued by the NPRA in 2011, “with the aim of stimulating to zero or low emission technology in the developmental, yet commercial, tendering process.” [7]. All respondents highlighted the Ampere tender as the key event that sparked the ferry transition. As the county respondents emphasized, ferries constituted a substantial source of emissions and had to be decarbonized for emission targets to be reached. Thus, the proof-of-concept and experience from the Ampere process meant that ambitious climate targets set by politicians could more feasibly be pursued.

Hessevik [34] emphasizes how the actors of the innovation system actively lobbied for the state (both national, regional, and local levels) to take a more active role in terms of procurements. The importance of procurements was also mentioned by many of the respondents, as well as the literature [7,9,31]. The public transport administrative company respondents clarified that while everyone wanted to find the most environmentally friendly solution at the lowest possible cost, it is expensive to be a first mover. The interviews made it obvious that there had been a lot of discussion within the counties on how to best transition ferries toward more climate-friendly solutions. This led to a range of approaches. Some counties explicitly stated in their tenders that the operators’ bidding needed to provide a battery-electric ferry, while others set absolute emission limits or eligibility specifications and otherwise maintained technology-neutrality. Some counties stated that they would prioritize the most polluting crossings with the largest budgets first, thus lowering the technology risk, while others opted for retrofit solutions on existing crossings. One respondent told us specifically that their county did not want all their ferry crossings to be first-generation electric ferries. Another added that they really had to make sure that the tender specifications were made with technology development in mind, as the battery technology is improving so fast that one feared locking in solutions that might soon be obsolete. Thus, the decision-making process was neither clear-cut nor simple. Crucially, this led to an innovation in the procurement contracts: one county added a climate bonus in one ferry procurement tender, giving the owners an incentive to lower the climate impact over the length of the contract, thus creating a dynamic, rather than a static, procurement. These are examples of how national policy and tender logic were implemented regionally and locally by actors on the ground.

Part of the role of the state as facilitator has been the active construction of meeting places between the industry and the public sector, linking actors that would otherwise not have engaged with each other, both nationally and on the county level. Hessevik [34] describes the inclusion of the NPRA in one of the major shipping networks. One of our respondents emphasized the importance of tying the entire system together, not just the industry. Another respondent hailed the importance of the in-between space between the business world and the public sector, linking procurements with the entire value-chain of actors. In this in-between space we find initiatives like the 'National Programme for Supplier Development', which has been instrumental in assisting public procurers accelerate innovations and develop new solutions through the strategic use of public procurement and by creating market opportunities for these solutions. The program is a broad collaboration between the public and the private sector [71].

It was underlined by several respondents that many of the solutions required for successful electrification involve too many actors for electrification to happen by itself. Without working with the entire value-chain, including the financial sector, change is unlikely. This applies especially to the grid and dock-side infrastructure for the ferries, which several respondents described as often overlooked. For all practical purposes, expensive infrastructure upgrades are necessary for electrification, especially in remote areas and locations where ferry docks are far away from the main gridlines. Dock-side battery banks and longer scheduled charging times are among the options to offset some of these costs. Battery banks can also be utilized as grid assets to provide peak shaving or demand response services for local distributed system operators.

5.2.2 Politically staking out a low emission course

Through the strategic use of public procurements, the public sector created a market for low-carbon ferry solutions. Additionally, the strong political signals from Prop. 78S. [63], ambitious county climate targets, and a vocal NPRA, made it clear that sectors with public stakeholders would move toward low-carbon solutions, thus assuring the private sector that their new solutions would have a sizeable market. This led to several key developments and subsequent decisions by Corvus Energy and Siemens to build two maritime battery factories in Norway. Several of our respondents highlighted that the link between the ongoing electrification of the ferries, strong political commitment, and access to cost-competitive renewable energy were all key determinants of the decisions to place the battery factories in

Norway, and of the decision to produce batteries for the maritime sector in the first place. Here we see a clear example of the confluence of climate policy and industrial policy.

It is no understatement that Norway created a market for maritime battery solutions that has contributed to an ongoing battery-electric revolution in the maritime sector, not just in Norway, but globally [72]. The technological spillover from the ferries and other early adopters of these technologies into other segments of shipping has clearly motivated suppliers and shipyards across the value chain to commit considerable resources to clean-tech related capacity. Additionally, based on our conversations with the industry actors, what was eminently clear was how big of an advantage it was to be located in a region and in a country which could showcase first-hand the utilization of the technology in harsh Norwegian climate, with the added benefit and commercially attractive prospect of producing the batteries with clean renewable power.

The instrumental role of the NPRA looks to be replicated with Norway's recent endeavors into the maritime hydrogen space. The agency has adopted the same pioneering role for the first Norwegian hydrogen ferry (fall 2021) and the hydrogen solution for the Vestfjorden-crossings in Lofoten (2024). The institutional capacity and know-how of the NPRA is benefitting counties and the national maritime scene tremendously, and it will be a key agency in the much tougher challenge of decarbonizing high-speed ferries, expected to start after 2024. Being a national agency with stronger governmental control and fewer budget restrictions than the counties, there was a consensus among the respondents that the NPRA has been crucial for the electrification of ferries. Essentially, the agency has been a key transition actor for the Norwegian entrepreneurial state.

5.2.3 A support system rigged for change and market transformation

The Norwegian climate and energy support agency, Enova,[11] is one of the central economic instruments through which the government reduces GHG emissions and supports and accelerates the development of climate and energy technologies. Arguably, Enova is a part of the innovation system. Rather than categorically separating the two, we see Enova as an example that there often is no clear distinction between the state and the innovation system. Enova is an integral part of the innovation system and simultaneously one of the foremost

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[11] Owned by the Norwegian Ministry of Climate and Environment [73].

levers for the Norwegian entrepreneurial state to support and accelerate market creation and transformation. For ferries specifically, the applicants can apply for funding from Enova for infrastructure expenses for up to a maximum of 40% of the cost. As Enova is bound by EFTA regulations on state support, the project must show that the funding leads to innovation or measurable results that would not otherwise have occurred.

Enova's mandate has changed considerably over time, from an original emphasis on energy/emission savings to now allowing it to focus on market transformation possibilities. To our respondents, this shift has allowed Enova to think more strategically and longer-term with a stronger presence and focus on supporting a green maritime shift and battery supply chain in Norway, two areas that the electrification of ferries benefit from.

As an additional de-risking support scheme, Enova administers the PILOT-E funding scheme, which has contributed to significant advances in the development of zero-emission and autonomous ferries and has contributed to creating new maritime-related industry. The program provides financial support for "fast-track from concept to market" for projects that deploy and develop "new environment-friendly energy technology products and services to help to reduce emissions both in Norway and internationally" [74], another sign of the active participation of the state. The support agency respondents also highlighted that the support schemes are focusing on projects that will accelerate the transition toward cleaner, more competitive solutions in the maritime sector and that Enova seeks to support solutions that can stand on their own feet and not rely on government subsidies once competitive in the market. Additionally, suppliers and ship-owners can apply for funding from the NO_x fund, which is the result of a 2008 agreement between the state and the major business associations to reduce NO_x emissions.[12] The fund has contributed to several ferry-electrification projects [75]. Innovation Norway is another state program that has provided support for R&D and development funding on both sides of the procurement process.

5.3 Absence of strong vested interests to oppose transition

The ferry case is in many ways a showcase of how to create win-win situations among key stakeholders. The fact that it happened in a hard-to-decarbonize sector makes it even more interesting. Looking at the case through a Schumpeterian evolutionary economy lens

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[12] Between 2008 and 2019 the fund awarded NOK4.4 billion for NO_x-reducing projects and measures [73].

highlights that structural change, here a ferry transition, is considerably easier when there are few structural barriers or opposing vested interests. In the ferry case, existing actors were not replaced and made obsolete by competing actors with rival technologies. Instead, they were able and willing (and aided by the state) to pursue the necessary transition—in Kelsey's [53] words, to go from transition losers to convertibles. At every conference attended, the sentiment among the shipping industry actors was that the industry saw the shift toward lower emission solutions as a strategic priority. This was echoed by our respondents. The unique culture among the stakeholders, mentioned in several interviews with both industry and public support system actors, is integral to why Norway was able to bypass some of the inertia and resistance that usually comes from vested interests facing a transition. These claims were backed up by comments and presentations given by industry and public sector stakeholders at conferences and seminars. As one industrial manager put it; "If the public sector orders ferries with high climate ambitions, the industry will be ready to provide it, with the technological and price developments getting to a favorable point for competitiveness." Given Hessevik's [34] account of the lobbying power of the maritime sector, the short-term interest of the sector could easily have been to stick with familiar solutions. Instead, the industry recognized electrification as necessary and something that might produce long-term competitive advantage. None of our respondents noted any efforts on the part of the industry to influence policymakers to abandon or slow down electrification efforts. Instead, we saw widespread cooperation between industrial actors, the support system, and the state to find solutions to the mutual benefit of all the actors in the system. Thus, lobbying power was not used to block change but to actively appeal for the need for the public sector to create the necessary green markets, develop infrastructure, and remove system barriers for cleaner shipping. The outcome was that the public sector tendered for highly ambitious ferries with large emission savings and that the industry developed and provided them.

To the extent that vested interests mattered, they did so in the sense that it was becoming ever more obvious that the sector was steadily losing market shares internationally, becoming more vulnerable, which was impressed upon the state by the unions [76]. The maritime sector argued forcefully that the contribution of the state would safeguard the national industry and make Norway into a showcase for the world [34]. For the state, a maritime energy transition took on greater importance once it became a matter of merging climate and industrial politics.

5.4 The oil price shock as accelerator

Not only did vested interests not oppose change, they were, in a very fundamental sense, given a stimulus to transition after the crisis caused by the oil price drop in 2014, which resulted in a near drying-up of contracts for newbuilds. A recent report highlights just how reliant the yards were on orders from the offshore segment. There were more than 2,000 offshore-related newbuilds both between 2006 and 2010 and 2011-2015, but they fell steeply to 760 between 2016 and 2020, resulting in an order book of only 363 at the end of 2020 [6]. In the same period orders for ferries and high-speed ferries increased from 562 (2006-10) to 817 (2016-2020). One respondent was clear that numerous shipyards would have been in serious trouble if it were not for the new battery ferries. It was a stroke of good luck for the shipyards that there were ferries to be built. At the same time, without the oil price shock, there would have been far less of an incentive for the shipyards to reform as they would have been running at full capacity because of orders from the petroleum sector. Thus, with respect to creative destruction, the oil price crashing was a blessing in disguise, with electrification partially a result of the drop in demand from petroleum [72,77]. The oil price crash also prompted the aforementioned broad coalition across party lines in 2015 to pass a motion in the parliament obligating the government to present measures for how to increase the use of low- and zero-carbon technologies in the maritime sector [63].

The oil price crash effectively meant that the industry had to undergo a green industrial restructuring, but the crisis also constituted an opportunity and a lifeline. Many shipyards did not even build ferries until the transition toward electric ferries, thus making it a costly affair with plenty of new and challenging integration issues to be solved. While building new capacity and overcoming integration challenges with battery-electrical ferries implied steep learning curves and unintended costs, the industry actors amongst our respondents were adamant that electrification and other clean-tech technologies will pay dividends, as more maritime segments adopt these low-carbon solutions.

6. A case of an accelerated transition

Ferries are an integral and traditional part of the Norwegian road system and the path to their ongoing electrification is a fascinating mix of active governmental policy and regulations, support scheme alignment and private sector initiatives that, together with an unexpected and beneficial crisis, combined to accelerate the transition. Most of the respondents were clear that the process that led to the first electric ferry, Ampere, was very much politically driven, and that the experience and momentum from Ampere created a snowball effect. In general, our respondents asserted that the shipping industry and its suppliers were an active part of the directional shift toward cleaner solutions and that the shift was supercharged by the dramatic fall in oil prices, as many shipyards were forced to diversify and look for new markets.

Shipyards produce local revenues and jobs, which makes them politically potent. Yet, the transition did not happen *because of* the crisis but accelerated it, as Ampere had preceded it by several years. However, no oil shock would arguably have resulted in vested interest opposition from a maritime sector still prioritizing lucrative orders from the petroleum sector, thus delaying the transition. The crisis thus created a policy window for politicians and industry to combine climate efforts and industrial development in pursuing a cleaner and more competitive maritime sector, in the process also facilitating a domestic maritime battery supply chain and erecting transition-enabling infrastructure. The merging of climate and industrial politics was key to the acceleration of change.

The case fits Mazzucato's [18] notion of an entrepreneurial state. The Norwegian ferry case is an example of an accelerated transition where the state not only acted as "de-risker" of the first pilot projects, but also acted entrepreneurially, bringing industrial and public actors together, creating and shaping a new market through public procurement processes and hands-on facilitation, and coordinating the construction of the enabling infrastructure needed for this market. One thing this case clearly shows is the importance and the potency of active, knowledgeable public procurers that engage in dialogue with the suppliers and industry to create well-specified tenders. In short, the public sector envisioned the risk space and operated within it to create and accelerate the transition, and the private sector responded and provided solutions. This all represents a departure for Norwegian climate, energy and industry policy, which since the 1990s has been distinctly market-oriented, with industrial neutrality and cost-effectiveness as key notions (e.g. [78,79] (the other noticeable expectation being the transition toward electric vehicles).

Our respondents amongst the procurers were clear that creating and transforming the new markets required more than simple market-based solutions; instead, it required a whole mix of policy, regulations, and incentives. Additionally, they suggested that close market dialogue and identifying win-win situations between the public, private and academic sectors were key parts of getting the transition underway. Our industrial respondents suggested that they primarily needed assurances that there would be a market for the new solutions they created. In that sense the parliamentary ruling for low- and zero emission tenders, combined with ambitious climate goals, gave the industry a very clear direction. While a ferry transition is probably inevitable in the long run, market-based solutions alone would not have produced the present transition.

6.1 Four success factors leading to the electrification of ferries in Norway

The ferry case enables us to identify success criteria for the transition organized loosely around the four theoretical explanations presented earlier:

1. **An innovation system characterized by close collaboration and extensive dialogue among stakeholders**

The stakeholders in the ferry segment, and by extension the maritime industry cluster, are small and part of larger clusters. The actors *collaborate when they can and compete when they have to*. Both public and private stakeholders cooperate, learn and lean on each other, which creates a unique environment where solutions are invented and refined, increasing the chances of eventual success. The extensive dialogue between stakeholders in the ferry innovation system is highlighted by nearly all our respondents as a massive success criterion for the accelerated transition toward electric ferries.

2. **An interconnected innovation system and an active entrepreneurial state**

The range of support schemes and process-knowledge in various programs that facilitate knowledge sharing, dialogue, and provide financial support, have been vital to the transition. The shift in Enova's mandate toward a stronger focus on market transformational goals and market creation was a contributory factor to the accelerated transition, with an added strategic focus on supporting national competitive supply chains within the Norwegian maritime sector and battery production.

3. **An entrepreneurial state and ambitious climate targets set the direction for a decarbonized ferry sector**

The Norwegian state apparatus pulled in one direction to transform the market. This made it possible for regional and local stakeholders to act ambitiously. Secondly, the de-risking actions of the Norwegian counties combined with the NPRA taking on responsibility, coordination and costs for dockside infrastructure, assisted by the public support system, also contributed to the ferry operators' ability to compete with low-emission solutions in new ferry tenders. The procurers in both counties and NPRA were aided by ambitious climate targets and a strong parliamentary ruling. This created a clear direction and opportunity space for ambitious tenders, which eventually solidified low emission solutions as the clear preference in the ferry segment.

4. Undermining resistance from vested interests by transforming would-be transition losers into convertibles and making the best out of a crisis

The focus on developing competitive national supply chains by leveraging public procurements as part of market creation and transformation is a clear success criterion and has helped transform some would-be transition losers into convertibles, thereby conceivably undermining resistance from vested interests. Instead, vested interests used their lobbying power to accelerate change, rather than attempting to slow it down. Finally, stakeholders in both the public and the private sector used the window of opportunity created by the oil price crash to transition to a more competitive and cleaner maritime sector.

7. Concluding remarks

The electrification of Norwegian ferries is still not complete, and obviously, until fossil fuel lock-in has been replaced by electric lock-in, any change is reversible. Recently, Norwegian shipyards have lost market shares internationally, thus pressures are mounting to make sure that the clean-tech capacity these yards have acquired is not lost to foreign competitors [6,76,77]. Electrification and costs related to grid upgrades and new dock- and charging infrastructure has also triggered a rise in ferry ticket prices, with subsequent protests and demands for ticket price cuts, prompting the government to cut ticket prices by 25% over the national budget [80,81]. Also, Enova recently announced that it is scaling back charging infrastructure support schemes, citing the foothold that electrification has gained in the market [82]. Thus, the true test of the continued transition toward electric ferries might still lay ahead. This does not mean that there is nothing to learn from the electrification of ferries.

This is a story of political will and facilitation combined with an absence of resistant vested interests—absent partly because of a severe oil shock. With orders from the petroleum sector nosediving, the politically induced push for a more climate-aligned maritime sector gave the shipyards and the supply chains a welcome break and a crisis-avoiding outlet. The government could claim to be saving both jobs and the climate through a public support system that used active public procurements to strategically facilitate market creation and transformation and building national supply chains. In summary, the electrification of Norwegian ferries shows that transitions *can*, in fact, happen quickly.

We show that electrification was testament to a potent mix of the alignment of climate and industrial policy goals through the means of public-private partnerships, with facilitated dialogue and the use of public procurement as a tool for market creation. The case is also a reminder that transitions can be fast in the absence of opposition from vested interests, especially when potentially refractory interests are given incentives to adapt and transition to a new paradigm.

Mowery [83] warns that we cannot simply cut and paste lessons from one mission-oriented program to another. They all have their own specificities, and the Norwegian case is no exception. Norway has a long and proud shipping and maritime history, thus there are strategic and historical reasons as to why both the Norwegian public and private sector have been eager to take a leading role in a green maritime shift. Also, Norway's electricity sector is close to 100% renewable. This means that Norway, more eagerly than other countries, has looked toward transportation for sectors that are conducive to emissions cuts. Furthermore, Norway's renewable prowess has made the country attractive for energy-intensive production, such as batteries. Thus, there are several reasons why we would expect Norway to be a frontrunner in the electrification of shipping.

Yet, we believe that the Norwegian case provides key insights that can be transferred to other countries as well in the pursuit of energy transitions in other hard-to-decarbonize sectors. Besides having a well-functioning innovation system and a state that actively facilitated structural change, one of the lessons is that finding national competitive advantages in the energy transition is increasingly important as policymakers and public support systems allocate scarce resources in their attempts to identify sustainable growth impulses. Linking the green maritime shift with a national chain of suppliers and battery providers has aligned climate and industrial policy goals. This has accelerated the process of change. Other countries and regions may have different competitive industries, sectors, and niches conducive to an energy transition. This case shows how Norway did it with ferries.

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Appendices

Appendix A1

Respondents

- Project manager for ferry projects in a Norwegian county
- Senior advisor in national support agency
- Project manager in national support program
- Project manager in global company with solutions for the electrification of the maritime sector
- Project manager, advisor and technical manager in a Norwegian county public transportation administrative company
- Project- and technical manager in a Norwegian country public transportation administrative company
- Project manager in a ferry operator company
- Technical manager in a shipyard
- Project manager and chief advisor for the maritime sector in a national NGO

- In addition the authors led two focus groups and four interviews where the subject of ferries was not the main goal of the focus group interview, but where ferries and the electrification of ferries in Norway were discussed and questions were answered accordingly by relevant stakeholders.

Appendix A2

Attendance at case specific workshops and conferences in addition to numerous small-scale relevant presentations and talks on the subject in various arenas.

- Zero conference in Oslo, Norway 2018
- Workshop on the electrification of maritime sector in Bergen, Norway 2018
- Ocean week 2019 in Trondheim, Norway 2019
- Workshop on Mobilization for green growth in Trøndelag County in Trondheim, Norway 2019
- Zero conference in Oslo, Norway 2019
- Enova conference in Trondheim, Norway 2020

Appendix A3

Interview guide – electric ferries-crossings

Introduction of the interviewer(s) and the project.

I would like to talk to you in more detail about the ZZ connection (s), and go deeper into the decision-making processes, support schemes and political framework conditions that have led you to decide to go for an electric low-emission solution. So today I am talking to you in XX and I look forward to hearing more about how this has been from your point of view. I would also like to remind you that I will record the conversation so that I do not miss important comments. At the same time, I want to assure you that our discussion will be kept anonymous in accordance with public guidelines, the information sheet and the consent form.

1. Description of the case and actor:

a) Tell me briefly about which relevant areas XX is responsible for/work with when it comes to the topic of electric ferries and preferably also briefly about your background, what you work with here and how long you have worked in XX?

b) Can you briefly describe the XX role in the ZZ project/s?

c) Please give me a brief historical overview of events and context that led to XX helping to create a more climate-friendly solution for the ZZ connection/s.

d) Can you tell us about whether the county or whether this particular ferry connection had any special conditions for such a solution to be chosen? For example, geography, distance, vessel size or departure frequency?

2. Analysis of existing alternatives:

a) Solutions are now being worked on for the transition to a low-emission society in most sectors and areas of society. How do you experience this in your job as a project manager / leader / advisor / actor, and how did you assess the importance of this focus in society when it came to the solution that was chosen for the ZZ connection/s?

b) Can you say something about what other alternatives were on the table for the ZZ connection(s)?

c) Tell me a little about how you chose from among the alternative solutions? Feel free to tell us in detail how you proceed when you prepare a tender like this.

d) Would you say that the decision-making processes in the project can best be described as primarily top-down or bottom-up driven? Feel free to tell us a little about how this has unfolded in this project.

3. Development of roadmaps and solution approach:

a) How would you consider the rationale behind the choice of the solution, based on this decision-making process?

b) Can you describe any obstacles in the process before the tender process was completed and decided? For example, of a political, economic or technological nature.

c) After the solution was chosen, which processes were then started from XX side?

d) Can you identify which planning steps have been followed during the process and feel free to describe any methods you used to follow up the implementation.

4. Implementation phase:

a) Can you say which factors have been important after the tender process was concluded on your part?

b) What would you say has been challenging in the implementation phase? Have you encountered any obstacles or barriers that have been problematic during the implementation?

c) Can you identify any success criteria for successful implementation?

5. The results of the implementation:

a) As a project manager / manager / advisor / stakeholder, how will you assess the success of the solution that has been chosen and why? Comment if you consider that the expected results have been achieved.

b) As a project manager / manager / advisor / stakeholder, how would you evaluate the result, in terms of the views of the key stakeholders?

c) How do you evaluate goal achievement?

d) What factors would you say played a key role in making the solution as optimal as possible? Feel free to also comment on factors you consider to be essential for success.

6. The effect and dissemination of the results:

a) In the longer term, what ripple effects do you think this project will have for the organization, other and future tenders in the sector and other relevant actors? Feel free to tell us about what experiences you will bring from the ZZ project into future projects.

Interview guide – electric ferries – Actors

Introduction of the interviewer(s) and the project.

I would like to talk more about how you have worked with electric / low-emission ferries in Norway and to go deeper into the decision-making processes, support schemes and political framework conditions that have now led to Norway coming a long way on the path to lower emissions from the ferry sector and the road ahead for the Norwegian maritime sector.

So today I am talking to you in XX and I look forward to hearing more about how this has been from your point of view. I would also like to remind you that I will record the conversation so that I do not miss important comments. At the same time, I want to assure you that our discussion will be kept anonymous in accordance with public guidelines, the information sheet and the consent form.

1. Description of actor:

a) Tell me briefly about which relevant areas XX is responsible for/work with when it comes to the topic of electric ferries and preferably also briefly about your background, what you work with here and how long you have worked in XX?

b) Which actors do you work most closely with in the ferry sector and how would you describe your collaboration with them?

c) What expertise/competence does XX have that makes you an important actor in the ferry sector and its development toward lower emissions?

2. Analysis of existing alternatives:

a) Can you say something about what alternatives the counties and the Norwegian Public Roads Administration have when they work with tenders? We know that electric/hybrid has come a long way in recent years, but that there are tenders/connections where other solutions may be relevant – if so, which are these? And feel free to tell us what you think about the technological development for electric ferries going forward? Are there any barriers on the on the technology side, say, onboard the ferries? Or on the infrastructure side, such as grid capacity/getting enough charging effect etc. that are barriers holding back the development?

b) Tell us about how you work with the actors who contact you about assistance/assessment/ competence.

3. Development of roadmaps and solution approach:

a) Do you know of any obstacles in the processes before the decision to go for electric/low emission solutions was taken? For example, of an economic or technological nature, which was resolved/possibly not resolved?

b) Has XX had any role after the decisions were made? In which case, feel free to tell us about the methods you used to follow up the actor.

4. Implementation phase:

a) Has XX been involved in any implementation phase?

b) Do you know if there have been any challenges in the implementation phase among the projects you have been involved in? Have you encountered any obstacles or barriers that have been problematic during the implementation?

c) Can you identify success criteria for projects that have been successful?

5. The results of the implementation:

There are more and more connections that are getting new ferries, and many more are on the way. Of approx. 200 ferries in Norway about 60 be low emissions by the end of 2021:

a) How would you like to assess the preliminary transitions we have witnessed in Norway, in terms of the views of the key stakeholders?

b) What factors would you say have played a key role in making the solutions as optimal as possible?

c) How do you evaluate goal achievement in XX?

6. The effect and dissemination of the results:

The technological development within electric/low emission ferries is very rapid and many classify this as a new industrial adventure for Norway, where Norway can take a leading role internationally:

a) In the longer term, what ripple effects do you think this may have in the Norwegian maritime sector, such as high-speed ferries and more demanding ferry connections?

b) Also feel free to tell us about what experiences you in XX will take with you from the projects you have been a part of into future projects.

Appendix B

Table B1: Progression of the electrification of Norwegian ferry crossings expanded

Viken	Electric	Electric 2021	Electric 2022	Electric 2023	Electric 2024-	Not electric
Bastø Fosen	1		1			

Agder	Electric	Electric 2021	Electric 2022	Electric 2023	Electric 2024-	Not electric
Boreal sjø		2				

Rogaland	Electric	Electric 2021	Electric 2022	Electric 2023	Electric 2024-	Not electric
Norled		1[13]				2
Fjord1						1
Small company					1[14]	
Will be replaced by road						2

Vestland (Hordaland)	Electric	Electric 2021	Electric 2022	Electric 2023	Electric 2024-	Not electric
Fjord1	8	2				
Norled	3					
Boreal	1	2				
Torghatten Nord	1					
Small company	2					

Vestland (Sogn og Fjordane)	Electric	Electric 2021	Electric 2022	Electric 2023	Electric 2024-	Not electric
Fjord1	1*E39 1					6
Norled	1*E13 2		1[15]			
Small company	2					

Møre og Romsdal	Electric	Electric 2021	Electric 2022	Electric 2023	Electric 2024-	Not electric
Fjord1	4	2			3	4 (2[16])
Norled	2		1			2
Torg						1
Boreal		1				

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[13] One electric and one ferry that will go on 50% hydrogen (MF Hydra).

[14] This crossing will be electric from 2025.

[15] This crossing might go on hydrogen if Norled decides to go forward with a hydrogen solution.

[16] The ferry crossings Brattvåg–Dryna–Fjørtofta–Harøya and Skjeltene–Lepsøya–Haramsøya will be replaced by new roads in 2022.

Trøndelag[17]	Electric	Electric 2021	Electric 2022	Electric 2023	Electric 2024-	Not electric
Fosen Namsos Sjø	1					7
Fjord1	1	1				1
Torghatten trafikk	1					
Small company	1					

Nordland	Electric	Electric 2021	Electric 2022	Electric 2023	Electric 2024-	Not electric
Operator not decided yet					Hydrogen[18]	
Torghatten Nord	2					8[19]
Boreal		1				8
Torghatten Trafikkselskap		2				6
Small company						

Troms og Finnmark	Electric	Electric 2021	Electric 2022	Electric 2023	Electric 2024-	Not electric
Norled				3		1
Torghatten Nord						2
Boreal sjø						6

Total	Electric	Electric 2021	Electric 2022	Electric 2023	Electric 2024-	Not electric/replaced by roads
Ferry crossings	34	15	2	3	4	55 / 5

*Two hydrogen ferries and one 50% hydrogen ferry are planned in 2021, 2022 and 2024.

Data and overview is cross-referenced using data from [64,69,70] and the ferry operators.

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[17] The two crossing: Edøya – Sandvika and Halsa – Kanestraum are crossing borders between Trøndelag and Møre-Romsdal and are counted in Trøndelag.

[18] This crossing is Vestfjorden and will be run on hydrogen.

[19] Some ferry crossings cross into Troms and Finnmark.

Appendix C

Table C1: Norwegian public transport administrative companies

Norwegian Public Road Administration (Statens vegvesen)

Statens vegvesen	Norwegian government

Oslo and Eastern Norway

Ruter AS	Oslo and part of Viken county (earlier Akershus county)
Brakar AS	Viken county (responsible for earlier Buskerrud county)
Østfold kollektivtraffikk	Viken county (responsible for earlier Østfold county
Innlandstrafikk	Innlandet county

Western Norway

Krigom	Vestland country (responsible for earlier Sogn og Fjordane area)
Skyss	Vestland county (responsible for earlier Hordaland area)
Kolumbus AS	Rogaland county

Mid-Norway

AtB AS	Trøndelag county
Fram	Møre og Romsdal county

Southern Norway

AKT AS	Agder county (80%) and Kristiansand municipality (20%)
Vestfold og Telemark fk	Vestfold and Telemark county

Northern Norway

Nordland fylkeskommune	Nordland county
Troms fylkestrafikk	Troms and Finnmark county (responsible for earlier Troms area)
Snelandia	Troms and Finnmark county (responsible for earlier Finnmark area)

Article 4:

Do Democratic Governance styles matter in the Energy Transition? An empirical inquiry into 46 developed and developing countries from 1990 to 2018

Democratic Governance Styles and the Energy Transition: An Empirical Test of 46 High-Income & Developing Countries, 1990-2018

Simen Rostad Sæther
simen.r.sather@ntnu.no

Indra de Soysa
indra.de.soysa@ntnu.no

Espen Moe
espen.moe@ntnu.no

Department of Sociology and Political Science, Norwegian University of Science and Technology, 7491 Trondheim, Norway

Abstract

How have the industrialized high-income countries and developing countries responded to the challenge of climate change? We address this by assessing to what extent democratic governance styles matter for achieving an energy transition, and whether some governance styles are better for producing structural change, rather than merely incremental change. To explore this, we use the Varieties of Democracy (V-Dem) framework to investigate the effect of egalitarian and liberal democratic governance styles on renewable energy production share, public environmentally-related R&D expenditure and CO_2 intensity in 46 OECD, BRICS and European countries from 1990-2018. Our main findings suggest that while there is no major difference between egalitarian and liberal democracies when it comes environmentally-related research funding or the share of renewable energy, egalitarian democracies actually perform worse than liberal democracies with respect to CO_2 emission intensity. Thus, the suspicion that egalitarian democracies struggle with energy transitions is supported by the data. Structural change may be a bigger problem here. The magnitude of the effects however also suggest that the results are driven as much by consumption as by governance type, and that greater opportunities for broad-based consumption in egalitarian democracies may be what leads them in the direction of higher CO_2 emissions.

Keywords

Democratic governance styles; Energy transitions; Renewable energy; Research funding; CO_2 intensity

1. Introduction

The question of climate change and how to achieve the Paris climate agreement goals of staying below 2°C, and strive for 1.5°C by cutting greenhouse gases to preindustrial levels by 2050 tops the global policy agendas of international institutions and individual governments across the world (UNFCCC, 2015; Stern 2015, UNEP 2019). The PEW research center´s polls among the general publics across the world suggest that doing something about climate change and global warming are priorities for the majority of citizens in most nations (Fagan and Huang 2019). A renewable energy transition – phasing renewable energy (RE) in and phasing fossil fuels out – is key to achieving the 2°C target and striving for 1.5°C. Historically, energy transitions have however been notoriously slow, and anything but smooth (e.g. Moe 2010; Smil 2010). Furthermore, for climate reasons the present renewable transition must be accelerated. We cannot simply wait for it to play itself out over a period of half a century. This puts the onus on politics. So far, attempts at politically accelerating the transition have however not met with any noticeable success.

There is a vast literature on how best to promote the deployment of renewable energy (feed-in tariffs, market-based instruments, RE auctions, green certificates, etc.). The literature on the role of regime types and emissions is far scarcer, and the results have so far been inconclusive. Much of the CO_2 emitted comes from energy use in the areas of heating, transportation, cooking etc. The International Energy Agency (2021) states that in order to reach net zero by 2050, 70% of global electricity generation needs to be derived from solar PV and wind power. How have the industrialized high-income countries and developing countries, particularly countries in Europe and North America and the BRICS countries, responded to prioritizing reduction in greenhouse gases, particularly by altering their energy production and use? We address this question by assessing the extent to which "governance" styles within democratic frameworks matter. We utilize a state-of-the art dataset on 46 OECD, BRICS and European countries from 1990 to 2018 to test whether egalitarian or liberal democracies are better at producing a renewable energy transition. We combine variables on renewable energy production share, public environmental R&D expenditure and CO_2 intensity with indicators of governance styles from the Varieties of Democracy (V-Dem) dataset.

While we find that there is no major difference between egalitarian and liberal democracies on research funding or the share of renewables in the power mix, egalitarian democracies perform worse than liberal democracies with respect to the intensity of CO_2 emissions. There is certainly literature suggesting that the more inclusive the democracy, the greater the environmental outcome (e.g. Niemeyer 2013). However, our suggestion is that our findings are instead compatible with a story that egalitarian democracies may struggle more to pursue structural change than other governance styles. The theoretical argument elaborated on below is that egalitarian democracies more easily than liberal run the risk of embedding carbon interests in the system, which makes anything but incremental change to the energy system hard to achieve. Thus, while egalitarian democracies may be excellent at renewable energy research funding or for that matter at phasing renewable energy into the energy system, they struggle at phasing fossil fuel emitters out.

Caution is however advised. The magnitude of the effects suggests that the results are driven as much by consumption as by governance type. In fact, the greater opportunities for broad-based consumption in egalitarian democracies may be what pushes them towards higher emissions. Free-riding and rent-seeking sees to it that the societal consensus necessary for concerted climate action is not easily translated into action, either in liberal or egalitarian democracies (Hovi, Underdal and Prinz 2009).

2. Theory

Which form of democratic governing style is more conducive to producing a renewable energy transition –egalitarian or liberal democratic styles? Indeed, some argue that autocracies might be less constrained than democracies in pursuing environmentally friendly policies (Wurster 2013). Several scholars argue that democracies often end up with irrational outcomes (Schumpeter 1943; Caplan 2008; Achen and Bartels 2017), that voters often choose contradictory policies even on simple matters, and that voters often fail to recognize policy failures and punish their politicians in retrospect (Achen and Bartels 2017). Instead, democratic leaders, intent on political survival, are liable to promise economic growth, increased consumption, and forms of pork-barrel spending (Roeland and de Soysa 2021). Some governments may also increase potentially environmentally damaging public spending, for example by building and expanding roads and dams as political patronage rather than considering alternative, more eco-friendly, public projects. Many would undoubtedly also argue that a country such as China is transitioning faster, because it has the ability to think farther ahead and pursue structural change with less political constraints than many Western democracies. Some autocracies, in other words, might be free to follow technocratic policy paths targeted at achieving a future-oriented goal whereas democracies might become stuck in status quo politics (Wurster 2013). Yet, not all democracies generate similar policy output (Collier and Levitsky 1997, Roeland and de Soysa 2021).

There is however also a rich literature suggesting that democracy is better for the climate and for an energy transition than autocracy (Dryzek, Norgaard and Schlosberg 2011). An open democratic society allows people to demand a more climate friendly energy path and for civil society actors to take political action in highlighting environmental issues. Elections and a vibrant public sphere allow a democratic public to control elites, who may otherwise plunder nature for profit. Inclusive policymaking might gain more legitimacy and thereby might be more effective (Niemeyer 2013), thus the more inclusive the democracy, the better the environmental outcomes it produces. Further, the vibrant public spheres characteristic of inclusive societies may in themselves produce a commitment to environmental thinking, or sympathy for future generations.

Here, we seek to go further by examining whether liberal or egalitarian democracies, as defined by the Varieties of Democracy project, are better for achieving an energy transition. Not all democracies are the same, even if they might contain some core features, such as free and fair election (Coppedge et al. 2011). Even the freest political system, however, some people may command access to politically relevant resources that advantage them over others. As the famous Norwegian political scientist, Stein Rokkan argued, “votes count, but resources decide the outcome in the end.” (Rokkan, 1966 p. 105). Democracies tend to suffer many levels of the principal-agent problem, where the agents (e.g. politicians, bureaucrats) have enormous structural and informational advantages over the “agent” (the voter). Thus, how democratic institutions and societal organization minimizes “power relations” within society can be decisive.

A common argument is that climate and energy policy is oftentimes captured by vested interests seeking to perpetuate the existing system, thereby eschewing major structural change (Moe 2015; Aklin and Urpelainen 2018; Mildenberger 2020; Stokes 2020). The renewable energy transition constitutes the biggest process of structural change to the energy system in at least a century. Structural change of any kind, however, creates winners and losers (Acemoglu and Robinson 2012). Within energy, the potential losers are oil and gas companies, electric utility companies, coal companies, etc. – some of the biggest industrial giants the planet has ever seen. They typically have had major influence in forming the policies and institutional structures of their host countries, as well as easy access to political decision-makers. For a politician, going against major incumbents potentially comes at the steep cost of losing the next election. Thus, the political strategy that minimizes risk is one of incremental change over more "disruptive" structural change. The literature is clear that all democracies are likely to be victims of rent-seeking to varying degrees when it comes to questions of adopting more climate friendly policies (Roeland and de Soysa 2021). Thus, the influence of vested interest is well documented, some going as far as to say that modern-day societies are "carbon locked-in" (Unruh 2000).

One argument is that institutional/regulatory capture or lock-in can only be broken in countries with strong political consensus, social cohesion, trust and legitimacy (Moe 2007; Ferguson 2013; Fukuyama 2014). High societal trust and legitimacy stems from the ways in which people see the system as being fair and equitable (Rothstein 2011). Legitimacy and trust in government are features that insulate decision-makers against knee-jerk reactions from voters, and thus reduces the risk for politicians for pursuing policies with major redistributive consequences, such as an energy transition. Other scholars stress that this is not enough, and that often no structural change, i.e., energy transition, will occur without a major external shock to break up the existing structure (Olson 1982; Moe 2012; Aklin and Urpelainen 2018; Stokes 2020).

The above tells us that structural change to the energy system is hard to attain. However, regarding whether different types of democratic systems are better at pursuing energy transitions than others, the literature is mixed. Christoff and Eckersley (2011) suggests that more consensual democracies may be more able to change than more liberal democracies. Roeland and de Soysa (2017) states that there is much to commend the idea that a broad-based democracy, where ordinary people have an equal chance of influencing the system, and where the system distributes resources through public goods more evenly, are likelier to produce more sustainable economic policies (Christoff and Eckersley 2011). Equal societies will be more consensual when it comes to pursuing common goals (Wilkinson and Pickett 2009; Rothstein 2011) This squares with research on the failures of neo-liberal capitalism and the idea that resistance to climate change mitigation is rooted in "unfair" economic development, inequality, and a backlash against globalization and elite-led democracy (Milanovic 2016, Stiglitz 2019). These claims also suggest that neo-liberal democracies are more prone to being captured by special interests than other democratic styles because these democracies are likelier to pander to capital, more likely to constrain the power of labor, and resist redistributive processes that can placate the "losers" of reforms (Collier 2018). Contrarily, egalitarian democracies should be better at building broad consensus around the importance of combating climate change and producing a renewable energy transition.

The literature however provides no unambiguous case for egalitarian democracies. It is far from obvious that for instance democracies with strong labor unions produce more climate-friendly policies. Unions have a strong incentive to protect polluting industry, such as coal and oil, resisting less polluting, labor-saving technological change (Bernauer and Kouby, 2009). Large corporations, particularly those dominating the hydrocarbon and mining industries, lobby governments to escape tight regulation, with much left up to voluntary compliance rules that are mostly side-stepped (Moe 2012; Wenar, 2016; Collier, 2018). Mildenberger (2020) thinks of climate policy as more distinctly carbon-captured than most policy areas. The problem for climate policymaking is that carbon polluters are dispersed across the political spectrum. Labor actors and business actors have captured policymaking on the political left and the right. No matter who controls government, carbon polluters are part of policy design. These factors may not provide egalitarian democracies with any advantages over other forms of democracy.

There are many ways of categorizing democracies. In this article, we follow V-Dem, which means dividing democracies into liberal or egalitarian (Coppedge et al. 2021).[1] Similar but somewhat distinct typologies are suggested by others. Mildenberger (2020) distinguishes between corporatist and pluralist styles of governance. The overlap with egalitarian and liberal is however significant, especially between his pluralist conception and V-Dem's liberal conception. The Varieties of Capitalism (VoC) literature separates between LMEs (Liberal Market Economies) and CMEs (Coordinated Market Economies), which also roughly mirror the V-Dem classifications of liberal and egalitarian. Both Mildenberger and the VoC literature conceptualize the differing forms of governance very similarly. In Mildenberger, corporatist countries can adopt more costly climate policies than the pluralist types, but they are rarely existential threats to the status quo, as carbon polluters preserve their access to climate policy design. This leads to incremental reform, for instance by allocating more research funding for renewable energy, but otherwise to an unchanged distribution of power. Germany's Feed-in Tariff was a costly measure that led to the rapid phase-in of solar and wind power, but had no direct cost for coal producers, who "stayed in the game" (Mildenberger, 2020 p. 246). It was renewable phase-in without a corresponding fossil phase-out. In contrast, pluralist economies are typically less ambitious but have a greater capacity for transformative change. Here, carbon polluters can conceivably actually be shut out of the policy process because of relative price change. A similar point is made in the VoC literature. In analyzing national carbon regimes, Hübner (2018) shows that variations in types of capitalism are crucial for understanding

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[1] V-Dem also includes participatory democracies. We have left these out because of their closeness to and major overlap with both liberal and egalitarian democracies.

national pathways to low-carbon economies. CMEs, with their stronger and more stable political coalitions, more easily pass green policies, but these are incremental, since carbon actors are amongst the many actors that are included in policy design (Hübner 2018). In contrast, the greater autonomy of LMEs potentially enables them to shut carbon actors out and pursue disruptive policies, even if the likelihood of any change happening at all, incremental or radical, might be smaller in LMEs since LMEs are less able to create the stable political coalitions necessary for change to be realistic. Schaffer et al. (2021) echoes this as they find that majoritarian electoral systems (many of which would be categorized as LMEs or as liberal democracies) are more likely to adopt what they call target-specific climate policies than systems with proportional representation.[2]

With neither Mildenberger nor Hübner is it obvious that the cohesion, consensus and trust, or the willingness to produce public goods, often associated with egalitarian democracies have any relevance for an energy transition. Instead, while such democracies might have the capacity for structural change, they more often prefer not to use this capacity, instead prioritizing social welfare, jobs, economic growth and consumption goods – in other words, they might prioritize the fight against inequality – with labor and employers' unions actively seeking to protect jobs and increase consumption goods. Research on inequality and environmental quality also casts doubt on the argument that egalitarian democracies are better at producing energy transitions. A more unequal society may be less fixed in its pursuit of consumption goods. Further, as preferences for environment and climate are likely to cut across traditional income and power groups, elites may demand better environmental policies, including energy transition policies, irrespective of the living conditions of the poor (Scruggs, 1998; Roeland and de Soysa, 2017). Thus, beyond classification schemes like governing styles, indicators of societal inequality, such as GINI coefficients and V-Dem's two measures for equality to access to health and strength of the welfare states will also be empirically examined alongside measure of our two competing varieties of democracy on several indicators measuring the policy commitments of countries to the energy transition. We thus test the following hypothesis:

Egalitarian democracies are likelier than liberal democracies to adopt policies consistent with achieving the energy transition

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[2] By target-specific policies Schaffer et al. (2021) refers to the link between the demand for climate policy targets with the supply of such policies.

3. Data & method

Our primary dependent variables are: Renewable electricity generation as a share of total electricity generation; share of environmental R&D budget of total government R&D, and CO_2 emission intensity per kWh of electricity generation. The share of renewable electricity in total electricity generation (*Renewable power % of total power generation)* measures the share of renewable energy generation as a percentage of total electricity generation and was obtained from the OECD Green Growth dataset (Organization for Economic Cooperation and Development 2020). The second dependent variable measures environmentally related government R&D budget in the total public R&D budget (*Environmental R&D budget % of total public R&D budget*). There are several other good indicators for measuring R&D related to the power sector, such as energy-related R&D, and renewable energy R&D, but these data are incomplete and lack consistent measurement suitable for panel data analysis. Thus, we use the broader environment related R&D indicator. The variable was collected from the OECD Green Growth dataset (Organization for Economic Cooperation and Development 2020). Finally, data on CO_2 emission intensity in the electricity sector (*CO_2 emission intensity per kWh*) is purchased and obtained from the IEA Emissions Factors database.[3] The measure is a ratio expressed in grams of CO_2 per kWh. The ratio is based on total emissions from fossil fuels consumed for electricity generation, in both electricity-only and combined heat and power plants (CHP), divided by the output of electricity generated from all fossil and non-fossil sources (International Energy Agency 2020b). As a ratio of two physical measurements, CO_2 intensity per kWh works as a transparent and unambiguous variable that can be compared across countries and over time (Ang and Su 2016). The variables are log transformed for reducing bias from extreme values.

Our primary independent variables broadly measure two important varieties of democracy—namely, liberal democracy and egalitarian democracy. These measures are generally very highly correlated with each other and share one component measured as "polyarchy", or electoral democracy, which measures the extent to which free and fair elections exist—namely, clean elections, a competitive party system, widespread political participation without coercion and violence. The other components of these measures of democracy differ on the basis of their individual components conceptualized in three fundamentally differing ways, but capture aspects of society and governance in accordance with a specific variety of

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[3] For full calculation see page 35 in http://wds.iea.org/wds/pdf/CO2KWH_Methodology.pdf International Energy Agency. 2020a. "Emission Factors 2020 – Database Documentation." Vol. http://wds.iea.org/wds/pdf/CO2KWH_Methodology.pdf. Vienna: IEA.

democratic style (Coppedge et al. 2011). The liberal dimension essentially gauges the extent to which the power of executive bodies is checked and the extent of minority rights and guarantees. The liberal element of democracy contains the following rationale.

> The liberal principle of democracy emphasizes the importance of protecting individual and minority rights against the tyranny of the state and the tyranny of the majority. The liberal model takes a "negative" view of political power insofar as it judges the quality of democracy by the limits placed on government. This is achieved by constitutionally protected civil liberties, strong rule of law, an independent judiciary, and effective checks and balances that, together, limit the exercise of executive power (Coppedge et al., 2021 p. 44).

Egalitarian democracy emphasizes egalitarian values and processes, where individuals and groups enjoy rights and have access to resources to act on these rights on more equitable bases. Generally, egalitarian democracies have states that actively provide basic needs, welfare, and other social insurance schemes for minimizing the concentration of economic power within a select group or class. According to V-Dem coders, the egalitarian component emphasizes the following.

> The egalitarian principle of democracy holds that material and immaterial inequalities inhibit the exercise of formal rights and liberties and diminish the ability of citizens from all social groups to participate. Egalitarian democracy is achieved when 1 rights and freedoms of individuals are protected equally across all social groups; 2 resources are distributed equally across all social groups; and 3 access to power is equally distributed by gender, socioeconomic class and social group (Coppedge et al., 2021: 45).

In addition to the two varieties of democracy, we also test two more narrowly defined indicators of societal inequality—namely, income inequality measured by the GINI coefficient and V-Dem´s equality of access to health. We use the standardized GINI that uses various GINI´s reported by national governments and international institutions, such as the IMF and World Bank, and standardizes them against the Luxembourg Income Study´s GINIs based on household data (Solt 2019). While income inequality measures inequality of outcome and perhaps other structural processes, equal access to health is an indicator of a society´s (state´s) commitment to equality of opportunity. In other words, greater equality of access measures pro-poor policy designed to reduce structural disparities between rich and poor and other social groups. According to the coders;

> Poor-quality healthcare can make citizens unable to exercise their basic rights as adult citizens by failing to adequately treat preventable and treatable illnesses that render them unable to work, participate in social or political organizations, or vote (where voting is allowed) (Coopedge et al., 2021 p. 207).

The standardized GINI and equality of access to health are highly correlated (r = -0.85). Finally, we use V-Dem´s measure for the strength of a welfare state indicated by the extent to which welfare services are extended on a universal rather than means-tested basis, where everyone is generously covered in terms of access to services and social insurance, such as unemployment benefits. According to V-Dem coders, the following concerns motivate this measure.

> The purpose (…) is not to gauge the size of the welfare state but rather its quality. (...) A means-tested program targets poor, needy, or otherwise underprivileged constituents. Cash-transfer programs are normally means-tested. A universal (non-means tested) program potentially benefits everyone. This includes free education, national health care schemes, and retirement programs. Granted, some may benefit more than others from these programs (*e.g.*, when people with higher salaries get higher un- employment benefits). The key point is that practically everyone is a beneficiary, or potential beneficiary (Coppedge et al., 2021 p. 162).

For robustness purposes, we include an alternative test for the CO_2 indicator using CO_2 emissions measured in metric tons per capita. The alterative CO_2 indicator and our control variables; Income per capita, Population density and share of urban population were all collected from the World Bank´s World Development Indicators database (World Bank 2021).

We utilize a cross-sectional time series (TSCS) dataset for 46 countries (the OECD plus the BRICS countries and some European countries) for the time period between 1990 and 2018 (28 years). The dataset is unbalanced in that data are not available for all countries for all years depending on which of the dependent and independent variables are in use. Regardless, most of our tests cover the industrialized West including most of Western Europe, North America, and Oceania (Australia, New Zealand). Brazil, Russia, India, China, and South Africa (BRICS), East-European and (Bulgaria, Romania, Croatia, Poland, Slovakia, Hungary), some Eurasian countries (Turkey, Israel) and some Central- and South American countries (Mexico, Chile) are also included in most of the tests. Table A1 in the appendix lists all included countries. TSCS data contain complicated correlation patterns across space and over time, thus, the standard GLS method can produce overly optimistic standard errors (Beck and Katz 1995). Following the advice of Beck and Katz, we use both OLS fixed and random effects regression but utilize Driscoll-Kraay standard errors robust to 1st order serial correlation and general forms of spatial autocorrelation (Hoechle 2007).[4] The fixed effects specification, or within estimation, accounts for fixed unmeasured omitted variables, such as culture and geography, allowing us to be a bit more confident about the causal associations in the relationships we do investigate.[5] In the cases where the Hausman test found random effect estimator appropriate, we have included models with random effects. The basic results estimated with Beck and Katz´s panel corrected standard errors with an AR1 process for accounting for temporal dependence yielded very similar results as did the Newey-West method with two-way fixed effects accounting for country heterogeneity. We estimate a time trend in each of the models to account for any mutually trending relationships and common shocks time-specific shocks.

4. Results

Table 1 presents the results of the regressions of the varieties of democracy; namely, liberal, and egalitarian democracy on the share of renewables of total power generation. Recall that this variable measures how well a country is currently positioned for reaching a clean energy transition. Keep in mind that the ability to generate power from renewables is dependent on a variety of environmental (atmospheric, geologic, geographic, and demographic) factors, independently of the policy priority of a government. As seen in Table 1, column 1, when random effects are estimated, liberal democracies have no effect on the share of renewables of total power generation, but the effect is negative and statistically highly significant (column 2) in the fixed effects specification.

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[4] The Wooldridge test suggested that our data were 1st order serially correlated.

[5] Since environmental factors, such as renewable resource use, should not determine political factors, we do not think our estimations suffer bias from reverse causality.

Table 1. Random & fixed effects regressions of varieties of democracy on the share of renewable energy of total power generation, 1990-2018

Dep var = Renewable energy / Total Power Generation	(1) RE	(2) FE	(3) RE	(4) FE	(5) FE	(6) FE
Income per capita(log)	0.06	-0.11	0.06	-0.11	-0.12	-0.10
	(0.08)	(0.10)	(0.08)	(0.10)	(0.10)	(0.10)
Population density(log)	-0.69**	-1.41***	-0.68**	-1.39***	-1.41***	-1.37***
	(0.28)	(0.23)	(0.28)	(0.23)	(0.22)	(0.21)
Urban population %(log)	-1.21***	-0.86***	-1.21***	-0.87***	-0.81***	-0.86***
	(0.14)	(0.23)	(0.14)	(0.22)	(0.24)	(0.23)
Liberal democracy	-0.33	-0.42**				
	(0.21)	(0.16)				
Egalitarian democracy			-0.25	-0.33		
			(0.27)	(0.21)		
Liberal component					-0.59**	
					(0.25)	
Egalitarian component						-0.27
						(0.36)
Constant	10.13***	13.39***	10.06***	13.24***	13.45***	13.11***
	(1.60)	(1.26)	(1.66)	(1.29)	(1.26)	(1.37)
Observations	1,292	1,292	1,292	1,292	1,292	1,292
Number of groups	46	46	46	46	46	46

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

This mean, that on average, the within-country effect of increasing liberal democracy is to reduce the share of renewables of total power generation. Substantively, a within standard deviation increase in liberal democracy reduces the renewable share of total energy production by roughly 5% of a standard deviation of the share of renewables of total generation. In fact, this turns out to be roughly 1/3rd of a percent (.38), which is substantively quite small. Results in columns 3 and 4 reveal that egalitarian democracy also shows negative effects but is not statistically significant. In columns 5 and 6, we test only the components of the democracy indexes. As seen in column 5, the liberal component again shows a negative, statistically highly significant effect while the egalitarian component is not different from zero.[6] Substantively, a within standard deviation increase in the liberal component decreases the renewable share of total generation by roughly .5 of a percentage. Interestingly, our two demographic variables, population density and the urban populations share show negative effects that are statistically highly significant on the renewable mix, suggesting that such factors as the availability of agricultural land (biofuels) and uninhabited areas for hydro-electrical and wind power generation etc. may matter more than does the policymaking environment alone. Per capita incomes, or wealth, has no discernible impact on the share of renewable of total electricity generation.

Next, in Table 2, we test the effects of our varieties of democracy and their components on the policy intentions and commitments of governments by observing their association with the share of environmental R & D in the total R & D budget. A higher share of environmental R & D should indicate a government´s commitment to accelerating the energy transition, assuming that R & D spending is not plagued by rent-seeking.

Table 2. Random & fixed effects regressions of the varieties of democracy on the share of environmental R & D of the government´s total R & D budget, 1990-2018

Dep var = Environmental R & D	(1)	(2)	(3)	(4)	(5)	(6)
Total R & D Budget	RE	FE	RE	FE	FE	FE
Income per capita(log)	-0.13	0.03	-0.15*	0.02	0.09	0.04
	(0.08)	(0.11)	(0.09)	(0.12)	(0.10)	(0.11)
Population density(log)	-0.03	0.84**	-0.03	0.82**	0.85**	0.80**
	(0.05)	(0.38)	(0.05)	(0.38)	(0.36)	(0.36)
Urban population %(log)	-0.60*	-0.89	-0.55	-0.94	-0.83	-1.04
	(0.34)	(0.68)	(0.33)	(0.70)	(0.68)	(0.72)
Liberal democracy	0.79**	0.63*				
	(0.33)	(0.32)				
Egalitarian democracy			0.88**	0.46		
			(0.36)	(0.38)		
Liberal component					1.31***	
					(0.46)	

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[6] The statistical significance for the liberal component only obtains in the FE specification.

Egalitarian component						1.04*
						(0.52)
Constant	4.54***	0.75	4.51***	1.23	-0.79	0.97
	(1.27)	(2.16)	(1.20)	(2.35)	(1.97)	(2.48)
Observations	885	885	885	885	885	885
Number of groups	38	38	38	38	38	38

Standard errors in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

As seen in columns 1 and 2, liberal democracy has a positive and statistically significant effect, albeit the random effects association is stronger. Substantively, a standard deviation (within) increase in liberal democracy would increase the budgetary share of environmental R & D by roughly 9% of a standard deviation (within) of the environmental share of R & D in the total R & D budget. In real terms, this amounts to roughly 0.13 percentage points, which seems like a trivial increase. In any case, these effects are statistically more significant than the effects of egalitarian democracy, which also shows a positive effect in the random effects but not in the fixed estimation. When the components only are tested in columns 5 and 6, both components are positive and significant, but liberal democracy shows stronger effects. Substantively, a standard deviation (within) increase in the liberal component, increases the share of the environmental R & D budget by roughly 16% of a standard deviation of the share of the budget, which amounts to 0.22 of a percent. These results suggest rather consistently that liberal processes seem to enhance budgetary allocation reflecting a greater green priority better than do egalitarian processes, although both point in positive directions.

In Table 3, we present the results of our varieties of democracy and their components on CO_2 emission intensity in electricity generation. This measure captures the actual CO_2 intensity of each kilowatt hour of electricity being produced. This measure thus separates "green intentions" of governments from actual "practice." As seen in columns 1 and 2, liberal democracy reduces CO_2 intensity in line with the previous results on environmental R & D budget share. Substantively, a within standard deviation increase in liberal democracy reduces CO_2 intensity in electricity production by roughly 3% of a standard deviation of CO_2 intensity share of electricity production. In real terms, it is 2.9 parts CO_2 per kWh of electricity produced.

Table 3. Random & fixed effects regressions of the varieties of democracy and CO_2 emission intensity in electricity generation, 1990-2018

Dep var = CO_2g/kWh energy produced	(1) RE	(2) FE	(3) RE	(4) FE	(5) FE	(6) FE
Income per capita(log)	0.00	0.02	0.01	0.03	0.02	0.04
	(0.05)	(0.06)	(0.05)	(0.06)	(0.06)	(0.06)
Population density(log)	0.34**	0.29**	0.35**	0.30**	0.30**	0.27***
	(0.16)	(0.11)	(0.16)	(0.11)	(0.11)	(0.09)
Urban population %(log)	0.13	0.15	0.13	0.16	0.16	0.16
	(0.13)	(0.11)	(0.13)	(0.11)	(0.11)	(0.11)
Liberal democracy	-0.16**	-0.14**				
	(0.06)	(0.06)				
Egalitarian democracy			-0.05	-0.01		
			(0.09)	(0.10)		
Liberal component					-0.07	
					(0.06)	
Egalitarian component						0.37**
						(0.14)
Constant	3.86***	3.76***	3.74***	3.61***	3.67***	3.29***
	(0.51)	(0.55)	(0.51)	(0.56)	(0.52)	(0.54)
Observations	1,292	1,292	1,292	1,292	1,292	1,292
Number of groups	46	46	46	46	46	46

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Since the standard deviation of this variable is 83.1, again the substantive impact seems trivial. Egalitarian democracy does not seem to significantly impact CO_2 intensity, but its component increases CO_2 intensity in electricity production. Substantively, a within standard deviation increase in the egalitarian component increases CO_2 intensity in electricity production by 6% of a standard deviation of CO_2 intensity, amounting to 4.5 part of CO_2 per kWh of electricity produced. Compared to the actual amount of 75.5 within standard deviation, this impact again does not seem particularly large. The main point here, however, is that liberal democracy matters in a more positive direction for the renewable energy transition than does egalitarian governing processes.

In Table 4, we shift gears and test narrower conceptions of egalitarian structural features by estimating the effects of income inequality measured as the GINI coefficient, equal access to health care sourced from the V-Dem data, and V-Dem´s quality of welfare state indicator measured as the degree to which a welfare system is universal on the share of renewable of total electricity generation and the environmental R & D share of the total R & D budget (the dependent variables tested in Tables 1 and Table 2 respectively). We continue with random effects estimations.

Table 4. Random effects regressions of social inequities & commitment to renewable energy, 1990-2018

	(1)	(2)	(3)	(4)	(5)	(6)
Dep vars.	ren.energy%	ren.energy%	ren.energy%	Env.R&D%	Env.R&D%	Env.R&D%
Income per capita (log)	0.06	0.04	0.11	-0.12	-0.09	-0.15*
	(0.09)	(0.09)	(0.08)	(0.09)	(0.09)	(0.08)
Population density (log)	-0.65**	-0.72**	-0.62**	-0.04	-0.03	-0.03
	(0.29)	(0.28)	(0.28)	(0.05)	(0.05)	(0.05)
Urban population % (log)	-1.25***	-1.26***	-1.22***	-0.70*	-0.52	-0.43
	(0.17)	(0.13)	(0.15)	(0.37)	(0.32)	(0.32)
Electoral democracy	-0.15	-0.21	0.09	0.71**	0.87***	0.72**
	(0.17)	(0.20)	(0.22)	(0.31)	(0.29)	(0.35)
Income inequality (GINI)	0.02**			-0.02**		
	(0.01)			(0.01)		
Equal access to health		0.11**			-0.06	
		(0.04)			(0.05)	
Quality of welfare state			-0.21***			0.11**
			(0.06)			(0.04)
Constant	9.51***	10.45***	9.42***	5.50***	3.80***	3.89***
	(1.77)	(1.65)	(1.66)	(1.25)	(1.14)	(1.29)
Observations	1,264	1,292	1,292	875	885	885
Number of groups	46	46	46	38	38	38

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

As seen in column 1, higher income inequality predicts a higher share of renewable energy of total electricity generation, perhaps mirroring the effects of more liberal democracy, which may indeed have higher income inequality comparatively (Table 1). Substantively, a standard deviation increase in income inequality increases the renewables share of total electricity generation by 13% of a standard deviation of the share of renewable energy of total electricity generation. This effect is not trivial, amounting to roughly 3.6 percentage points. In column 2, equitable access to health also increases the renewable energy share. Interestingly, this result is in line with the effect of egalitarian democracy (See Table 1). Substantively, a standard deviation increase in equitable access to health increases the renewable share by a little less than the effects of income inequality (2.5 percentage points compared with 3.6). Interestingly, thus, while income inequality and equitable access to health are highly negatively correlated, their effects on the share of renewables are similar. In column 3, even more interestingly, higher quality (more universalistic) welfare states lower the renewable share in electricity production, a result that is statistically highly significant. Substantively, a standard deviation increase in a quality of the welfare state reduces the renewable energy share of total electricity generation by 3.6 percentage points. These results taken together suggest that more egalitarian and equitable structural factors associate negatively with factors associated with energy transition.

Columns 4, 5 and 6 present the results for our inequality measures when the environmental R & D budget share is estimated (as in Table 2). Column 4 shows clearly that higher income inequality reduces the commitment to environmental R & D. This result does not mirror the effect of liberal democracies as seen in Table 2. Substantively, a standard deviation increase in the GINI, reduces the environmental R & D share by roughly 23% of a standard deviation, which amounts to roughly 0.5 percentage point, which is not trivial. In column 5, equal access to health does not seem to matter, while in column 6, greater access to a quality welfare state increases the environmental R & D budget. Substantively, a standard deviation increase in the quality of the welfare state increases the environmental R & D portion of the total budget by roughly 0.35 percentage points.

Table 5 tests our measures of inequality on CO_2 emission intensity in electricity generation and total CO_2 emissions per capita. Ultimately, whatever the intentions of governments in terms of budget allocation, or the mix of electricity produced, the ultimate concern about environmental impacts should be judged by the output of CO_2 if the renewable energy transition is going to be meaningful for avoiding disastrous global warming.

Table 5. Random effects regressions of societal equity on CO_2 emission intensity in electricity generation and total CO_2 emissions per capita, 1990-2018

	(1)	(2)	(3)	(4)	(5)	(6)
Dep vars.	CO_2/ele	CO_2/ele	CO_2/ele	CO_2/pc	CO_2/pc	CO_2/pc
Income per capita (log)	0.04	-0.01	-0.02	0.55***	0.50***	0.47***
	(0.04)	(0.05)	(0.05)	(0.05)	(0.06)	(0.06)
Population density (log)	0.30**	0.32*	0.31**	0.23***	0.27***	0.21***
	(0.14)	(0.17)	(0.15)	(0.08)	(0.08)	(0.07)
Urban population % (log)	0.09	0.10	0.13	1.12***	1.07***	1.09***
	(0.10)	(0.12)	(0.13)	(0.10)	(0.09)	(0.10)
Electoral democracy	-0.20***	-0.28***	-0.26***	-0.15*	-0.21*	-0.29**
	(0.06)	(0.07)	(0.07)	(0.09)	(0.11)	(0.12)
Income inequality (GINI)	-0.02***			-0.02***		
	(0.00)			(0.00)		
Equal access to health		0.05**			0.02**	
		(0.02)			(0.01)	
Quality of welfare state			0.05			0.12***
			(0.03)			(0.02)
Constant	4.41***	4.18***	4.19***	-8.23***	-8.40***	-8.00***
	(0.46)	(0.56)	(0.45)	(0.47)	(0.30)	(0.36)
Observations	1,264	1,292	1,292	1,178	1,191	1,191
Number of groups	46	46	46	46	46	46

Standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

As seen in column 1, income inequality has a negative and statistically highly significant effect, a result in line with share of renewable of total electricity generation (Table 4). Substantively, a standard deviation increase in the GINI, reduces CO_2 emssion intensity per kWh of electricity produced by roughly 7% of a standard deviation of CO_2 intensity, amounting to roughly 19.5 parts CO_2 per kWh of electricity produced. Interestingly, in column 2, equal access to health works in the opposite direction despite having similar effects as the GINI on renewable energy share of total electricity generation. Substantively, a standard deviation increase in equity of access to health increases CO_2 intensity by roughly 4% of a standard deviation of CO_2 intensity, which amounts to 10 parts CO_2 per kWh of electricity produced.

Since the real value of a standard deviation is 285, this substantive effect seems trivial. The quality of a welfare state has no discernible impact on CO_2 emission intensity of electricity production.

In columns 4, 5 and 6, we test the inequality measures on total CO_2 emissions per capita on a national basis that includes all sectors. As seen in column 4, the GINI reduces total CO_2 per capita. Substantively, a standard deviation increase in the income inequality reduces CO_2 emissions per person by roughly 28% of a standard deviation in CO_2 emissions, which amounts to 1.1 metric tons per person reduction in CO_2 emissions. This is a large substantive effect given that the average for our sample of countries is 8.0 metric tons per person. In column 5, equity of access to health increases total CO_2 emissions per person. These results are in line with the previous set of results on CO_2 emission intensity in electricity production. Substantively, a standard deviation increase in pro-poor health policy increases CO_2 emissions by 4% of a standard deviation of CO_2 metric tons per person, amounting to a fairly small 0.17 percentage points. In column 6, a quality welfare state (high levels of social insurance) also increases total CO_2 emissions per person annually at the national level. Substantively, a standard deviation increase in the quality welfare state increases CO_2 per capita emissions by 17% of a standard deviation of CO_2 emissions, which amounts to 0.7 percentage points, which is not trivial given that the sample average is 8 points. The results taken together across the columns suggest that greater equity and social insurance produces higher CO_2 emissions per capita while electoral democracy reduces it independently of our demographic variables and income per capita. Unsurprisingly, the modernization variables, wealth per capita and urbanization have strong statistically significant effects on total CO_2 emissions per capita. Environmental destruction, thus, seems unambiguously to be associated with higher wealth and consumption.

The results taken as a whole, thus, provide rather mixed results about governance styles and environmental outcomes. In many ways, more liberal versus more egalitarian styles of democratic government sometimes have differing impacts and in others seem more congruent. By and large, more liberal aspects of governance correlate better with actual outcomes, such as CO_2 intensity and government intentions in terms of environmental R & D budget allocations. Egalitarian processes show less meaningful results on actual outcomes, except for the quality of welfare state that generally shows environmentally damaging outcomes. Quite surprisingly, the individual component measures of inequality, particularly income inequality measured as the GINI, show better outcomes for both government intentions and actual emissions in terms of CO_2, results that support several previous studies on inequality and sustainability (Scruggs 1998; Clement and Meunie 2010; Roeland and de Soysa 2021). Arguments that base social trust and social capital driven by greater equity and social insurance impacting climate policies seem in general not to be supported in our findings. Clearly, it seems that the greater opportunity for consumption drives harmful emissions even if the rich world´s inhabitants supposedly espouse post-modern values reflecting greater concern for environmental outcomes (Inglehart and Welzel 2005).

5. Conclusion and Policy Implications

The question of climate change is the most pressing global policy challenge of our time (Stern 2015). Accelerating the renewable energy transition is arguably the most pressing concern when it comes to creating the kind of economic change that yields sustainable development. Naturally, how democratic governing styles can matter is of utmost policy concern given that ultimately people must act on convictions within structural and institutional frameworks. While the question of whether democracy or more autocratic governance reduces environmental harm will continue to be debated (Ward 2008; Dryzek, Norgaard and Schlosberg 2011; Wurster 2013), we have addressed specifically how varying democratic governance styles might impact the prospects for energy transitions.

While one should of course apply caution when interpreting results that are not extremely strong in either direction, our findings support and are very much compatible with our theoretically derived suggestions outlined earlier. First, our findings quite clearly do not support the widespread belief that egalitarian or consensual democracies unambiguously produce better climate policies, here thought of in terms of policies and practices favoring an energy transition. On no single measure does egalitarian democracies perform unambiguously better than those regimes characterized as liberal.

Second, the findings are very much compatible with the expectation that it is the structural change component to climate policies that egalitarian democracies struggle the most with. Thus, our main findings do *not* suggest that there is any major difference between egalitarian and liberal democracies when it comes to research funding or the share of renewables in the power mix. Parts of the VoC literature (e.g. Hübner 2018) and Mildenberger (2020) expect CMEs and corporatist systems respectively, to be better at incremental policy change than LMEs and pluralist systems. Research funding is a very obvious measure of incremental policy change, whereas increasing the share of renewables in the power mix can be easily pursued incrementally, without any structural changes to the energy system. Here, the findings show that the differences between the two governance styles are too small to be substantively interesting. Thus, egalitarian democracies are no worse than liberal democracies when it comes to climate policies where structural change is absent or only a minor component.

On the other hand, egalitarian democracies clearly perform worse than liberal democracies with respect to intensity of CO_2 emissions. This is a measure that to a far greater extent entails structural change. Phasing renewable energy in is comparatively easy. It has often been expensive (Feed-in tariffs a primary example) but can be done without much harm coming to established vested interests (e.g. Moe 2015). A renewable energy transition however hinges on also phasing carbon-based sources of fuel out, in other words a process of structural change with major consequences for established energy actors (e.g. Mildenberger 2020). For this, CO_2 intensities constitute better measures than renewable share of the power mix as they establish the extent to which the economy as a whole is changing, and not just the rapidity with which renewable energy has been phased in.[7] Here, the suspicion that egalitarian democracies struggle with energy transitions, is supported by the data. Liberal democracies clearly exhibit higher CO_2 intensity figures. Thus, structural change may indeed be a bigger problem in egalitarian systems. The magnitude of the effects however also suggest that the results are driven as much by consumption as by governance type, and that the greater opportunities for broad-based consumption in egalitarian democracies may be what pushes them in the direction of higher CO_2 emissions, suggested among other things by the results on income inequality. Because of free-riding and rent-seeking (Hovi, Underdal and Prinz 2009), there is little to suggest that the societal consensus necessary for concerted action for climate friendly policies is easily translated into action because of free-riding and rent-seeking.

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[7] One thing that we have not explored in this article is energy efficiency. In principle, it could obviously be the case that the differences that we have found in terms of CO_2 intensities are because of better energy efficiency policies in liberal countries. However, from a theoretical point of view, energy efficiency policies is something that egalitarian democracies (or CMEs/corporatist systems) would be expected to excel at, being incremental solutions with no structural change involved. Thus, we do not expect our results to have been driven by energy efficiency.

Appendix A

Table A1

OECD	Australia Austria Belgium Canada Chile Czech Republic Denmark Estonia Finland France Germany Greece Hungary Iceland Ireland Israel Italy Japan South Korea Latvia Lithuania Luxembourg Mexico Netherlands New Zealand Norway Poland Portugal Slovakia Slovenia Spain Sweden Switzerland Turkey United Kingdom United States
BRICS	Brazil Russia India China South-Africa
European countries	Bulgaria Croatia Cyprus Malta Romania

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