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Political Acceleration in Energy Transitions: Historical Interventions and Their Outcomes in the G7 and the EU, compared to Net-Zero Targets

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Author’s declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Furthermore, this dissertation contains no materials previously written and/or published by another person, except where appropriate acknowledgement is made in the form of bibliographical reference, etc.

鈴木 暢大

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Authorship notice for included journal article

This dissertation incorporates the content of the following journal article, which I published with two co-authors including my dissertation supervisor (Aleh Cherp).

> Suzuki, M., Jewell, J., Cherp, A., 2023. Have climate policies accelerated energy transitions? Historical evolution of electricity mix in the G7 and the EU compared to net-zero targets. Energy Res. Soc. Sci. 106, 103281. https://doi.org/10.1016/j.erss.2023.103281

As the first and corresponding author of this article, I played a leading role in conceiving the study, developing the research design, collecting, analysing, and visualising data, as well as writing and revising the manuscript.

Abstract

Avoiding dangerous climate change requires a significant political acceleration in energy transitions, where fossil fuels must be replaced by low-carbon technologies within the next decades. Are there historical precedents for such acceleration? Are recent transitions faster with climate policies? Existing studies do not answer these questions due to their analysis being too broad, emphasising the slowness of global transition, or too narrow, highlighting recent short-term changes in specific countries without assessing their significance compared to historical experiences or climate target requirements.

Against this backdrop, this dissertation develops a middle-range methodology with the typology of energy transitions to systematically categorise, trace, and compare energy transitions towards decarbonisation across countries and time-periods. I apply this methodology to comparatively examine the historical and planned transitions in the electricity sector in the G7 and the EU, where political acceleration is expected, given their leadership in decarbonisation and climate policies. I compare this historical analysis with climate target requirements to elucidate the challenges to keeping the global temperature increase below 1.5°C.

I find that, throughout the last six decades, electricity transitions in the G7 and the EU have been primarily driven by the changes in electricity demand, and the developments under climate policies since 1990 have not been accelerated in terms of the growth of low-carbon electricity or the decline of fossil fuels beyond historical trends. Moreover, none of these countries have yet empirically demonstrated or even planned the rates of acceleration necessary to achieve 1.5°C. In other words, in contrast to the claim in the literature, there has been no 'successful' case of transitions comparable with the magnitude of acceleration required to mitigate climate change. Meeting the 1.5°C target, therefore, requires radically different energy transitions in the future with the unprecedented level of political acceleration.

The middle-range approach developed in this dissertation can be applied to track future progress in the G7 and the EU and analyse other sectors and countries. Taking stock of empirical evidence and advancing discussions on what then needs to be done is more warranted.

Keywords: energy transitions, climate change, political acceleration, G7, EU

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My PhD journey has been quite an adventure. It began with my move to Budapest in 2017, knowing that the university would soon need to relocate to a different country. After much uncertainty, a decision was made to move the entire campus to Vienna in 2019. This relocation coincided with the onset of the COVID-19 pandemic, adding unprecedented challenges to an already complex transition. Like many other non-EU students, I had to return to my home country, move to a country where I could apply for a residence permit, and eventually stay there to finalise my dissertation, unfortunately without fully integrating into the new campus life in Vienna.

Why am I listing all these challenges? Because I managed to overcome them, all thanks to the unwavering support, kindness, and encouragement I received from numerous people.

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ARERA	Italian Regulatory Authority for Energy, Networks, and the Environment (In Italian: Autorità di Regolazione per Energia Reti e Ambiente)
BASE	German Federal Office for the Safety of Nuclear Waste Management (In German: Bundesamt für die Sicherheit der nuklearen Entsorgung)
BEIS	British Department for Business, Energy, and Industrial Strategy
BMU	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (In German: Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit)
BMUB	German Federal Ministry for the Environment, Nature Conservation, Building, and Nuclear Safety (In German: Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit)
BMW	German Federal Ministry for Economic Affairs and Energy (In German: Bundesministerium für Wirtschaft und Energie)
BMWA	German Federal Ministry of Economics and Labour (In German: Bundesministerium für Wirtschaft und Arbeit)
BMWK	German Federal Ministry of Transport, Building, and Urban Development (In German: Bundesministerium für Verkehr, Bau und Stadtentwicklung)
BMWT	German Federal Ministry of Education and Research (In German: Bundesministerium für Bildung und Forschung)
CCC	British Committee on Climate Change
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation, and Storage
CEGB	British Central Electricity Generating Board
CER	Canadian Clean Energy Regulator
CME	Coordinated Market Economy
CRE	French Energy Regulatory Commission (In French: Commission de Régulation de l'Énergie)
DECC	British Department of Energy and Climate Change
DESNZ	British Department for Energy Security and Net Zero
DOE	United States Department of Energy
DTI	British Department of Trade and Industry
EC	European Commission
ECCC	Canadian Department of Environment and Climate Change
EDF	Électricité de France (French electric utility company)
EEG	German Renewable Energy Sources Act (In German: Erneuerbare-Energien-Gesetz)
EIA	United States Energy Information Administration

ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development (In Italian: Energia Nucleare ed Energie Alternative)
EPA	United States Environmental Protection Agency
ETS	Emissions Trading System
EUR	Euro (currency)
EWI	Institute of Energy Economics at the University of Cologne (In German: Energiewirtschaftliches Institut an der Universität zu Köln)
FDP	German Free Democratic Party (In German: Freie Demokratische Partei)
FIT	Feed-in-Tariff
G7	Group of Seven (Canada, France, Germany, Italy, Japan, the United Kingdom and the United States. The European Union joins as a "non-enumerated member".)
GEA	Global Energy Assessment
GHG	Greenhouse Gas
GW	Gigawatt
IAEA	International Atomic Energy Agency
IAM	Integrated Assessment Model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LC	Low-carbon
LME	Liberal Market Economy
LNG	Liquefied Natural Gas
MATTM	Italian Ministry for the Environment, Land and Sea (In Italian: Ministero dell'Ambiente e della Tutela del Territorio e del Mare)
METI	Japanese Ministry of Economy, Trade, and Industry (In Japanese: 経済産業省)
MIMIT	Italian Ministry of Infrastructure and Transport (In Italian: Ministero delle Infrastrutture e dei Trasporti)
MISE	Italian Ministry of Economic Development (In Italian: Ministero dello Sviluppo Economico)
MW	Megawatt
NEB	Canadian National Energy Board
NECP	National Energy and Climate Plan
NEMS	United States National Energy Modeling System
NFFO	British Non-Fossil Fuel Obligation
OECD	Organisation for Economic Co-operation and Development
PE	Primary Energy
PNIEC	Italian National Integrated Energy and Climate Plan

	(In Italian: Pubblicato il testo definitivo del Piano Energia e Clima)
POPE	French Program Law establishing the Guidelines for Energy Policy (In French: loi Programme fixant les Orientations de Politique Energétique)
PPCA	Powering Past Coal Alliance
RES	Renewable Energy Sources
RITE	Japanese Research Institute of Innovative Technology for the Earth (In Japanese: 地球環境産業技術研究機構)
RO	British Renewable Obligation
RPS	Renewable Portfolio Standard
RTE	French Electricity Transmission Network (In French: Réseau de Transport d'Électricité)
SEP	Japanese Strategic Energy Plan (In Japanese: エネルギー基本計画)
SME	State-influenced Market Economy
SPD	German Social Democratic Party (In German: Sozialdemokratische Partei Deutschlands)
TIMES	British Energy System Model (The Integrated MARKAL-EFOM System)
TWh	Terawatt hours
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar
USSR	Union of Soviet Socialist Republics

1. Introduction

Avoiding dangerous climate change requires a significant political acceleration in energy transitions, where fossil fuels must be replaced by low-carbon alternatives within the next few decades. According to the International Energy Agency (IEA), to keep the global temperature increase below 1.5°C, developed countries must decarbonise electricity by 2035 while increasing power generation to electrify other sectors (IEA, 2021a). To demonstrate leadership in spearheading this transition, the Group of Seven (G7) countries and the European Union (EU) committed in 2022 to achieving this target (G7, 2022).

The existing literature provides various and often contrasting arguments regarding such rapid energy transitions. On the one hand, scholars analysing historical energy transitions highlight the consistently growing trend in the global use of energy resources, the increasing accumulation of energy technologies and infrastructure, and the correspondingly increasing greenhouse gas (GHG) emissions in the past centuries (Fouquet and Pearson, 2012; Grubler, 2012; Smil, 2010; Stoddard et al., 2021). Looking at these global trends, these scholars observe no substantial political interventions to change the trajectory to date. This is why some scholars assert that "none of today's promises for a greatly accelerated energy transition from fossil fuels to renewable energies will be realized" (Smil, 2010, p. 28).

On the other hand, by analysing more recent transitions, particularly after 1990, transition scholars and climate policy researchers have identified a growing number of rapid technological changes taking place at the national level. Prominent examples are often drawn from Europe and other developed countries, such as the recent renewable growth in Germany (Chapman and Itaoka, 2018; Jänicke, 2012; Kern and Rogge, 2016; Rogge and Johnstone, 2017), the UK (Geels et al., 2016b; Kern et al., 2014, 2015), Spain (Jänicke, 2012), and Denmark (Jänicke, 2012; Kern and Rogge, 2016), as well as the recent coal decline in Canada

(Rosenbloom, 2018; Sovacool, 2016) and the UK (Brauers et al., 2020; Pollitt, 2012; Turnheim and Geels, 2012).

Attributing these changes to political acceleration by referring to the growing international climate regime since the 1990s and the climate policies adopted in these countries, these scholars argue that recent energy transitions are more politically governed and increasingly accelerated by climate policies (Hoppe et al., 2023; Kern and Rogge, 2016; Roberts et al., 2018; Sovacool and Geels, 2016). From their perspective, achieving rapid energy transitions to mitigate climate change is therefore possible, particularly if political interventions identified in these cases are replicated and reinforced globally (Kern and Rogge, 2016; Köhler et al., 2019; Roberts et al., 2018; Sovacool and Geels, 2016). Such global acceleration is expected to take place, given that almost all countries in the world have collectively committed to keeping the global temperature increase below 1.5°C by adopting the Paris Agreement in 2015 and the Glasgow Climate Pact in 2021 (Depledge et al., 2022; Kern and Rogge, 2016).

These contrasting views on rapid energy transitions, in particular the rates of political acceleration, are caused by their respective scopes of observation. One group examines highly aggregated transitions over long periods, encompassing various sectors and countries. Consequently, this approach dismisses more granular changes that may be occurring in a specific sector or country at a particular point in time. This is problematic because revolutionary technological transformations often originate from such initially insignificant niches that expand and diffuse exponentially (Sovacool and Geels, 2016).

In contrast, the other group focuses on recent technological and policy changes in a specific sector and country, often over a short period of time. These highly granular studies often lack comparative analysis (Grubler et al., 2016; Sorrell, 2018), raising questions about whether and to what extent the identified technological changes are faster than historical trends.

An even more critical issue in these highly granular studies is the ambiguity surrounding how significant such individual short-term technological changes are in terms of the more long-term systemic shifts required in the energy sector towards decarbonisation. For instance, the recent policy-driven growth of renewables in Germany has been accompanied by the concurrent decline of nuclear power and occasionally increased reliance on fossil fuels (Cherp et al., 2017), leading to intermittent rises in the country's GHG emissions over the past decade (Alkousaa and Wacket, 2023). Similarly, the recent decline of coal in Canada has been coupled with the increased use of natural gas, potentially perpetuating reliance on fossil fuels rather than accelerating the shift to low-carbon alternatives (Gürsan and Gooyert, 2021; Kemfert et al., 2022). Notably, Canada's GHG emissions increased by ca. 14% between 1990 and 2021 (ECCC, 2023). These examples underscore the need to analyse more long-term systemic transitions rather than individual short-term technological changes and assess whether and how recent transitions are systemically more accelerated compared to the past.

Against this backdrop, this dissertation aims to contribute to understanding the political acceleration in energy transitions and the challenges implied by this historical analysis for mitigating climate change. These aims are achieved by pursuing the following three research objectives:

(1) Developing a methodology with an appropriate granularity to examine political acceleration in energy transitions.

(2) Applying this approach to analyse historical political interventions in the energy sector and their outcomes in terms of the nature and speed of energy transitions.

(3) Comparing this historical analysis with climate target requirements to elucidate the challenges in accelerating energy transitions to mitigate climate change.

Figure 1.1 shows the structure of the rest of this dissertation. In Chapter 2, I conduct a literature review by exploring the imperatives, theories, and empirical observations of political acceleration in energy transitions to mitigate climate change while identifying the gap in the literature. Chapter 3 describes the ontological and epistemological assumptions of this dissertation based on critical realism and develops the 'middle-range' methodology with conceptual frameworks and methods to address the gap in the literature identified.

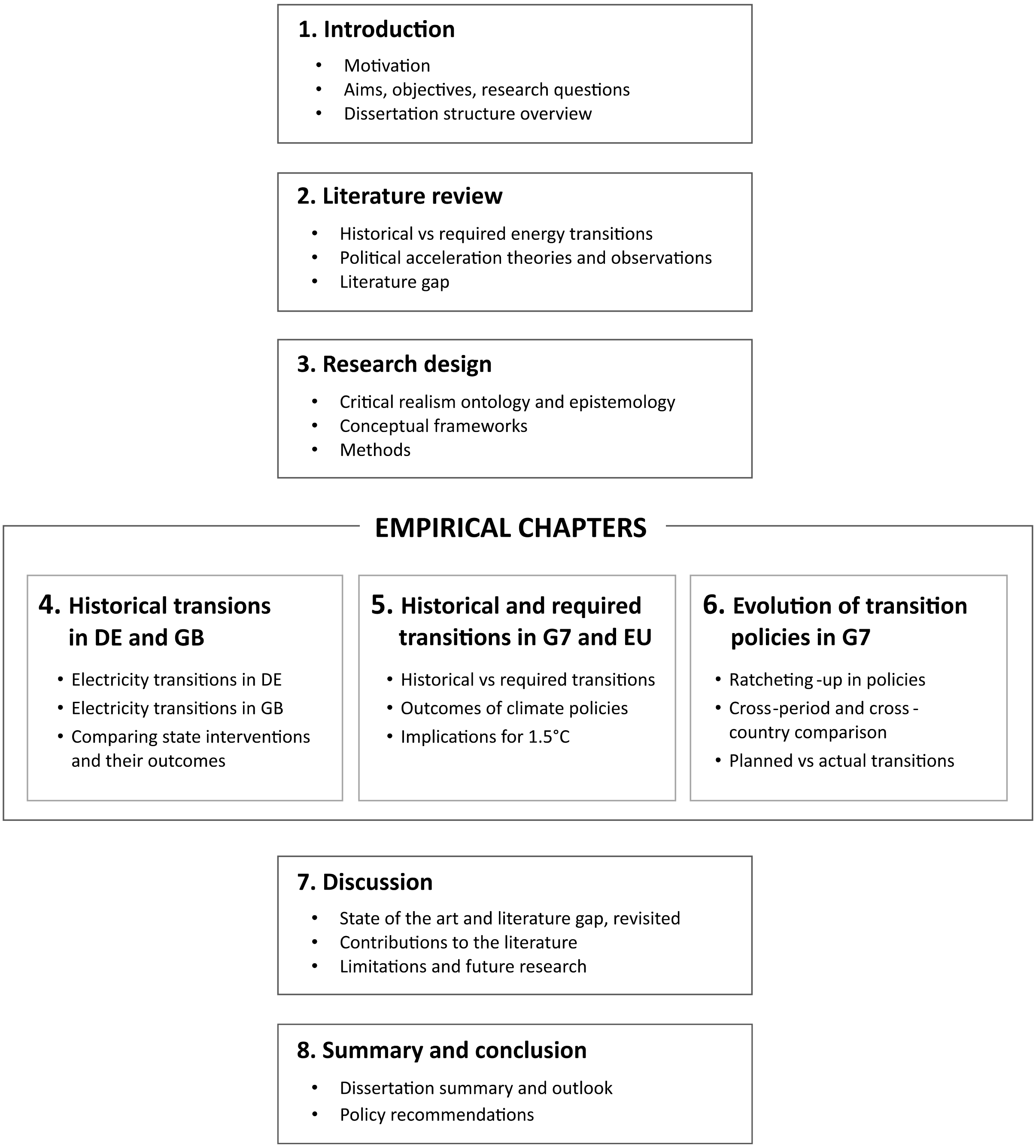


Figure 1.1: Dissertation structure

There are three empirical chapters in this dissertation: In Chapter 4, I focus on analysing the historical electricity transitions in Germany and the UK. These countries are selected because they are often considered ‘climate leaders’ in the existing literature (Kern and Rogge, 2016; Tobin, 2017), thus offering a promising opportunity to analyse political interventions and their outcomes in accelerating energy transitions. In Chapter 5, I expand this scope of analysis to the G7 countries and the EU, particularly focusing on examining whether and how energy transitions under climate policies have taken place differently compared to past transitions in light of achieving climate target requirements for 1.5°C. In Chapter 6, I further investigate how the stringency of energy transition policies has evolved in the G7 countries over the last decades, comparing this evolution once again to climate target requirements for achieving 1.5°C.

The following research questions, developed to address the literature gap (see Section 2.4), respectively guide these empirical chapters:

- Chapter 4: How have the state interventions in the energy sector differed across countries, and how have the differences affected their transition outcomes?
- Chapter 5: Have climate policies altered energy transitions beyond historical trends, if so, how in light of climate target requirements?
- Chapter 6: How has the stringency of national energy transition policies changed over the last decades, and how does this evolution compare to historical and required transitions?

Following these three empirical chapters, in Chapter 7, I revisit the state of the art and the literature gap that I aim to address in my dissertation research and clarify how I methodologically, empirically, and theoretically contributed to the understanding of the political acceleration in energy transitions. Lastly, Chapter 8 provides the dissertation summary and conclusion.

2. Literature review

An extensive body of scholarly literature analyses energy transitions from diverse perspectives, such as energy historians exploring the evolution of energy systems, political scientists examining various political approaches at the given time, and transition scholars scrutinising granular changes in actors and technologies. In this literature review, my focus is to explore the imperatives, theories, and empirical observations of political acceleration in energy transitions to mitigate climate change.

The chapter is organised as follows: In Section 2.1, I comparatively review historical and required energy transitions to elucidate the imperatives of political acceleration to mitigate climate change. Section 2.2 delves into the literature theorising political acceleration in energy transitions, while in Section 2.3, I review empirical observations that present mixed evidence, accompanied by correspondingly different and often conflicting arguments. Section 2.4 scrutinises the gap in the literature to examine political acceleration in energy transitions. Finally, a summary of the chapter is provided in Section 2.5.

2.1 Climate mitigation requires a significant political acceleration in energy transitions

This section provides a comparative review of the literature concerning historical energy transitions and required transitions to mitigate climate change. There is a significant disparity between the two, underscoring the urgent need for significant political acceleration in energy transitions to bridge the gap.

2.1.1 Historical transitions – slow and technological additions

Energy transitions are commonly defined in the literature as long-term structural changes in energy systems, with two key features characterising their historical developments. First, as the definition indicates, energy transitions have taken place remarkably slowly in the past, typically requiring many decades, if not centuries (Grubler, 2012). This slowness stemmed from the fact that the development and diffusion of new energy technologies were inherently ‘protracted processes’ requiring many decades, if not centuries, to take place (Smil, 2008, 2010, 2016a). This observation, initially put forth by Marchetti and Nakicenovic in the 1970s (Marchetti and Nakicenovic, 1979) has since been consistently substantiated as a prevailing trend in the use of primary energy sources (Smil, 2010), and technologies across diverse energy sectors including electricity supply (Wilson, 2012; Wilson and Grubler, 2011), transportation (Grubler and Nakicenovic, 1991), heating and lighting (Fouquet, 2010), as well as end-use technologies such as cars and washing machines (Bento and Wilson, 2016).

Another key feature of historical energy transitions is that new energy technologies were typically added on top of older technologies instead of replacing them (Smil, 2016a). While existing technologies may have experienced a decrease in market share, they rarely declined in absolute terms (Figure 2.1) (Vinichenko et al., 2021; York and Bell, 2019). Thus, scholars argue that past energy transitions are more accurately described as ‘energy additions’ rather than energy transitions (Fouquet and Pearson, 2012; York and Bell, 2019).

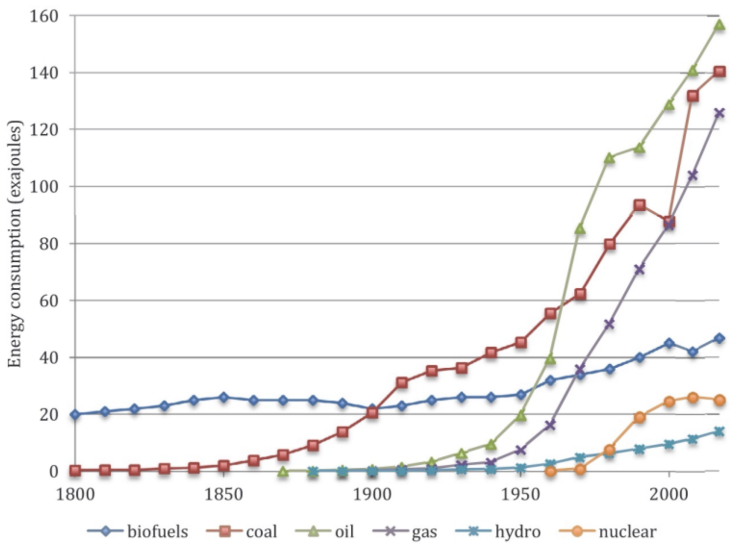


Figure 2.1: Global primary energy consumption by source

Image source: York and Bell (2019).

The lack of technological substitution in historical energy transitions has resulted in a dramatic increase in global energy consumption since the Industrial Revolution (GEA, 2012). Putting it differently, historical energy transitions were primarily driven by the dramatic growth of energy demand, requiring the rapid expansion of new technologies (Fouquet and Pearson, 2012).

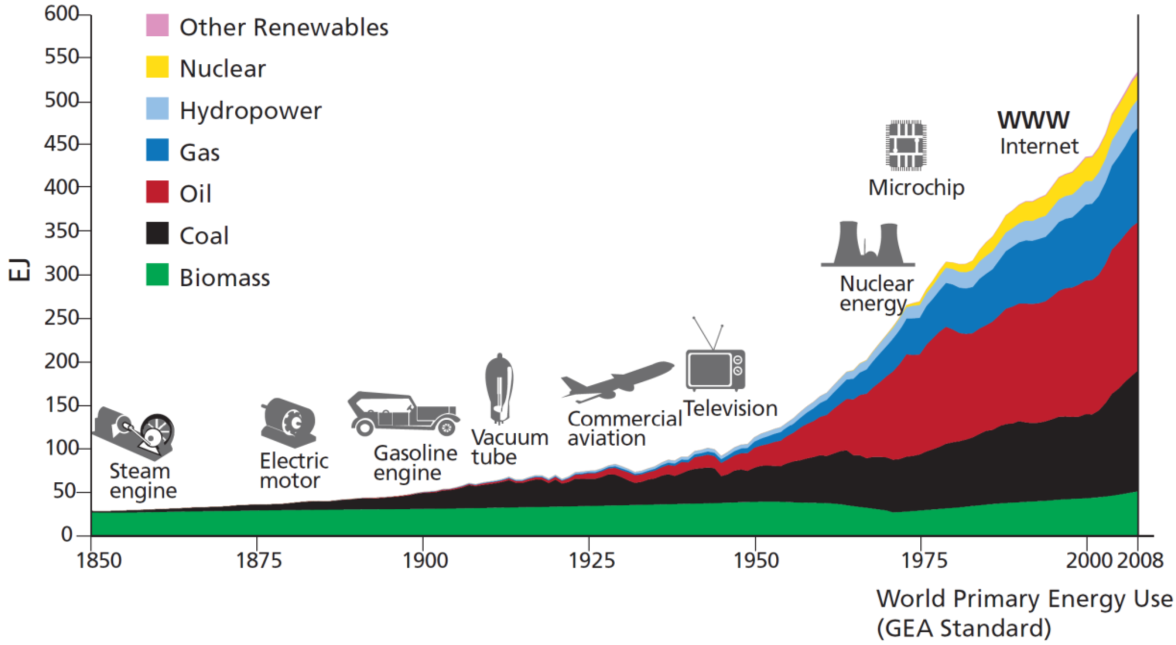


Figure 2.2: Global primary energy consumption since 1850

Image source: GEA (2012).

2.1.2 Required transitions – rapid and drastic technological substitution

In contrast to historical energy transitions, mitigating climate change requires pursuing significantly different pathways in the future. Such pathways are commonly developed by the use of mathematical models including integrated assessment models (IAMs) and other energy and climate models, which illustrate necessary technological developments to achieve particular socio-economic objectives, including temperature limits to mitigate climate change. According to the IEA, meeting the 1.5°C target requires rapidly replacing fossil fuels with low-carbon alternatives within the next few decades (Figure 2.3).

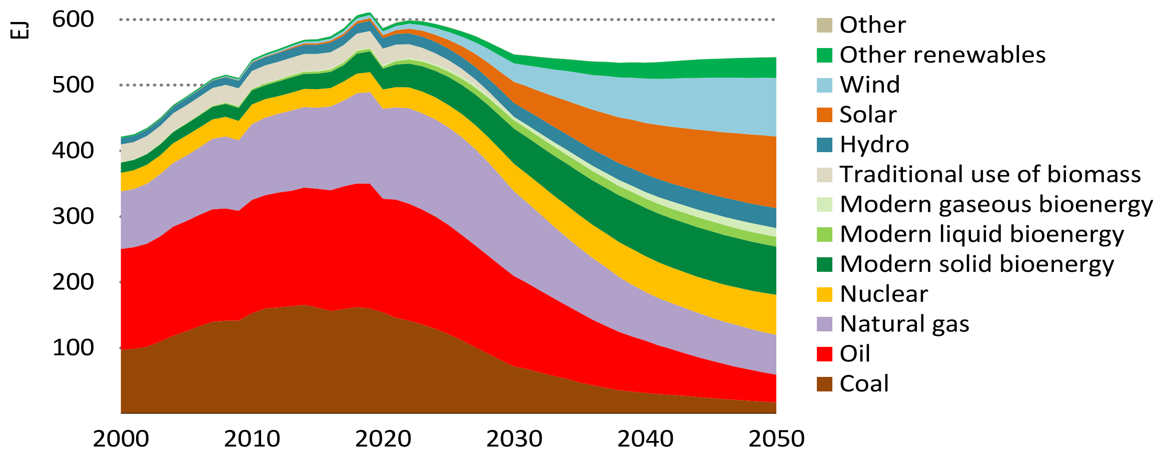


Figure 2.3: Total energy supply to achieve 1.5°C under the IEA net-zero pathway

Image source: IEA (2021b)

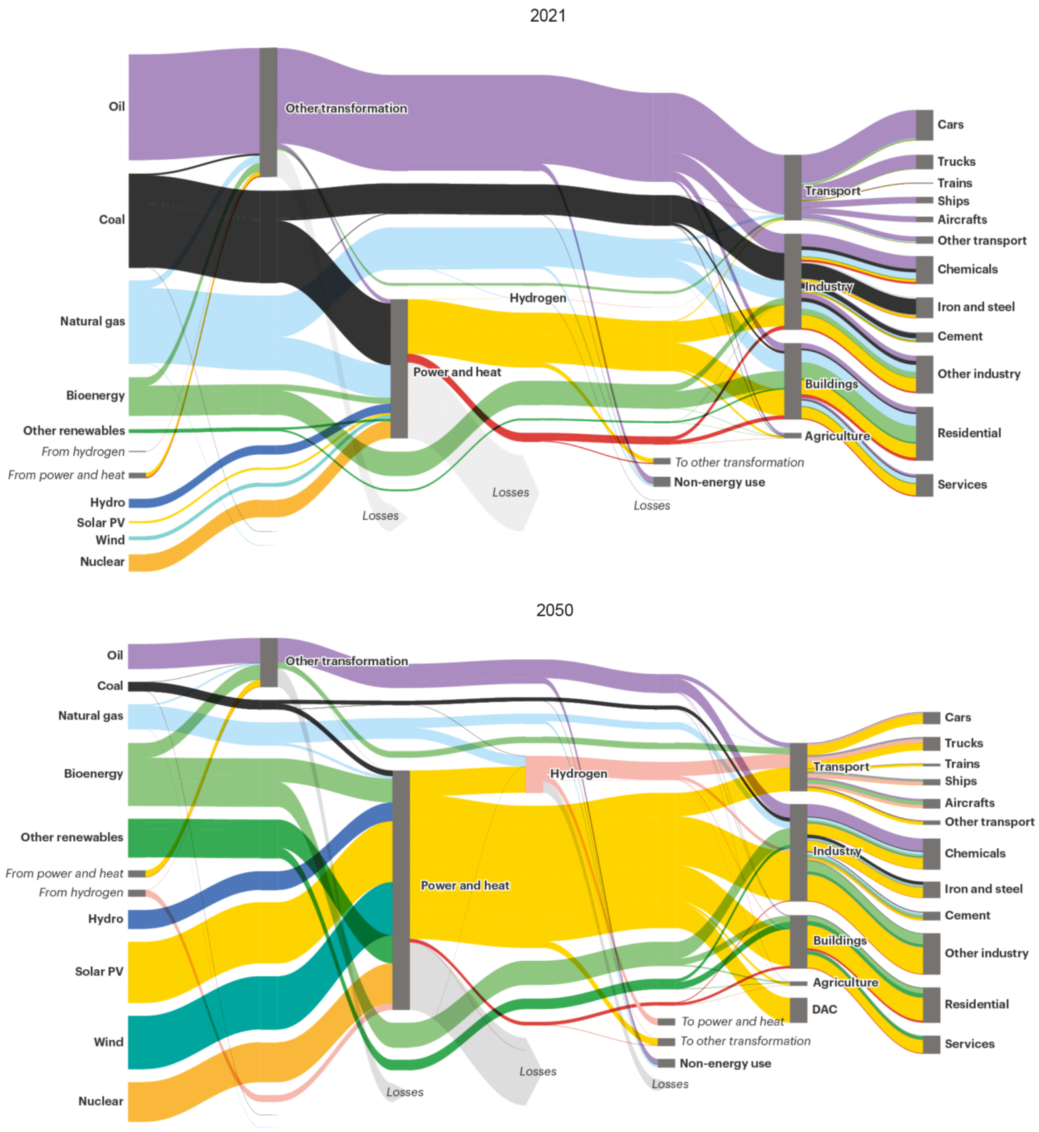


Figure 2.4: Role of electricity in energy supply in 2021 and in 2050 under the IEA net-zero pathway

Image source: IEA (2023a)

To facilitate such rapid transitions, it is imperative to accelerate the decarbonisation of electricity while significantly expanding its supply. According to the IEA net-zero pathway, electricity is expected to supply most of the energy demand by 2050 (Figure 2.4). This is attributed to the substantial electrification required in the energy demand sectors including transport, building, and industry to reduce emissions. Consequently, decarbonising electricity stands as the foundational step in mitigating climate change (IEA, 2021b; Williams et al., 2012).

Figure 2.5 further shows the importance of prioritising the decarbonisation of electricity, showing a steep decline in emissions starting in the electricity sector, followed by gradual reductions in other sectors.

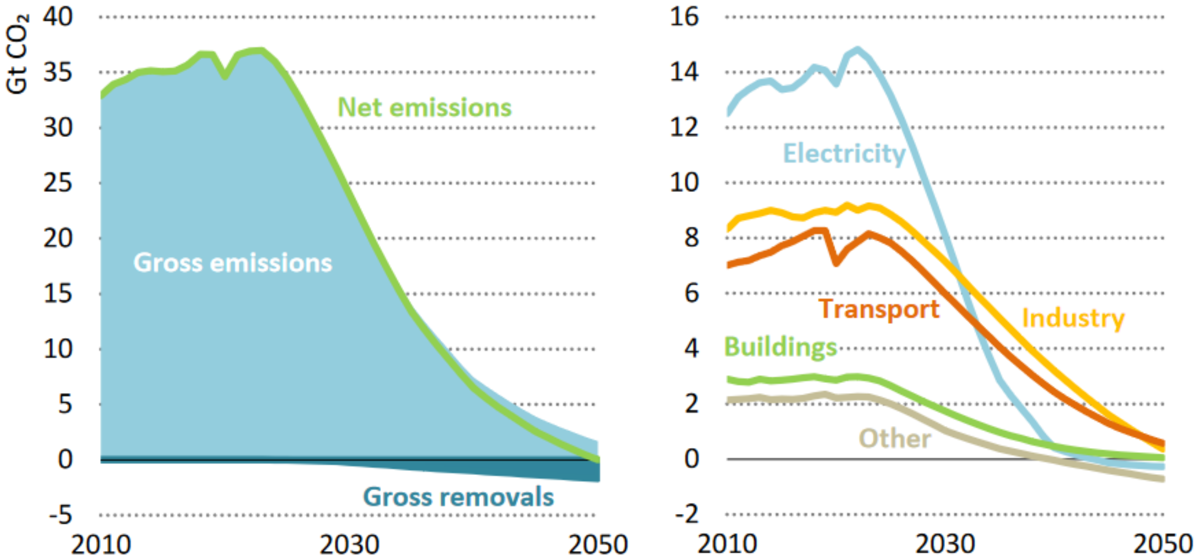


Figure 2.5: Sectoral emission pathways to achieve 1.5°C under the IEA net-zero pathway

Image source: IEA (2023b).

In developed countries, electricity decarbonisation must be completed already by 2035, according to the IEA net-zero pathway, to achieve 1.5°C (IEA, 2021b). This rapidity of required transitions significantly deviates from the historical development of the energy sector, both in nature and speed: they require not only a much faster development of low-carbon technologies but also the rapid substitution of fossil fuels—a process rarely, if at all, observed in the past centuries (Vinichenko et al., 2021; York and Bell, 2019).

It is important to emphasise that while these ‘normative’ scenarios outline what needs to happen based on certain assumptions and values to achieve distinct objectives (Ellenbeck and Lilliestam, 2019), they do not show what can actually take place in the real world (Pielke et al., 2008; Smil, 2008; Süsser et al., 2022). This limitation arises because contemporary modelling exercises, rooted in mathematical algorithms, can typically account only for techno-economic variables such as costs and technology diffusion rates. Consequently, they have not been able to incorporate other factors that exist in the real world but are challenging to parameterise, such as political priorities, regime resistance, and public acceptance (Geels et al., 2016a; Jewell and Cherp, 2023; Süsser et al., 2022).

2.1.3 Political acceleration in energy transitions to bridge the gap

The significant disparity between historical and required transitions calls for a substantial political acceleration in energy transitions (Roberts et al., 2018). Recognising that energy transitions are primarily accelerated by national policies—a mechanism also institutionalised under the Paris Agreement (Falkner, 2016)—a rapidly expanding body of scholarly work has delved into the roles, mechanisms, and dynamics of political acceleration at the national level—a topic I further elaborate on in the following Section 2.2.

2.2 Theories on political acceleration in energy transitions

The scholarly exploration of how energy transitions are politically accelerated intensified in the 1970s, a pivotal era marked by the urgent need for substantial political intervention in the energy sector to address the threats to energy security posed by the oil crises. This scholarly interest has dramatically amplified in recent decades, driven by a consistent rationale: the imperative of state intervention to accelerate energy transitions to mitigate climate change.

2.2.1 States steer energy transitions to achieve national objectives

Political scientists have long recognised that national governments, often referred to as 'the states', have always played a significant role in 'steering' energy transitions (Helm, 2002; Hughes and Lipscy, 2013; Ikenberry, 2009; Jordan and Matt, 2014; Pierre and Peters, 2020). This persistent involvement stems from the understanding that "energy is too important to the economy and society" (Helm, 2002, p. 174). Put differently, various state objectives such as ensuring energy security, generating employment, maintaining technological leadership, and addressing urgent problems like climate change (Cherp et al., 2017; Goldthau, 2012; Ikenberry, 1986; Jacobsson and Lauber, 2006a), cannot be achieved solely by relying on market forces. Hence, even in highly liberalised and privatised energy markets, the state remains a crucial player in designing and adjusting market rules by implementing regulatory frameworks and influencing price mechanisms (Helm, 2002).

2.2.2 But state motivations and capacities are constrained

However, the motivation and capacity of national governments to steer energy transitions, despite being a vital force, are constrained by various mechanisms and factors (Cherp et al., 2018; Ikenberry, 1986; Jewell and Cherp, 2019; Meckling and Nahm, 2018; Skocpol, 1985). As noted in subsection 2.2.1, national governments pursue a range of state objectives (Jordan and Matt, 2014; Pierre and Peters, 2020), and climate mitigation may not always be the state's priority. In developing countries, for instance, priorities often revolve around eliminating energy poverty and promoting economic development rather than climate mitigation (Spilker, 2013). Prioritising these objectives may lead to an increased consumption of fossil fuels (Jakob and Steckel, 2014; Semieniuk et al., 2021). Even in developed countries, addressing concerns related to energy security may necessitate reinvesting in fossil fuels. This is evidenced by advanced economies consistently subsidising fossil fuel exploration, extraction, transportation, and consumption, reaching a peak of 1.4 trillion USD in G20 countries in 2022 following the Russo-Ukrainian War (Laan et al., 2023).

At the same time, even when national governments are motivated to mitigate climate change, they may lack the necessary capacity to achieve this objective. State capacity, as defined in the existing literature, refers to the ability of the state to attain desired outcomes through policies (Feng and Jiang, 2021; Singh, 2023). Developed countries are generally considered to possess greater technological, institutional, and economic capacity compared to developing countries. This disparity is a fundamental reason why various resource transfers from developed to developing countries are facilitated under the Paris Agreement (Falkner, 2016; Sforna, 2019).

However, even when sufficient resources are available, the implementation of ‘ideal’ policies may be hindered by various political constraints. The existing literature engages in several critical debates on this topic, exploring the impact of specific state features influencing the political capacity of the state in energy transitions. There is no consensus yet in the literature regarding which feature dominates, enables, or hinders state intervention in the energy sector. These debates primarily revolve around three key aspects: (1) centralisation vs decentralisation of state power; (2) democracy vs autocracy; and (3) state-industry relationships.

First, the literature engages in a debate about whether centralisation or decentralisation of state power is more effective in accelerating energy transitions, a discussion that dates back to the 1970s when abrupt state interventions were called for to address energy security challenges following the oil crises (Ikenberry, 1986; Katzenstein, 1976). The inquiry was motivated by a perplexing question back then: Why did the United States, as the world superpower, struggle to address energy challenges compared to other countries like France, which swiftly responded to the oil crises in the 1970s?

Historical and recent studies offer conflicting perspectives. On the one hand, some argue that the centralisation of state power enabled rapid and robust responses to the crisis, exemplified by the swift development of nuclear power in France and Sweden (Grubler, 2010; Kaijser, 1992; Katzenstein, 1976). On the other hand, more recent studies contend that decentralisation, often in the form of federalism, may facilitate faster development of new energy technologies (Cherp et al., 2021; Drezner, 2001; Schaffer and Bernauer, 2014). However, federalism is also argued to create more entry points for veto-players, such as fossil fuel industries, potentially delaying climate mitigation efforts, including the development of renewable technologies, both at regional and national levels, as they seek to protect their vested interests (Karapin, 2020; Moe, 2011; Unruh, 2000).

Another debate revolves around whether democracy or autocracy leads to faster energy transitions. China, an autocratic state, has been acknowledged for its remarkable efforts in mitigating environmental problems, leading some scholars to argue that autocratic states perform better in addressing climate change (Beeson, 2010; Drahos, 2021; Shearman and Smith, 2007). Conversely, proponents of democracy assert that democratic states are better positioned to enhance national climate commitments due to the increasing climate awareness among citizens (Colvin and Jotzo, 2021; Povitkina, 2018). Moreover, studies find that democratic states tend to exhibit better international cooperation with other nations in mitigating climate change (Bättig and Bernauer, 2009; Povitkina, 2018). Contrastingly, scholars also argue that policymakers in democratic countries, akin to federalist states, tend to prioritise the short-term gains of their electorates rather than long-term benefits for the whole country (Congleton, 1992; Povitkina, 2018). This means that voters' preferences, which may not consistently align with climate mitigation goals (Spilker, 2013), particularly in areas bearing the costs of climate policies (Stokes, 2016, 2013), significantly influence national policies in democratic states, potentially blocking or weakening their effectiveness.

The third debate delves into how different state-industry relationships shape national policies. A foundational theory upon which numerous historical and contemporary studies have been built is the varieties of capitalism framework proposed by Hall and Soskice (2001). This framework categorises modern states into distinct types, including ‘coordinated market economies (CMEs)’, ‘liberal market economies (LMEs)’, and ‘state-influenced market economies (SMEs)’ (Hall and Soskice, 2001; Schmidt, 2009). Ikenberry (1986) characterises the roles of these states in energy transitions as follows:

- In SMEs (e.g., France), the state assumes the role of ‘producer’, as it publicly owns much of the energy sector and exercises direct control over it.
- In CMEs (e.g., Germany and Japan), the state acts as the ‘negotiator’, closely collaborating with nationally representative industries and often formulating transition policies as part of industrial strategies.
- In LMEs (e.g., the UK and US), the state operates as the ‘facilitator’, adopting a more ‘hands-off’ approach and employing price mechanisms to influence the functioning of the energy market.

Similar to the previous debates on centralisation vs decentralisation, and democracy vs autocracy, there is no consensus in the literature regarding which type of capitalism accelerates energy transitions more effectively. For instance, Rentier et al. (2019) argue that LMEs tend to phase out coal generation faster due to their looser connections with fossil fuel industries. Conversely, it is contended that CMEs develop renewable technologies more rapidly because of greater coordination between the state and relevant industries (Ćetković and Buzogány, 2016). Although France (an SME) significantly accelerated energy transitions through the rapid development of nuclear power after the 1970s oil crisis, Grubler (2010) argues that such level of acceleration may not be possible in today's more liberalised and democratised energy markets.

These ongoing debates suggest that even if states are motivated to mitigate climate change, their actions are likely constrained, albeit to varying degrees. In other words, implementing 'ideal' policies to mitigate climate change may not always be possible. Moreover, state motivations and the structures enabling or hindering state actions can change over time. This changing landscape has led to increasing scholarly attention to understanding how national policies can evolve over time.

2.2.3 Policies can be strengthened or weakened over time

The mechanisms and factors discussed in the previous subsection 2.2.2 may evolve over time due to exogenous shocks, such as energy crises, leading to the reordering of state objectives and changes in voters' preferences, thereby influencing policy adjustments. Additionally, endogenous changes, including those initiated by policies, can also open or close windows of opportunity for subsequent policies. In essence, therefore, national policies can be reinforced or weakened over time.

Policy sequence, increasing socio-economic support, and ratcheting-up

Such dynamics of national policies are extensively studied in the literature on policy sequence, increasing returns, and ratcheting up (Falkner, 2016; Meckling et al., 2017; Pahle et al., 2018; Pierson, 2000).

To steer energy transitions, states are found to often begin with relatively easy policies, such as research and development (R&D) subsidies, and gradually implement more challenging but stronger measures such as carbon pricing to mitigate climate change (Meckling et al., 2017; Pahle et al., 2018). This sequence in policy developments helps increase support from positively affected stakeholders (e.g. low-carbon technology industries) while reducing the transition costs for negatively affected ones (e.g. fossil fuel industries as well as other industries and households facing higher energy bills) by making alternative technologies affordable over time (Meckling et al., 2017; Pahle et al., 2018).

For instance, Germany’s state-led Energiewende started off by providing subsidies to develop renewable technology industries, which, in turn, supported the government in strengthening renewable policies over time while phasing out nuclear power and coal (Cherp et al., 2017). Similarly, to replace the coal industry with gas and later renewables, the UK also followed a similar sequence: first reducing policy support to coal, subjecting it to market competition through the liberalisation of the electricity market, and then ultimately imposing taxes on it (Geels et al., 2016b; Turnheim and Geels, 2012).

This sequential progression of policies—closely related to concepts such as ‘path-dependence’ (Mahoney, 2000) in general, and ‘increasing returns’ (Pierson, 2000), ‘positive policy feedback’, and ‘ratcheting up’ (Falkner, 2016) in particular—is the most important mechanism under the Paris Agreement where countries are expected to adopt progressively stronger climate policies to collectively achieve global climate targets (Falkner, 2016; Nascimento et al., 2023).

Lock-ins, negative feedback, increasing socio-economic resistance, and ratcheting-down

However, policies may also create unfavourable path-dependence and lock-ins. Pierson (2000) argues that once policies establish a specific development pathway, it is very difficult to reverse it.

Historically, there are many examples of this irreversibility in technological developments, as seen in the case of QWERTY keyboards dominating the typewriter market over many decades

(David, 1985), fossil fuels predominantly supplying energy over the last centuries (Unruh, 2000), or the continued reliance on nuclear power even after a major nuclear accident (Suzuki, 2014). In more recent transitions, the lock-in effects of policies in developing renewables have also been observed. It is argued, for example, that cost-effective policies often lock in mature renewable technologies at the time of policy adoption, consequently locking out immature but potentially more desirable technologies in the long term (Eitan and Hekkert, 2023; Haelg et al., 2018; Santana, 2016).

Moreover, while ambitious policies are necessary to mitigate climate change, these policies often come with high costs and face strong socio-economic and political resistance, which may lead to the ratchet 'down' of policies over time (Breetz, 2020; Jacobs and Weaver, 2015; Patterson, 2023; Sewerin et al., 2023). This societal resistance against policies is commonly referred to as 'backlash' in the literature such as by Patterson (2023) who further defines it as a process of counter-action which "contests the very legitimacy of policy action, involving particularly strong and volatile grievances" (2023, p. 69). Unlike mere disagreement with policies, backlash thus involves stronger actions aimed at delegitimising a policy or a national government more broadly (Patterson, 2023).

The presence of these accelerating and decelerating mechanisms in state-led energy transitions as well as the sudden and potentially significant influences of exogenous shocks suggests that accelerating energy transitions is most likely a non-linear process.

2.3 Mixed observations and arguments on political acceleration

On the one hand, theories suggest that political acceleration in energy transitions exhibits a non-linear nature, involving periods of both acceleration and deceleration, accompanied by shifts in direction. On the other hand, the literature recognises the stably growing trend of political interests in mitigating climate change across the world, exemplified by the emergence and progressively established international climate regime and increasing introduction of climate policies since 1990. Whether such a trend of more climate policies has resulted in an accelerated energy transition towards decarbonisation, however, remains highly uncertain with mixed observations and correspondingly different and often conflicting arguments.

2.3.1 Growing international climate regime and climate policies

Since 1990, the international climate regime has undergone a noteworthy evolution, marked by several key milestones that underscore a growing political interest in mitigating climate change, followed by the increased adoption of climate policies over time.

First, the establishment of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 signified the global acknowledgement of the urgency to mitigate climate change, and operationalised subsequent developments (Kuyper et al., 2018). In 1997, the Kyoto Protocol was adopted as the first international agreement addressing climate change, implementing binding emission reduction targets for developed countries (UNFCCC, 1998). The scope of these efforts was substantially expanded by the Paris Agreement in 2015, involving both developed and developing countries in a collective effort to keep the global temperature increase below 1.5-2°C (UNFCCC, 2015). This agreement adopts a bottom-up approach, enabling each country to voluntarily shape its climate action plan while progressively accelerating efforts to mitigate climate change (Falkner, 2016; Nascimento and Höhne, 2023). Furthermore, the Glasgow Climate Pact in 2021 reinforced the temperature target by countries collectively committing to aim for 1.5°C (Depledge et al., 2022).

Accordingly, a growing number of climate policies have been introduced in recent decades, with more than 1600 policies in the G20 targeting the energy sector in 2019 (Iacobuta et al., 2018; Nascimento et al., 2022b). Studies claim that these policies contributed to cost reductions and the diffusion of low-carbon technologies, as well as accelerating the decline of fossil fuels

(IRENA, 2022; Kern and Rogge, 2016; Loftus et al., 2015). As a cumulative impact, Hoppe et al. (2023) estimate, based on the meta-analysis of existing studies, that climate policies introduced by 2020 reduced global emissions by several billion tons of CO^2 compared to the counterfactual world without these policies.

2.3.2 Seemingly no political acceleration at the global level

Despite the growing international climate regime and the increasing adoption of climate policies, there seems to be no discernible change in the global development of the energy sector. New technologies have consistently been added on top of existing ones rather than replacing them (Figure 2.2). This pattern has resulted in a stable and dramatic growth in global energy consumption, a trend observed over the last centuries including the recent decades (Pielke et al., 2008; Ritchie et al., 2023; Smil, 2016b) (also see subsection 2.1.1). As a result, carbon dioxide (CO_2), a primary anthropogenic GHG, has not only increased but has done so at an unprecedentedly rapid speed since 1990 (Figure 2.6). This has led to more emissions being released in the last three decades than the cumulative emissions before that (Stoddard et al., 2021).

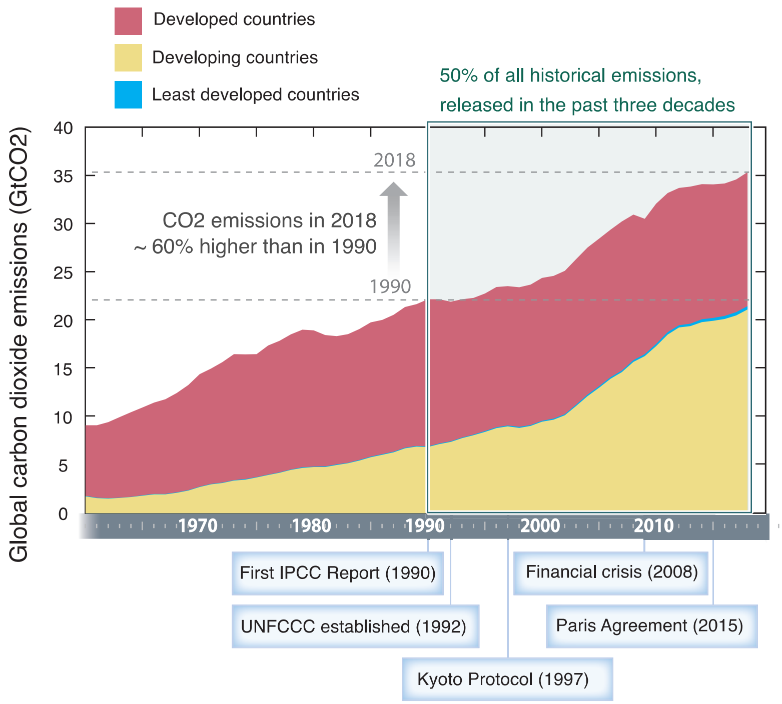


Figure 2.6: Global carbon dioxide emissions

Source: adapted from Figure 1 in Stoddard et al. (2021).

Given these stable growth trends in energy consumption and GHG emissions in the last centuries, scholars focusing on analysing global transitions argue that energy transitions have consistently been primarily driven by market forces (i.e., demand growth) and technologies (i.e., the availability of new, superior technologies to meet demand), with the impact of political acceleration deemed minimal (Fouquet and Pearson, 2012; Smil, 2016a; Wilson and Grubler, 2011). This analytical perspective leads some scholars, such as Smil (2024, 2010), to contend that "none of today's promises for a greatly accelerated energy transition from fossil fuels to renewable energies will be realized" (2010, p. 28). This view has recently been reiterated as "[t]he goal may be desirable, but it remains unrealistic" (Smil, 2024, p. 20).

2.3.3 Increasingly identified cases of political acceleration at the national level

Contrary to the analysis and argument presented on a global scale in the previous subsection 2.3.2, scholars dedicated to analysing sustainable transitions[1] and the role of (often climate) policies have identified a growing number of national transition cases characterised as 'accelerated', emphasising the importance of political acceleration in them (see my discussion on the issues related to the ambiguity surrounding terms such as 'accelerated', 'successful' or 'rapid' without comparative analysis in subsection 2.4.1).

The majority of these studies have focused on examining rapid technological changes in Europe or other developed countries in recent decades. Notably, Germany and the UK have received particularly extensive attention to analysing their recent growth of renewables and their decline of fossil fuels (Bang et al., 2022; Chapman and Itaoka, 2018; Geels et al., 2016b; Jänicke, 2012; Kern et al., 2015; Kern and Rogge, 2016; Lechtenböhmer and Luhmann, 2013; Pollitt, 2012; Rogge and Johnstone, 2017; Sovacool, 2016; Turnheim and Geels, 2012). This focus can be attributed to the perception of these countries as 'climate leaders' or 'front runner countries' (Kern and Rogge, 2016; Tobin, 2017), making them natural subjects for in-depth analysis and serving as successful models for broader replication. Other country cases include the recent growth of renewables in Spain (Jänicke, 2012; Kern and Rogge, 2016), Denmark (Jänicke, 2012; Kern and Rogge, 2016), the historical growth of nuclear power in France (Sovacool, 2016), as well as the decline of coal in the Netherlands (Kern and Rogge, 2016; Normann, 2019; Sovacool, 2016) and Ontario in Canada (Rosenbloom, 2018; Sovacool, 2016).

Drawing upon these 'successful' examples, scholars argue that politically accelerating energy transitions is not only possible (Roberts et al., 2018), but also an increasingly observed trend

[1] hereafter referred to as "transition scholars".

in recent decades (Kern and Rogge, 2016). In their view, the global impact of this recent trend has remained limited because the international climate regime initially encompassed only developed countries under the Kyoto Protocol in 1997. Given that the Paris Agreement in 2015 covers all countries, however, transition scholars argue that the acceleration effects have now spurred globally (Iacobuta et al., 2018; Kern and Rogge, 2016). Referring to the ‘accelerated’ and ‘successful cases’ in the literature, as well as other observations including corporate and civic efforts in developing low-carbon technologies worldwide, Kern and Rogge (2016) assert that “this level of activity... has generated significant momentum behind the low carbon transition, likely to expedite the process, and unparalleled in comparison to historical transitions’ (2016, p. 14).

2.3.4 But policies can also decelerate at the national level

In contrast to the growing recognition of political acceleration in energy transitions, there is also an increasing case of political deceleration reported in the literature. This counters the notion of continuous acceleration in the pace of energy transitions, potentially including shifts away from decarbonisation.

This is even true in countries mentioned in the previous subsection (2.3.3), where nationally accelerated technological changes were observed. For example, despite being commonly considered as ‘climate leaders’, both the governments of Germany and the UK recently increased their public investments in fossil fuel projects due to energy security concerns (Brauers et al., 2020; Höhne et al., 2022; The Government of the United Kingdom, 2022). Scholars argue that this shift away from climate mitigation efforts jeopardises their climate targets, making their national as well as global temperature goals unachievable (Abram et al., 2023; Höhne et al., 2022).

Moreover, Sewerin et al. (2023) empirically find statistically significant evidence that stronger climate policies are more likely to be weakened over time. There are also many qualitative case studies supporting such evidence. For example, Spain achieved the rapid deployment of renewables in the early 2000s with generous financial support through Feed-in Tariffs (FITs), a transition case often considered ‘accelerated’ in the literature (Jänicke, 2012; Kern and Rogge, 2016). However, electric utilities, who bore much of the transition costs, increasingly lobbied against the national government to dismantle the policy (Gürtler et al., 2019). This led to a change in the governing political party in 2011, with the new government suspending financial incentives for all renewable sources, resulting in the stagnation of renewables in the country throughout the 2010s. Similar cases of such backlash against renewable policies and subsequently weakened policies exist in many other countries with accelerated transition cases reviewed in subsection 2.3.3 such as in Ontario (Canada) (Stokes, 2013), the Czech Republic (Gürtler et al., 2019), Germany (Hoppmann et al., 2014), the US (Breetz, 2020; Stokes, 2020, 2016), the UK (Lockwood, 2015), as well as the EU as a whole (Skogstad, 2017).

Furthermore, even if strong policies are sustained or even strengthened over time, it does not necessarily guarantee the desired outcome. For example, despite the strong and continuous support from national governments, recent nuclear construction projects and plans have often experienced significant delays with escalating project costs across the world (Haywood et al., 2023). Additionally, increasing opposition has taken place in the form of lawsuits in recent years to delay and cancel not only nuclear power projects (Kikuchi, 2021) but also renewable energy projects, including those in Japan (Kohsaka and Kohyama, 2022), Germany (Dehler-Holland et al., 2022), the UK (Jones and Eiser, 2010), and the US (Susskind et al., 2022). Perhaps most notably, a recent study found that the majority of wind projects had been vetoed by municipalities in Sweden between 2020 and 2022 (Westander and Risberg, 2022).

These observations on policy deceleration, taking place even in the countries where low-carbon transitions are considered 'accelerated', raise questions about whether, and if so to which extent, recent energy transitions have been accelerated beyond historical trends in the energy sector.

2.4 Literature gap in analysing political acceleration

Both theoretical and empirical studies in the literature suggest that energy transitions are non-linear processes characterised by periods of acceleration and deceleration, including potential changes in direction over time. To what extent are these transitions politically accelerated? Are more recent transitions under climate policies different and faster than historical transitions, as required to achieve climate targets? The existing literature does not answer these questions because the current analyses are either too broad or too narrow to allow for a comparative analysis of political acceleration across countries and time-periods.

2.4.1 Analyses being too broad or too narrow

There is a sharp divide in the methodologies for analysing energy transitions in the literature. On the one hand, scholars investigating generalisable patterns in historical energy transitions adopt very broad scopes of analysis, including: (1) temporal spans ranging from decades to even centuries; (2) a global focus on aggregated transitions; and (3) economy-wide or multi-sectoral analyses. While such low-granular analysis may be well-suited to examine the overall trends in global energy consumption and GHG emissions, it inevitably overlooks potential changes occurring at a more granular scale in terms of time, geography, and sectors. This is problematic because revolutionary technological transformations often originate from such initially insignificant niches that expand and diffuse exponentially (Sovacool and Geels, 2016). Since political acceleration in energy transitions has been primarily driven by national policies (Falkner, 2016; Helm, 2002; Ikenberry, 1986), a more appropriate scale of analysis to discern the rates of political acceleration should be national or sub-national.

On the other hand, scholars seeking to pinpoint 'successful' cases of accelerated transitions or evaluate the impacts of climate policies have adopted a much narrower scope of analysis: (1) a limited temporal scope, focusing on several years to a few decades, mainly post-1990; (2) specific attention to individual countries, including those with small economies; (3) examination of changes in individual technologies rather than a sectoral perspective. While focusing on national transitions is more suitable for analysing political acceleration, there are multiple issues in these studies to properly discern them due to their highly granular analysis.

Focusing on short-term, potentially insignificant changes

First, these transition studies and climate policy research focus on specific points in time when rapid changes took place and examine how national policies contributed to these processes. While these studies provide valuable insights into the mechanisms of political acceleration for short periods, they do not clarify whether these cases represent meaningful transitions compared to the long-term structural changes required to mitigate climate change. This is particularly true for studies focusing on small economies such as Denmark or Ontario in Canada, as the changes there may not be directly relevant to the magnitude of acceleration necessary in much larger economies worldwide.

Given that policies change over time (as discussed in subsection 2.2.3), it is more important to understand the sequence of these policy changes, the speed of transitions, and the duration required to achieve specific technological changes. For example, instead of solely focusing on how national policies accelerated the growth of renewables in Spain in the early 2000s (Jänicke, 2012; Kern and Rogge, 2016), it is crucial to understand the extent of renewable growth and how long this growth was sustained. Similarly, rather than concentrating only on the decline of coal power in the UK during the 1990s (Pollitt, 2012), it is essential to examine how long it took for the UK to phase out coal power completely and how the sequence of policies influenced the decline speed.[2]

Focusing on individual technological changes rather than systemic shifts

Secondly, prevalent studies in existing literature often focus on individual technological changes, such as the growth of solar or wind power or the decline of coal, rather than analysing systemic transitions in the energy sector towards decarbonisation. This approach can be highly problematic because the expansion of low-carbon technologies does not necessarily lead to a corresponding decline in fossil fuels and vice versa.

Consider Germany, one of the most extensively studied countries for its state-led 'Energiewende' towards a renewable-based economy. While Germany achieved record growth of renewables in 2022, the concurrent decline of nuclear power and resurgence of fossil fuels led to an increase in the country's greenhouse gas emissions in the same year (Alkousaa and Wacket, 2023). In other words, the expansion of renewable technologies does not necessarily accelerate energy transitions towards decarbonisation. Therefore, implying expedited low-carbon transitions solely based on the growth of renewables can be misleading.

Furthermore, the decline of coal in the UK, the Netherlands, and Canada—framed as rapid transition cases by multiple scholars (Brauers et al., 2020; Kern and Rogge, 2016; Normann, 2019; Pollitt, 2012; Rentier et al., 2019; Sovacool, 2016; Turnheim and Geels, 2012)—was accompanied by the increased use of natural gas, potentially perpetuating reliance on fossil fuels rather than accelerating the shift to low-carbon alternatives (Gürsan and Gooyert, 2021; Kemfert et al., 2022). Notably, Canada's GHG emissions increased by ca. 14% between 1990

[2] While Turnheim and Geels (2012) document such long-term decline of coal use in the UK since the 1960s, they do not compare this speed with that of other countries. Therefore, the significance of this case remains unclear.

and 2021 (ECCC, 2023). The same logic applies here: the decline of coal does not necessarily indicate that countries are accelerating low-carbon energy transitions.

Accelerated compared to what?

Thirdly, existing studies often lack clear definitions for terms like 'successful', 'rapid', or 'accelerated' transitions. For instance, the growth of renewables in Germany is frequently described using these terms (Chapman and Itaoka, 2018; Jänicke, 2012; Kern and Rogge, 2016; Pahle et al., 2018; Rogge and Johnstone, 2017), often with implicit or explicit arguments that other countries should emulate Germany's model. However, this speed is rarely contextualised against historical rates of technological growth in Germany or other comparable countries. This lack of comparative analysis—a significant issue in the literature(Grubler et al., 2016; Sorrell, 2018)—leaves it unclear whether these cases genuinely represent accelerated transitions.

Furthermore, while the existing literature concludes that climate policies have positive impacts in accelerating energy transitions towards decarbonisation including by expediting the growth of renewable technologies (Hoppe et al., 2023; Nascimento and Höhne, 2023), this finding is hardly surprising, given that policies are inherently designed to enact impacts. The essential question here is not merely whether climate policies have impacts but rather whether these impacts are significant enough to alter the nature and speed of energy transitions compared to the historical development of the energy sector.

Perhaps more importantly, uncertainty persists regarding whether the growth of renewables in 'frontrunner countries' or 'climate leaders' such as Germany and the UK (Kern and Rogge, 2016; Tobin, 2017)—even if accelerated by climate policies—is occurring at a pace sufficient to achieve climate targets. Advocating for the replication of such cases without validating the extent of acceleration could potentially hinder, rather than expedite, global decarbonisation processes.

2.4.2 Addressing the gap needs a more appropriate range of analysis

Addressing the gap in the literature caused by existing analyses being either too broad or too narrow (see subsection 2.4.1) necessitates a methodology to conduct a more appropriate range of analyses and examine the rates of political acceleration in energy transitions. Such an approach should analyse long-term systemic transitions in a specific sector at the national level and compare them across countries and time-periods. With this in mind, my dissertation explores the following research questions:

- How have the state interventions in the energy sector differed across countries, and how have the differences affected their transition outcomes?
- Have climate policies altered energy transitions beyond historical trends, if so, how in light of climate target requirements?
- How has the stringency of national energy transition policies changed over the last decades, and how does this evolution align with achieving climate targets?

2.5 Summary

This chapter began by highlighting the significant disparity between historical and required energy transitions to mitigate climate change, involving differences in both the nature and speed of energy transitions. While steering these transitions through policies towards decarbonisation is crucial to bridging this gap, existing literature debates their empirical role and ability.

This debate arises from the distinct and highly contrasting methodologies in the literature. On the one hand, there is an inclination to study energy transitions in an overly broad manner, focusing on global trends and potentially dismissing more granular changes. On the other hand, there is an inclination to adopt excessively narrow approaches, looking at specific and short-term technological and policy changes in specific countries without assessing their significance in comparison to other countries, historical transitions or climate target requirements.

To develop a greater understanding of political acceleration in energy transitions towards decarbonisation, this dissertation aims to develop a methodology to conduct a more appropriate range of analyses to answer the following research questions: (1) How have state interventions in the energy sector differed across countries, and how have the differences affected their transition outcomes?; (2) Have climate policies altered energy transitions beyond historical trends, if so, how in light of climate target requirements?; and (3) How has the stringency of national energy transition policies changed over the last decades, and how does this evolution compare to historical and required transitions?

The following chapter outlines the research design of this dissertation, encompassing the ontological and epistemological assumptions and the 'middle-range' methodology with conceptual frameworks and methods employed to answer the research questions.

3. Research design

Addressing the literature gap requires a methodology with a more appropriate granularity to examine political acceleration in energy transitions. This chapter develops such 'middle-range' methodology by employing the ontological and epistemological assumptions of critical realism in Section 3.1, building a set of conceptual frameworks to undertake the three empirical chapter analyses of this dissertation in Section 3.2, and describing the common and distinct methods used in these chapters in Section 3.3.

3.1 Ontological and epistemological assumptions

This dissertation is built on ontological and epistemological assumptions based on critical realism. This section describes critical realism and how I apply its ontological and epistemological assumptions to analyse the political acceleration of energy transitions.

3.1.1 Critical realism and mechanistic analysis

Critical realism is a philosophy of science originally developed by Roy Bhaskar in the 1970s (1978, 1975). As an alternative approach to other mainstream philosophies such as positivism and constructivism, critical realism distinguishes itself by the foundational assumption that ontology (i.e., the nature of reality) cannot be reduced to epistemology (i.e., our knowledge of reality) (Danermark et al., 2019; Fletcher, 2017). It argues that reality exists independent of our perception, observation, or knowledge of it.

According to critical realism, there are three domains of reality: the real, the actual, and the empirical. What we can observe is only the surface phenomena to which our perceptive scope is confined (i.e. empirical domain). Beyond our perceptions, there exist more phenomena which we do not observe but nonetheless actually exist (i.e. actual domain) (Bhaskar, 1975). These phenomena, commonly referred to as 'events', whether observed or not, are caused by the underlying structures and causal mechanisms which we cannot directly observe (Bhaskar, 1975).

The primary objective of critical realism is, similar to conducting experiments in natural science to uncover regularities, to identify these structures and mechanisms and examine how they contribute to the observations we perceive (Danermark et al., 2019; Sayer, 1992). This process deepens our understanding of reality through our perception and knowledge. It also underscores that what we comprehend as reality or scientific findings is not 'theory determined' but invariably 'fallible' and 'theory-laden' (Sayer, 1992). Consequently, social science progresses through scientific debates, where diverse 'facts' can be generated based on distinct theories and research designs (Hancké, 2009).

It is crucial to emphasise that, in contrast to positivism, critical realism distinctly acknowledges the significance of human agency in causing social phenomena (Elder-Vass, 2010). This is because it is the human actions, driven by ideas, beliefs, and interests, that 'consciously' and 'intentionally' maintain or change structures (e.g. institutions) and enable or hinder mechanisms (e.g. providing or abolishing subsidies) to produce a particular social phenomenon (e.g. emergence of new technologies) (Leca and Naccache, 2006). In other words, "social phenomena…cannot exist without human activity" (Danermark et al., 2019, p. 27).

However, this human action faces material and non-material limits and obstacles. For example, it is not possible for anyone to 'live freely' because our social life is constrained by the availability of financial resources, public regulations, social norms, and duties. Moreover, even when mechanisms are enabled (e.g. providing subsidies), they may not always yield the same effects, as these effects can be influenced by other confounding and evolving structures and mechanisms (e.g. material obstacles and actions constraining the effectiveness of subsidies). Knowledge of the social world is, therefore, always context-dependent (Leca and Naccache,

2006) compared to that of the natural world. In the view of critical realism, 'tendencies' that are context-dependent exist in the social world rather than 'regularities' in the natural world (Danermark et al., 2019, pp. 47–50).

3.1.2 Application of critical realism to analyse energy transitions

These ontological and epistemological assumptions of critical realism can help advance our understanding of political acceleration in energy transitions in three ways. First, it clarifies why the academic debate on the topic exists, as I reviewed in Chapter 2. For example, studies which argue that historical energy transitions have been very slow are those that look at the slowness in global changes (i.e. observed events of interest) and explain the underlying structures and causal mechanisms behind such as the speed of technology diffusions (Grubler, 2012; Grubler et al., 2016) and vested interests in fossil fuels (Stoddard et al., 2021). On the other hand, studies that identify accelerated transition cases focus on much more granular observations where rapid changes took place, such as the coal decline in the UK in the 1990s or the renewable growth in Spain in the 2000s. These studies then look for driving mechanisms such as increasing political will driving transitions (Kern and Rogge, 2016) or decisive policies like the liberalisation and privatisation of the electricity market in the UK in the 1980s (Pollitt, 2012). Resolving the debates, therefore, requires a more suitable scope of analysis such as national energy transitions, rather than global changes or individual technological changes, that can be compared to one another.

Secondly, it helps to systematically structure my empirical analyses. Cherp et al. (2018) argue that energy transitions should be analysed through the co-evolution of three systems: techno-economic, socio-technical, and political. This approach typically divides energy transitions into a distinct set of episodes (Cherp et al., 2018), which can then examine how respective episodes emerged as effects of certain combinations of these perspectives and corresponding structures and mechanisms. Using this mechanistic analysis, Cherp et al. (2017a) reveal the sequential developments of the electricity sector in Germany and Japan since the 1960s, where various mechanisms and their combinations resulted in diverged outcomes where Germany became a global leader in solar and wind power while Japan did not. This argument is more convincing than other studies based on a single theory/mechanism, such as the environmental tradition of Germany (Geels et al., 2016b) or the vested interests of Japan for nuclear power (Valentine and Sovacool, 2010) because these two mechanisms also existed for the other country (Cherp et al., 2017). Similarly, the political acceleration of energy transitions can be examined as the sequence of policies and its effects on the direction and the pace of energy transitions over time.

Thirdly, the assumption that there exist changing but also somewhat autonomous and stable structures constraining human actions to activate mechanisms in order to influence social phenomena resonates remarkably well with the various enabling and constraining factors in nationally accelerating energy transitions reviewed in Chapter 2. This relative stability and mutual as well as complex dependencies among structures, actions, and mechanisms may imply that there is a certain limit to the degree of politically accelerating energy transitions. For example, analysing the political-economic structures of national governments to explain their diverse responses to the oil crises in the 1970s, Ikenberry (1986) convincingly writes that:

> But responses to the energy crisis depended upon existing institutions even as they sought to effect changes. Officials confronted bewildering new international circumstances with established institutional resources and policy tools. **All was not created anew**. Rather, enduring institutional structures and established policy repertoires, despite efforts to move beyond them, became the central mechanisms for state policy (1986, pp. 105–106, bold added to the original).

While transition scholars argue that ‘politics may trump economics’ in low-carbon transitions (Kern and Rogge, 2016; Sovacool and Geels, 2016), the critical realist approach enables me to evaluate this hypothesis by analysing whether political mechanisms have over-ruled the direction and speed of energy transitions over other non-political mechanisms to mitigate climate change.

3.2 Conceptual frameworks

Employing the ontological and epistemological assumptions of critical realism, this section describes the conceptual frameworks of this dissertation to examine political acceleration in energy transitions.

3.2.1 Middle-range methodology to analyse national energy transitions

In the mid-20th century, Robert K. Merton advocated for the development of 'middle-range' theories within the field of sociology (Merton, 1968). His motivation mirrored the objective I pursue in my dissertation: reconciling the dichotomy between studies aiming to construct 'grand theories' to explain society as a whole and those focused on overly context-specific empirical observations which cannot be generalised at all (Coser, 2017; Merton, 1968).

Inspired by this terminology, my dissertation develops and applies a 'middle-range' methodology to analyse energy transitions at a more focused scope than the existing global and economy-wide analyses, but broader than the alternative approach looking solely at individual technological changes over short-term reviewed in Chapter 2 (see Table 3.4 at the end of this chapter for the summarised comparison of my middle-range methodology with the other major approaches in the literature). By doing so, my dissertation focuses on national energy transitions, examining all technological changes involved in their energy systems but within the same sector.[3]

[3] While this approach can be applied to various energy sectors, this dissertation specifically focuses on analysing the electricity sector. See subsection 3.3.1 for the reasons behind this choice.

Drawing on ontological and epistemological assumptions grounded in critical realism, I conceptualise national energy transitions as the cumulative outcome of changes in energy systems caused by co-evolving structures and mechanisms. My literature review in Chapter 2 identifies three major structures that encompass distinct mechanisms affecting national energy systems: changes in policies, technological and market trends, and other contextual factors related to energy, climate, and other social challenges. Interactions between these structures can be categorised into material impacts or other knowledge and power flows, as depicted in Figure 3.1.

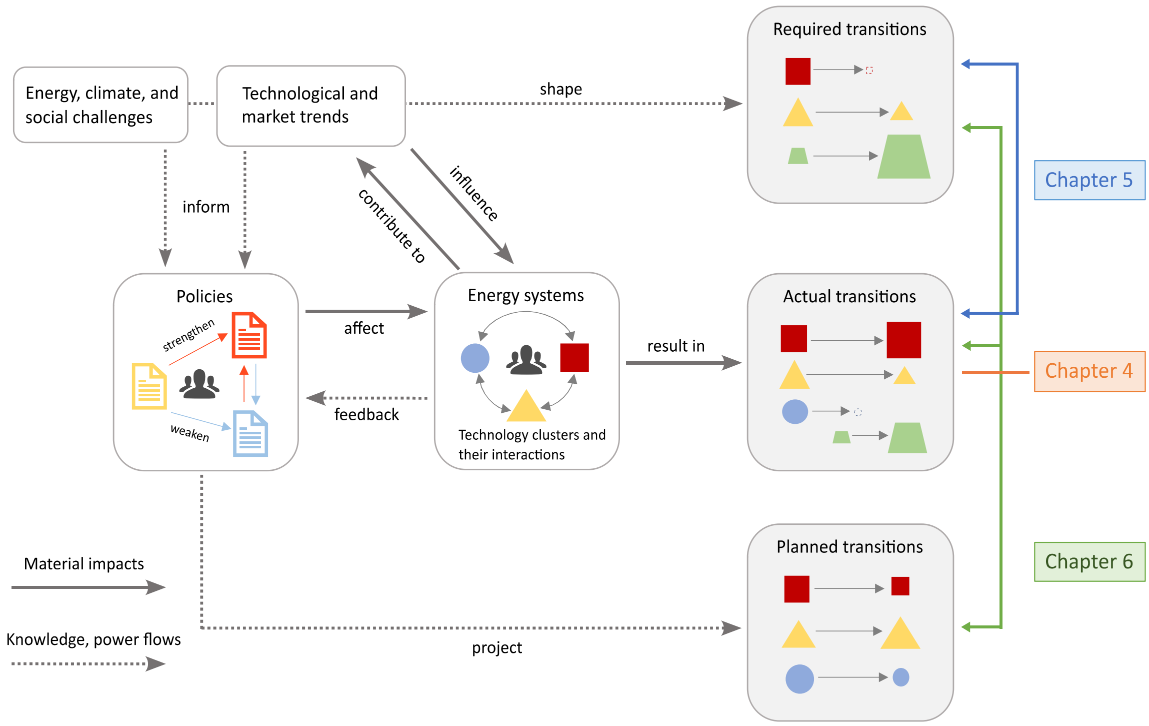


Figure 3.1: Overarching conceptual framework of this dissertation and the focused analyses of three empirical chapters

It is important to note that energy systems themselves constitute a semi-autonomous structure with multiple technology clusters with agency, each involving distinct technologies and their infrastructure, industries, and various supporting groups. These clusters may interact with one another, thereby causing changes within the system without external influence. Additionally, energy systems are not merely passive recipients of influences from other structures; they also actively shape them through lobbying for or against policies as feedback and contribute to technological and market trends.

Policies, on the other hand, are informed by evolving energy, climate, or other social challenges, as well as technological and market trends. In such an environment, policymakers may develop various policies, strengthening or weakening them over time depending on the state's motivation and capacity for energy transitions. These policies materially affect energy systems by altering cluster arrangements through manipulating market forces with subsidies or taxes, or more forcefully dictating developments with regulations and bans, including phase-out policies. This policy push, as I discussed above, may create a positive feedback loop with affected technological clusters, supporting the reinforcement of the policy (e.g., subsidy to renewable industries, supporting policymakers to strengthen it), or may trigger a negative feedback loop weakening it (e.g., utilities bearing the costs of the renewable subsidy, lobbying against the policy).

With this conceptualisation of national energy transitions in mind, the focus of my dissertation research is to examine how actual energy transitions have been influenced by policies and analyse this historical implication for achieving climate target requirements.

To achieve this aim, I adopt a step-by-step approach, conducting three empirical analyses while progressively broadening the scope. In Chapter 4, as the first empirical analysis, I focus on examining historical energy transitions by tracing material impacts, knowledge, and power flows over time to test this analytical approach. Reflecting on the results, in Chapter 5, I compare historical transitions and the required ones to mitigate climate change. The purpose of this chapter is to elucidate whether and how much acceleration is necessary to achieve climate targets compared to the historical rates of acceleration. Finally, in Chapter 6, I further incorporate planned transitions based on existing policies to examine how these plans compare to actual and required ones. The objective of this chapter is to analyse the extent of ratcheting up in policies over time in comparison to historical and required transitions.

3.2.2 Tracing systemic changes towards decarbonisation

To facilitate the comparative analyses of this dissertation among actual, planned, and required energy transitions and across countries, I develop and apply a typology of energy transitions based on the changes and their interplays in fossil fuels and low-carbon technologies (Figure 3.2, see Table 3.1 for source categories). These changes are most relevant to mitigating climate change, which requires the rapid replacement of fossil fuels with low-carbon technologies (IEA, 2023b). This analysis on more systemic transitions, rather than individual or some limited number of technological changes, goes beyond existing approaches in the literature which focus on analysing either the growth of low-carbon technologies (Cherp et al., 2017; Grubb et al., 2020; Kern and Rogge, 2016; Sovacool, 2016; Wilson et al., 2013) or the decline of fossil fuels (Brauers et al., 2020; Normann, 2019; Sovacool, 2016; Turnheim and Geels, 2012; Vinichenko et al., 2021, 2023b) separately.

Based on this typology, there are four types of energy transitions: (1) **energy additions** where low-carbon technologies are added (but do not replace) fossil fuels; (2) **low-carbon substitutions** where low-carbon technologies replace fossil fuels; (3) **high-carbon substitutions** where fossil fuels replace low-carbon technologies; and (4) **energy reductions** where both low-carbon technologies and fossil fuels decline through an overall contraction of the energy system.

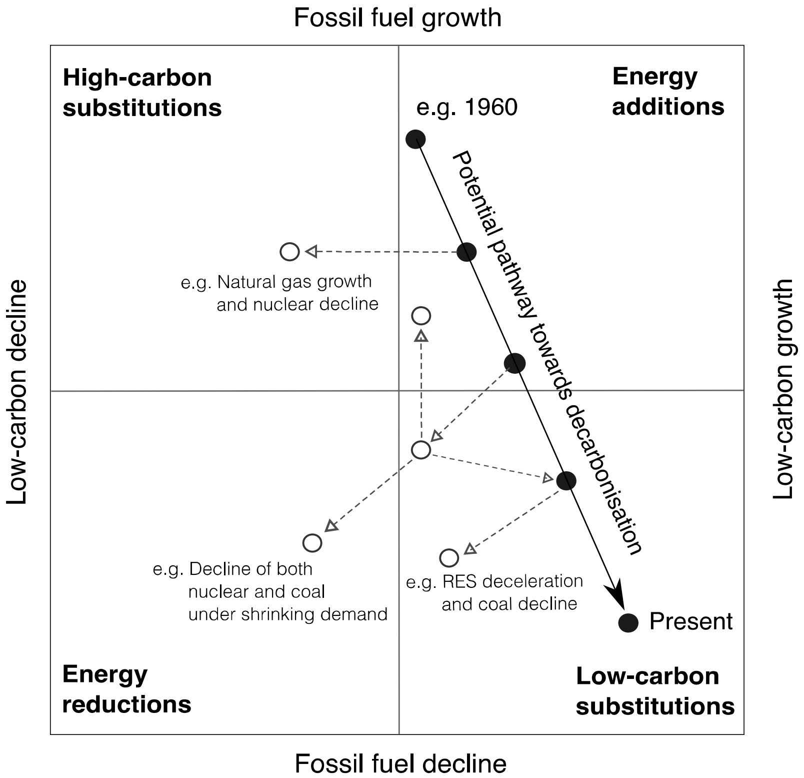


Figure 3.2: Typology of energy transitions

Notes: Energy transitions can be categorised into four types depending on the changes in the use of fossil fuels and low-carbon technologies. The arrows indicate a potential pathway and other possible developments towards (or away from) decarbonisation.

Historically, *energy additions* were the primary mode of development in the energy sector, where the rapidly growing demand was met by adding all sorts of technologies, with fossil fuels playing a major role (Fouquet, 2010; York and Bell, 2019). However, with the increasing availability of low-carbon technologies, recent and future transitions may involve more technological substitutions. These substitutions can be further divided into two types: *low-carbon substitutions* where fossil fuels are replaced by low-carbon alternatives such as nuclear or modern renewables, aligning with the concept of sustainable development including mitigating climate change (Dincer, 2000; Lélé, 1991). On the other end of the spectrum are *high-carbon substitutions*, which contradict the principles of sustainable development by replacing low-carbon sources with fossil fuels. Such substitutions may be caused by multiple factors including vested interests in fossil fuels (Cherp et al., 2017; Moe, 2015), or a sudden loss of low-carbon sources due to, for instance, adverse weather for renewables or nuclear accidents (Cho et al., 2016). Lastly, the energy system may evolve without the growth of new technologies and instead undergo shrinkage. This can be called *energy reductions* which may align with the concept of 'degrowth', although 'sustainable degrowth' often entails the development of low-carbon technologies to replace the currently dominant fossil fuels (Grubler et al., 2018; Kallis et al., 2018; Schneider et al., 2010), which is more closely related to *low-carbon substitutions*.

Table 3.1: Source categories used in this dissertation

Category	Source
Fossil fuels	- Coal - Oil - Natural gas - Other non-renewable
Low-carbon	- Hydro - Nuclear - Solar - Wind - Biofuel (including renewable waste) - Geothermal - Tidal
Modern renewables	- Solar - Wind - Biofuel (including renewable waste) - Geothermal - Tidal
Hydro	- Hydro
Nuclear	- Nuclear

Notes: While existing studies generally find biofuel-based electricity as low-carbon (Evans et al., 2010), its environmental impacts could vary rather significantly based on factors such as feedstock type, land-use change, water usage, and fertiliser type as well as quantity (Jeswani et al., 2020).

This systematic categorisation of energy transitions makes it possible to trace and compare the types and speeds of energy transitions over time. Given that historical transitions were predominantly energy additions, a potential pathway towards decarbonisation should be such that low-carbon technologies develop progressively faster to increasingly substitute fossil fuels over time, as depicted in Figure 3.2.

Additionally, systematically categorising, tracing, and comparing energy transitions enables us to examine the impacts of climate policies (see subsection 3.3.3 for more detailed methods). I follow the conventional definition of climate policies as "(national) sectoral or overarching policies that result in lasting emission reductions" (Nascimento et al., 2022b). My primary interest is to examine whether and how these policies have resulted in significant changes in the type and speed of energy transitions beyond historical trends.

3.2.3 Examining the level of required acceleration

To clarify how much acceleration in energy transitions is necessary to mitigate climate change, I compare the required rates of low-carbon substitutions outlined in climate mitigation pathways to historically relevant observations. Such comparative analysis, linking historical cases to analysing the challenges of meeting future scenarios or targets, has been so far utilised in examining global climate scenarios (Loftus et al., 2015; Semieniuk et al., 2021; Sluisveld et al., 2015), as well as analysing the speed of national and regional technological growth (Ewijk and McDowall, 2020; Odenweller et al., 2022), and technological decline (Jewell et al., 2019; Muttitt et al., 2023; Vinichenko et al., 2021, 2023b). This dissertation extends this analysis to examine both technological growth and decline simultaneously in order to analyse the level of acceleration necessary in energy transitions more comprehensively. To do so, I use a systematic method of mapping future transitions onto empirically grounded speed zones constructed from historically relevant cases and their density of observations (Jewell and Cherp, 2023; Odenweller et al., 2022; Vinichenko et al., 2021) (Figure 3.3).

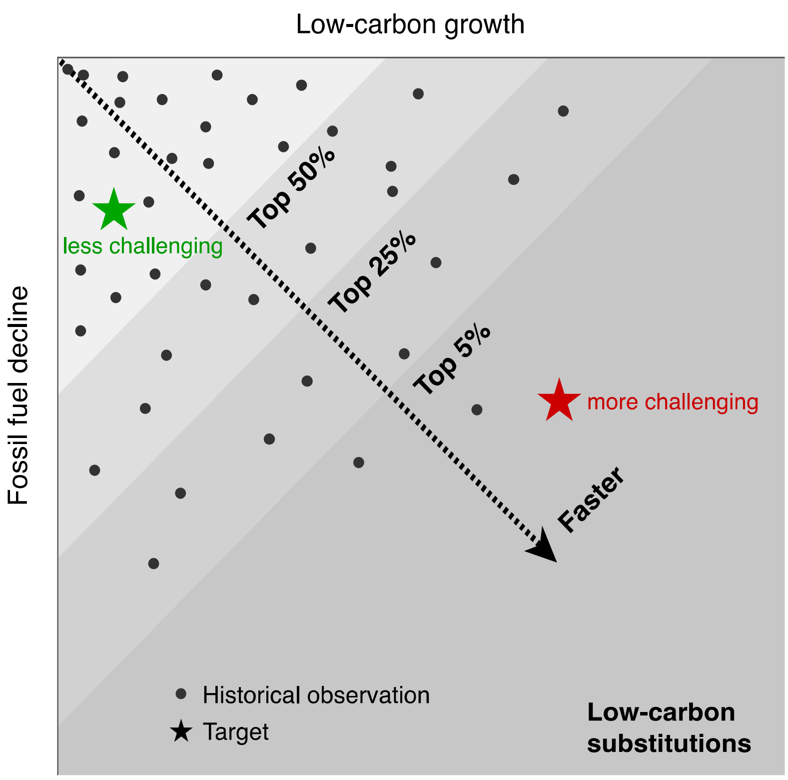


Figure 3.3: Empirically grounded speed zones and the required level of acceleration for targets

Notes: Areas with shaded colours show the different speed zones of transitions where the darkest area represents the fastest speeds (the top 5% of historical observations), the second darkest/second fastest (top 25% to 5%), the third darkest/third fastest (top 50% to 25%), and lightest/slowest (below 50%). Examples of historical observations (n = 40) are depicted with dots, while decarbonisation targets are shown with stars.

3.3 Methods

This dissertation encompasses three longitudinal comparative case studies that evolved as the research progressed. The subsequent subsections detail the shared methods utilised across these studies (subsection 3.3.1), followed by distinct methods specific to each study, outlining more precise scopes and supplementary data sources (subsections 3.3.2, 3.3.3, 3.3.4)

3.3.1 Common methods for the three empirical analyses

The three empirical analyses share three common research design features: (1) the choice of the sector and countries; (2) the metric to calculate the rate of technological changes; and (3) the main data source.

Firstly, I focused on analysing the electricity sector in the G7 and EU countries between 1960 and 2035 including their future targets and plans to mitigate climate change. I selected this specific scope for three reasons: (1) the majority of policies, particularly climate policies that are relevant to this dissertation, have been implemented in this sector so far (Iacobuta et al., 2018; Nascimento et al., 2022b); (2) these countries spearheaded in introducing these policies in the last decades and repeatedly committed to lead global climate mitigation efforts (Kirton et al., 2018; Kokotsis, 1999); and (3) these countries are among the largest economies in the world with significant economic, technological, and financial capabilities. Therefore, not only do electricity transitions in these countries offer a great opportunity to analyse political interventions and their outcomes, but the empirical insights from these countries (or lack thereof) also have significant implications for mitigating climate change globally.

Secondly, I applied the following metric to calculate the rate of technological changes in order to systematically identify the periods of rapid transitions in the energy system.

$$ACR_i = \frac{(S_{i1} - S_{i0}) * 2}{(T_0 + T_1)} * \frac{1}{(Y_1 - Y_0)}$$

where ACR_i represents the *annual change rate (%) of electricity generated (TWh) from a given source* (*i*) between the *start* year (S_{i0}) and *end year* (S_{i1}). This rate is normalised by the *average total electricity generation (TWh) during the start year* (T_0) and *end year* (T_1), and then further divided by the number of years between the *start year* (Y_0) and *end* year (Y_1). The original form of this metric to quantify the rate of energy transitions was developed by Vinichenko et al. (2021).

Thirdly, all three empirical chapters use IEA's Extended Energy Balances (2022) for historical data. As I aim to analyse the trends of technological changes in electricity generation, I smooth IEA's historical data by using three-year moving averages.

3.3.2 Specific methods for Germany-UK comparison (Chapter 4)

The primary focus of this chapter is to test the overarching conceptual framework of this dissertation (Figure 3.1) and examine the historical interventions of national governments in the electricity market and their outcomes in terms of accelerating energy transitions. To meet this objective, I focused on Germany and the UK because these two countries are often considered leading nations in climate change mitigation (Chapman and Itaoka, 2018; Kern and Rogge, 2016; Tobin, 2017) while pursuing diverse transition policies (Geels et al. 2016), offering a great opportunity to examine whether, and if so, how the differences in policies have affected the speed of energy transitions.

To facilitate this longitudinal comparative analysis, I employed the following steps. First, I segmented the electricity transitions in both countries into a series of decadal episodes. Such an approach to breaking down the temporal scope into a sub-set of analytical periods has been used by Cherp et al. (2017) to compare long-term energy transitions in Germany and Japan. Second, I used the metric described in 3.3.1 to calculate the rates of technological change of all major sources (oil, coal, gas, nuclear, hydro, and modern renewables) to identify annual changes exceeding 1% compared to other minor fluctuations. Thirdly, I analysed how the national governments of Germany and the UK contributed to the identified rapid changes by reviewing relevant scholarly literature and governmental policy documents. Lastly, I conducted a comparative assessment of these countries' electricity transitions, focusing particularly on the role of policies in facilitating them.

In this chapter, IEA's historical data (2022) was supplemented by the recent national transition targets of these countries towards 2030. The rate of technological change between 2020 and 2030 was calculated using the same metric to analyse how the recently adopted targets compare to their historical transitions in 1960-2020.

3.3.3 Specific methods for G7 and EU policy impact analysis (Chapter 5)

The central aim of this chapter is to analyse whether recent climate policies have influenced the nature and speed of energy transitions beyond historical trends. This objective emerged as the focal point following observations made during Chapter 4, where I identified great similarities in the speed of technological changes between Germany and the UK despite the great diversity in their policies. It became thus important to scrutinise whether this pace of change has been accelerating, particularly in light of the growing awareness of climate change in the last decades.

To achieve this objective, I expanded the scope of analysis to all the G7 countries and the EU, which have spearheaded the introduction of climate policies in recent decades (Iacobuta et al., 2018; Nascimento et al., 2022b), and have repeatedly committed to lead the global decarbonisation efforts (Kirton et al., 2018; Kokotsis, 1999). To examine the overall difference (or lack thereof) between energy transitions with and without climate policies, I mainly analysed the transitions of these countries as a whole, but I also supplemented this analysis by looking at the transitions in the individual countries. I used the Climate Policy Database (NewClimate Institute et al., 2023) to analyse the adoption of climate policies over time in the G7 and the EU.

To examine the evolving rates of change, I analysed the historical electricity transitions in the G7 and the EU between 1960 and 2020 by segmenting this period into sequential episodes over five years. This choice of five years, in comparison to 10 years in Chapter 4, was made to strike a balance between capturing trends and accounting for the fact found in Chapter 4 that rapid technological changes could take place within shorter timeframes. The typology of energy transitions that I developed in my dissertation (see subsection 3.2.2 and Figure 3.2) was applied in Chapter 5 to trace and compare the systemic developments in the energy sector towards decarbonisation across countries and time-periods. Moreover, I supplemented this historical analysis by using Ember's Yearly Electricity Data for the most recent data available between 2020 and 2022 (Ember, 2023) to examine the latest developments in these countries.

Furthermore, I compared this historical analysis from 1960 to 2022 with climate target requirements to elucidate the level of acceleration necessary in the future. This analysis applied the conceptualisation of "empirically grounded speed zones" described in subsection 3.2.3, encompassing the following steps. First, I calculated the required rates of low-carbon substitutions (find the definition of 'low-carbon substitutions' in subsection 3.2.2) in the G7 and the EU between 2020 and 2035 to achieve their "fully or predominantly decarbonised electricity" target by 2035 (G7, 2022), thereby keeping the global temperature increase below 1.5°C (i.e. this would be the star target rate as depicted in Figure 3.3). For this task, I used the specific pathway outlined in IEA's "Achieving Net Zero Electricity Sectors in G7 Members" (IEA, 2021a). I chose this pathway because the G7 and the EU requested the IEA to develop this report in 2021 and subsequently adopted the advised target in 2022, making this pathway highly relevant for their future transitions (IEA, 2021a).

Secondly, these required rates were compared to the density of relevant historical observations. To construct a dataset of such historical cases, I first identified all national five-year episodes of low-carbon substitutions worldwide in 1960–2020. I then calculated the transition speed as the annual total change rates as follows:

$$ACR_{Transition\_speed} = G_{low\_carbon} + \left|D_{fossil\_fuels}\right|$$

where $ACR_{Transition\_speed}$ (%) is a positive value aggregating the total growth rate of low-carbon electricity (G_{low_carbon}) and the absolute total decline rate of fossil fuel-based electricity (D_{fossil_fuels}). From this dataset, I selected the episodes with the highest values while ensuring that there was no overlap or double-counting of years. Table 3.2 shows the example of this approach, choosing four episodes with the highest values in France, namely a 14.3% annual change rate in 1979–1984, followed by 7.0% in 1984–1989, 4.3% in 1989–1994, and 1.3% in 2009–2014.

Table 3.2: Selection method of highest low-carbon transition episodes, France as an example.

Country	Year		Episode	Total avg. generation (TWh)	Generation change (TWh)		Annual change rate			
	Start	End			Low-carbon	Fossil fuels	Low-carbon	Fossil fuels	Transition speed	
France	**1979**	**1984**	**FR79-84**	**280.7**	**140.4**	**-61.5**	**10.0%**	**-4.4%**	**14.4%**	**Highest**
	1980	1985	FR80-85	299.9	148.5	-64.3	9.9%	-4.3%	14.2%	overlap
	1981	1986	FR81-86	315.2	150.4	-61.1	9.5%	-3.9%	13.4%	
	1978	1983	FR78-83	262.3	117.0	-43.9	8.9%	-3.3%	12.3%	
	1982	1987	FR82-87	329.5	144.8	-52.2	8.8%	-3.2%	12.0%	
	1977	1982	FR77-82	248.7	104.6	-35.6	8.4%	-2.9%	11.3%	
	1983	1988	FR83-88	344.4	129.8	-38.5	7.5%	-2.2%	9.8%	
	1976	1981	FR76-81	235.5	83.7	-13.8	7.1%	-1.2%	8.3%	
	1984	**1989**	**FR84-89**	**361.9**	**105.2**	**-21.7**	**5.8%**	**-1.2%**	**7.0%**	**2nd Highest**
	1975	1980	FR75-80	225.2	67.1	-1.9	6.0%	-0.2%	6.1%	overlap
	1985	1990	FR85-90	383.0	83.5	-1.4	4.4%	-0.1%	4.4%	
	1989	**1994**	**FR89-94**	**441.1**	**84.6**	**-9.8**	**3.8%**	**-0.4%**	**4.3%**	**3rd Highest**
	1990	1995	FR90-95	457.9	82.2	-14.7	3.6%	-0.6%	4.2%	overlap
	1988	1993	FR88-93	429.1	81.2	-3.2	3.8%	-0.1%	3.9%	
	1991	1996	FR91-96	471.7	70.0	-12.5	3.0%	-0.5%	3.5%	
	1992	1997	FR92-97	483.1	48.3	-2.9	2.0%	-0.1%	2.1%	
	2009	**2014**	**FR09-14**	**563.8**	**27.8**	**-9.9**	**1.0%**	**-0.3%**	**1.3%**	**4th Highest**
	2010	2015	FR10-15	560.7	22.5	-10.1	0.8%	-0.4%	1.2%	overlap
	2008	2013	FR08-13	562.7	22.0	-6.1	0.8%	-0.2%	1.0%	
	2007	2012	FR07-12	569.3	3.6	-0.1	0.1%	-0.004%	0.1%	

Notes: Data from IEA (2022), calculated by the metric described in subsections 3.3.1 and 3.3.3.

Subsequently, I further refined the selection from the compiled dataset of national low-carbon substitution episodes by focusing on those with an average total electricity generation exceeding 100 TWh. I set this threshold because systems smaller than this threshold tend to exhibit more rapid growth of renewables (Cherp et al., 2021) and decline of fossil fuels (Vinichenko et al., 2021), which I considered less relevant to future transitions in the G7 countries and the EU. This is because the total electricity generation of the G7 and the EU was, on average, ca. 100 TWh per country in 2021, including smaller EU countries who are 'non-enumerated' members, although the average among the main member states (Canada, France, Germany, Italy, Japan, UK, and United States (US)) was ca. 1100 TWh. Thus, I adopted an optimistic rather than conservative approach, considering that all episodes above this 100 TWh threshold have direct relevance to all the G7 countries and the EU. This resulted in a final selection of 19 countries and their 56 episodes (Table 3.3).

Finally, I performed kernel density estimation with the final selection of the dataset, using R's package ggdensity (Otto and Kahle, 2022) to delineate speed zones as depicted in Figure 3.3. Each zone was defined to encompass 50%, 75%, and 95% of these historical episodes, with the remaining 5% representing historically the fastest national low-carbon substitution episodes.

Table 3.3: Low-carbon episodes used to delineate speed zones of low-carbon substitutions.

Note: The top G7+EU required transition was not used to delineate the zones but is shown here as a reference. Data from IEA (2022), calculated by the metric described in subsections 3.3.1 and 3.3.3.

Period	Country	Year		Episode	Total average generation (TWh)	Generation change (TWh)		Annual change rate		
		Start	End			Low-carbon	Fossil fuels	Low-carbon	Fossil fuels	Transition speed
Required	G7+EU	2020	2035	G7_20-35	10893.6	8264.8	-4410.0	5.1%	-2.7%	7.7%
Historical	France	1979	1984	FR79-84	280.7	140.4	-61.5	10.0%	-4.4%	14.4%
	Spain	1982	1987	ES82-87	123.0	38.1	-17.9	6.2%	-2.9%	9.1%
	United Kingdom	2011	2016	GB11-16	352.4	58.0	-90.7	3.3%	-5.1%	8.4%
	Ukraine	1991	1996	UA91-96	230.6	0.9	-92.6	0.1%	-8.0%	8.1%
	Sweden	1979	1984	SE79-84	108.8	35.9	-7.8	6.6%	-1.4%	8.0%
	Italy	2008	2013	IT08-13	295.6	49.9	-65.5	3.4%	-4.4%	7.8%
	France	1984	1989	FR84-89	361.9	105.2	-21.7	5.8%	-1.2%	7.0%
	Brazil	1979	1984	BR79-84	152.4	52.4	-0.2	6.9%	0.0%	6.9%
	Spain	2008	2013	ES08-13	292.5	40.9	-59.0	2.8%	-4.0%	6.8%
	Japan	2015	2020	JP15-20	1038.9	103.8	-153.9	2.0%	-3.0%	5.0%
	Venezuela	2002	2007	VE02-07	103.0	23.7	-0.3	4.6%	-0.1%	4.7%
	France	1989	1994	FR89-94	441.1	84.6	-9.8	3.8%	-0.4%	4.3%
	Germany	2015	2020	DE15-20	611.2	39.5	-89.9	1.3%	-2.9%	4.2%
	Netherlands	2015	2020	NL15-20	115.9	18.5	-6.0	3.2%	-1.0%	4.2%
	Brazil	2014	2019	BR14-19	598.3	77.3	-41.9	2.6%	-1.4%	4.0%
	Brazil	1987	1992	BR87-92	224.7	38.3	-2.4	3.4%	-0.2%	3.6%
	Japan	1978	1983	JP78-83	584.8	78.2	-23.5	2.7%	-0.8%	3.5%
	Germany	1980	1985	DE80-85	491.2	66.1	-18.1	2.7%	-0.7%	3.4%
	Norway	2010	2015	NO10-15	135.4	18.9	-1.6	2.8%	-0.2%	3.0%
	Ukraine	2015	2020	UA15-20	159.6	2.6	-21.1	0.3%	-2.6%	3.0%
	Norway	1986	1991	NO86-91	108.7	15.6	-0.3	2.9%	0.0%	2.9%
	United Kingdom	1979	1984	GB79-84	286.6	17.6	-23.8	1.2%	-1.7%	2.9%
	Australia	2015	2020	AU15-20	258.1	25.0	-12.1	1.9%	-0.9%	2.9%
	Thailand	2014	2019	TH14-19	178.7	17.2	-6.3	1.9%	-0.7%	2.6%
	Sweden	2010	2015	SE10-15	151.1	15.1	-3.0	2.0%	-0.4%	2.4%

Period	Country	Year		Episode	Total average generation (TWh)	Generation change (TWh)		Annual change rate		
		Start	End			Low-carbon	Fossil fuels	Low-carbon	Fossil fuels	Transition speed
	United Kingdom	2006	2011	GB06-11	381.3	9.8	-35.0	0.5%	-1.8%	2.4%
	Sweden	1995	2000	SE95-00	148.9	13.5	-3.5	1.8%	-0.5%	2.3%
	Australia	2009	2014	AU09-14	248.6	14.1	-12.7	1.1%	-1.0%	2.2%
	Canada	1989	1994	CA89-94	522.5	54.7	-1.2	2.1%	0.0%	2.1%
	Netherlands	2009	2014	NL09-14	109.3	1.5	-9.9	0.3%	-1.8%	2.1%
	Canada	2002	2007	CA02-07	608.6	46.9	-16.8	1.5%	-0.6%	2.1%
	United States	2015	2020	US15-20	4312.7	226.5	-212.5	1.1%	-1.0%	2.0%
	United Kingdom	1989	1994	GB89-94	319.4	23.2	-9.2	1.5%	-0.6%	2.0%
	Poland	2006	2011	PL06-11	159.4	9.1	-6.8	1.1%	-0.9%	2.0%
	Canada	2011	2016	CA11-16	642.5	51.0	-11.4	1.6%	-0.4%	1.9%
	Spain	2015	2020	ES15-20	271.0	9.4	-16.8	0.7%	-1.2%	1.9%
	Sweden	1985	1990	SE85-90	139.0	13.0	-0.4	1.9%	-0.1%	1.9%
	Ukraine	1996	2001	UA96-01	178.7	2.2	-14.4	0.2%	-1.6%	1.9%
	South Africa	2015	2020	ZA15-20	244.6	7.2	-15.2	0.6%	-1.2%	1.8%
	Poland	2011	2016	PL11-16	163.7	9.6	-3.4	1.2%	-0.4%	1.6%
	Argentina	2015	2020	AR15-20	143.8	6.0	-4.9	0.8%	-0.7%	1.5%
	Germany	2010	2015	DE10-15	622.3	35.3	-7.2	1.1%	-0.2%	1.4%
	France	2009	2014	FR09-14	563.8	27.8	-9.9	1.0%	-0.3%	1.3%
	United States	2007	2012	US07-12	4304.4	129.8	-148.9	0.6%	-0.7%	1.3%
	Russia	2015	2020	RU15-20	1096.8	59.2	-10.2	1.1%	-0.2%	1.3%
	Sweden	2015	2020	SE15-20	162.0	9.8	0.0	1.2%	0.0%	1.2%
	South Africa	2010	2015	ZA10-15	251.4	4.3	-10.1	0.3%	-0.8%	1.1%
	Russia	1994	1999	RU94-99	872.9	0.2	-47.4	0.0%	-1.1%	1.1%
	Germany	2004	2009	DE04-09	614.4	18.7	-12.3	0.6%	-0.4%	1.0%
	Germany	1990	1995	DE90-95	541.6	7.2	-17.9	0.3%	-0.7%	0.9%
	Sweden	2003	2008	SE03-08	144.8	3.5	-3.0	0.5%	-0.4%	0.9%
	Poland	1989	1994	PL89-94	137.0	0.1	-5.9	0.0%	-0.9%	0.9%
	Russia	1984	1989	RU84-89	1493.9	40.9	-22.5	0.5%	-0.3%	0.8%
	Norway	2015	2020	NO15-20	146.1	5.1	-1.0	0.7%	-0.1%	0.8%
	Ukraine	2004	2009	UA04-09	183.9	2.9	-0.6	0.3%	-0.1%	0.4%
	Italy	2015	2020	IT15-20	283.8	3.3	-0.7	0.2%	0.0%	0.3%

3.3.4 Specific methods for G7 policy evolution analysis (Chapter 6)

The main objective of Chapter 6 is to examine whether and how the overall stringency of energy transition policies to mitigate climate change—as cumulative outcomes of factors related to policy acceleration and deceleration towards decarbonisation reviewed in Sections 2.2 and 2.3 —has evolved over the last decades.

However, systematically assessing the stringency of policies and comparing it across countries and time-periods is considered extremely challenging due to the high level of granular analysis required, even to examine the stringency of a single policy (Knill et al., 2012; Schaub et al., 2022). Applying such an approach to analyse all policies adopted in the G7 countries over the last decades would thus be virtually impossible.

To address this challenge, I aimed to identify and analyse the evolution of national transition projections developed or commissioned by national governments in recent decades. These projections are also commonly referred to as ‘reference’, ‘predictive’ or ‘forecast’ scenarios. They can serve as a proxy to understand how the overall stringency of energy transition policies has evolved because they reflect the anticipated cumulative impacts of existing and planned policies, judged by country experts at the time of projection development. Consequently, other ‘exploratory’ or ‘normative’ scenarios are not considered in this analysis as they include policies not implemented or planned.[4] Such an approach, using projections to evaluate overall progress in policies towards decarbonisation, has been employed by Nascimento et al. (2022a) in the context of GHG emissions reductions. To the best of my knowledge, this dissertation is the first attempt to apply this method in the context of energy transitions.

[4] Sometimes, a projection including planned policies is categorised instead as an ‘exploratory’ scenario in the G7 countries. In this case, I selected a scenario that best reflects the existing and planned policies at the time of projection/scenario development to ensure analytical coherence. See Table 6.1 for the national projections used in this analysis and subsection 6.2 for the justification of their selection.

Moreover, analysing the evolution of energy transition projections can shed light on the changing political motivation and capacity for accelerating energy transitions. The U.S. Energy Information Administration (EIA), the country's responsible authority for energy transition projections, explains the purpose of the projection development as "it gives decision-makers an opportunity to peer into a future without new policy. **If the projected outcomes are undesirable from their viewpoint, they can effect change**" (EIA, 2023, p. 1, bolded by the author). By comparing the changes in subsequent projections, therefore, one can discern whether policymakers acted in changing policies to alter the direction and speed of energy transitions.

To compare the evolving stringency of national policies to climate target requirements, I follow a similar method used for Chapter 5, which is described in subsection 3.3.3. However, the required energy mix data in 2035 specified by the IEA (IEA, 2021a) is only available for the G7 countries and the EU as a whole. I, therefore, calculated the required energy mix for the individual G7 countries based on the assumption that the same level of demand growth and the same share of energy mix (i.e. 'predominantly low-carbon') would be achieved by 2035 across these countries. Consequently, the nations with a lower share of low-carbon electricity (or higher share of fossil-based electricity) today would need to achieve a faster rate of change towards 2035.

The limitation of using national transition projections as proxies for political acceleration in energy transitions stems from the fact that it involves not only policies evolving over time affecting projections, but also various changing assumptions on macro-economic and technological trends (Nascimento et al., 2022a). These include economic growth, energy demand, resource prices, expected technological innovation without policies, behavioural changes, etc. While policies are introduced to manipulate these factors, robust causal analysis is required to extract the exact extent of manipulation and identify its material impacts. However, such analysis is beyond the scope of this chapter.

3.4 Summary

This chapter described the rationale behind selecting ontological and epistemological assumptions rooted in critical realism, forming the foundation for investigating the political acceleration of energy transitions in this dissertation. Energy transitions are accordingly conceptualised as the cumulative outcome of evolving structures and mechanisms. The primary aim of this dissertation is to elucidate whether and to which extent energy transitions are politically accelerated, with a specific focus on examining if such acceleration is more pronounced in recent decades with climate policies. Additionally, this dissertation aims to compare these historical observations with future requirements for mitigating climate change.

To fulfil these research aims, I developed a ‘middle-range’ methodology as summarised in Table 3.4, distinguishing it from the existing approaches in the literature, which are either too broad or too narrow to analyse political acceleration in energy transitions at the national level (subsection 2.4.1). To enable comparing energy transitions across countries and time-periods, which are significantly lacking in the literature (Grubler et al., 2016; Sorrell, 2018), I also formulated a typology of energy transitions based on the changes and their interplays in fossil fuels and low-carbon technologies (subsection 3.2.2). Further, by extending the existing methods, I also developed an approach to assess the necessary level of acceleration in decarbonising the energy system in the future in comparison to relevant historical observations (subsection 3.2.3).

This chapter also outlined the detailed methods applied across the three empirical chapters (subsection 3.3.1), along with supplementary methods tailored to each chapter's distinct research focus and objectives (subsections 3.3.2, 3.3.3, 3.3.4).

Using the conceptual frameworks and methods outlined in this chapter, the next chapters (Chapters 4, 5, 6) present the results responding to the three research questions of this dissertation: (1) What is the empirical role of the state and the impact of national policies in accelerating long-term energy transitions?; (2) Have climate policies altered energy transitions beyond historical trends, and if so, how in light of climate target requirements?; and (3) How has the stringency of national policies changed over the last decades, and how does this evolution compare to historical and required transitions?

Table 3.4: This dissertation's approach, in contrast to the two major methodologies

Object of analysis		Global energy transitions	National energy transitions (this dissertation)	Specific socio-technical changes
Scope		Broad	Middle-range	Narrow
Focus of analysis	Geography	Global or aggregated groups (e.g. OECD)	National (large economies)	National or sub-national (incl. small economies)
	Sectoral coverage	Economy-wide	Individual sector	Individual technologies
	Time horizon	Long-term (multi-decades to centuries)	Medium-term (more than six decades)	Short-term (typically since 1990 or after)
Perspectives		Techno-economic (outcomes in energy demand, technology diffusion rates)	Techno-economic, socio-technical, and political	Socio-technical and political (changes in actors, technology choices, and policies)
Methods		Largely quantitative	Mixed methods	Largely qualitative

4. Historical and planned transitions in Germany and the UK

4.1 Introduction

This chapter investigates historical and planned state interventions and their outcomes in electricity transitions in Germany and the UK from 1960 to 2030, with additional consideration of further plans towards 2050 where appropriate. The analysis begins by examining each country separately; Section 4.2 focuses on Germany, and Section 4.3 on the UK. This approach aims to systematically identify notable technological changes over time and examines the sequence of state interventions contributing to these changes. Section 4.4 comparatively analyses the similarities and differences between the two countries, followed by Section 4.5 further examining how diverse state approaches resulted in the speed of energy transitions. Finally, Section 4.6 provides a summary of the chapter.

4.2 Electricity transitions in Germany

The electricity supply in Germany had increased by six-fold from ca. 100 TWh in 1960 to ca. 600 TWh in the mid-2000s and has since stagnated at the same level (Figure 4.1). Until the early 1970s, the rapidly growing demand for electricity was predominantly met by domestic coal. Subsequently, there was an increasing contribution of nuclear power, which sustained the growing demand until the late 2000s when modern renewables began to experience substantial growth. While the growth of renewables has primarily replaced nuclear power to date, it is anticipated that its continuous expansion will replace the majority, if not all, of coal by 2030.

It is also noteworthy that the share of imported coal has progressively increased since the early 1990s, supplying around 50% of coal power in the 2010s. Additionally, Germany became a net electricity exporter around the mid-2000s.

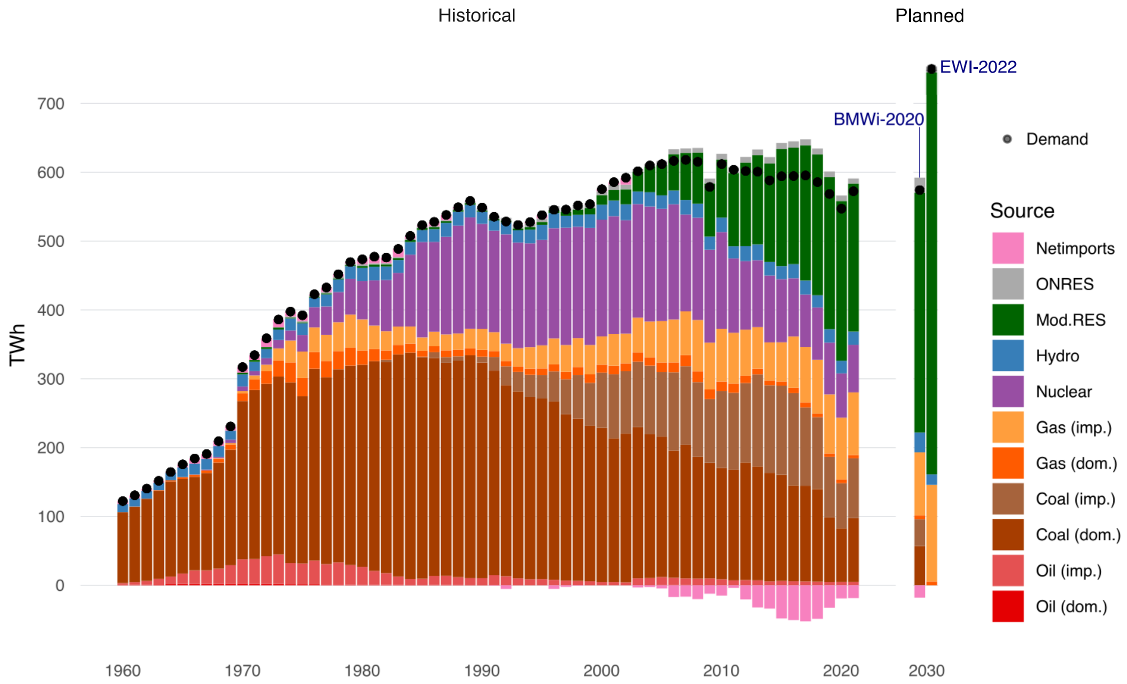


Figure 4.1: Historical and planned electricity supply in Germany in 1960-2030.

Notes: Historical data for 1960-2021 are from IEA (2022). There are two recent transition projections for 2030: "BMWi-2020" is an analysis commissioned by the federal government to Kemmler et al. (2020) to assess the impact of the country's Climate Protection Programme 2030. Subsequently, Germany's climate targets have been strengthened, particularly after the formation of the new coalition government in 2021 and its responses to the Russo-Ukrainian War in 2022 (Sprenger and Schäfer, 2022). This latest projection analysis, however, signals a lack of political instruments to achieve the targets, particularly in regard to targeted acceleration in developing renewables. In the legend, "imp." stands for "imported", while "dom." refers to "domestic".

There are several notable episodes of technological growth and decline in Germany from 1960 to 2030 (Table 4.1), particularly in regard to coal, nuclear power, and modern renewables, which are analysed more closely in the following subsections. Since the use of oil power and hydropower have been negligible in Germany, they are excluded from further analysis.

Table 4.1: Technological change rates in Germany in 1960-2030, divided into decadal episodes

Source	Annual change rate (%)						
	Historical						Planned
	1960-1970	1970-1980	1980-1990	1990-2000	2000-2010	2010-2020	2020-2030
Coal	5.0	2.1	0.6	-0.3	-0.5	-1.7	-1.9
Gas	0.7	1.3	-0.5	0.3	0.5	0.1	0.4
Nuclear	0.3	1.4	1.9	0.3	-0.7	-1.0	-1.1
Mod.RES	0.1	0.0	0.0	0.2	1.3	2.2	3.9

Notes: Data under "Planned 2020-2030" show the average of the two projections displayed in Figure 4.1, considering the feasibility concerns raised in the new projection.

4.2.1 Coal

In the 1960s to 1980s, coal power continuously grew to supply, at its peak in 1984, ca. 330 TWh (65% of the total electricity supply). The state strongly supported this rapid expansion of coal power to support the domestic coal industry, which became increasingly uncompetitive against international coal after the European coal crisis in 1958 (Oei et al., 2019). The main measures were to forcefully consolidate the particularly uncompetitive domestic hard coal mining companies into Ruhrkohle AG (current RAG AG) in 1969 and provided subsidies—most notably through the Kohlepfennig ('coal penny') scheme—to secure the consumption of domestic coal (Storchmann, 2005).

In the 1990s, coal power became increasingly import-dependent as the 'coal penny' was abolished in 1995 following a ruling by the German Federal Court declaring it unconstitutional. Consequently, domestic hard coal production sharply declined (Storchmann, 2005). In contrast, lignite remained competitive, although its production underwent a one-time sharp decline in the early 1990s due to the closure of many inefficient mines and power plants in East Germany after the German reunification in 1990 (Herpich et al., 2018).

In the 2000s, the state continued its intervention in multiple ways to sustain the use of coal power. Foremost, the nuclear phase-out policy in 2002 made coal power the only viable base-load electricity source in the country. Additionally, the state ensured the competitiveness of coal power through tax exemptions on coal and the introduction of taxes on other fossil fuels (Cherp et al., 2017). Furthermore, the grandfathering scheme of the emission trading system (ETS) generated windfall profits for coal generators, with which one of the country's largest investments in new coal power was made in the late 2000s (Pahle, 2010). It is estimated that by the end of the 2000s, the total subsidies provided to the coal industry amounted to more than 350 billion Euro (in 2008 euro price) (Meyer et al., 2010).

In the 2010s, state policy in Germany faced turbulence, notably influenced by the aftermath of the Fukushima nuclear accident in 2011. The Energy Concept, adopted a year prior to the accident, initially signalled a clear transition towards predominantly renewable-based electricity in the long term, with nuclear power serving as a bridging source (Bundesregierung, 2010). However, the state's decision to accelerate the phase-out of nuclear power post-Fukushima resulted in a resurgence of coal power, witnessing the construction of 10 GW of new capacity in the mid-2010s (Cherp et al., 2017). Further investment in coal power became more favourable than natural gas, as the growing output of renewables reduced electricity prices, diminishing the profitability of natural gas as a source for peak-load electricity (Lauber and Jacobsson, 2015). Nonetheless, the state reiterated in its Climate Protection Plan that coal power would gradually phase out (BMUB, 2016). Under the policy, the multi-stakeholder coal exit commission was established to discuss the timeline as well as the corresponding compensation scheme and proposed in 2019 the year 2038 as the latest deadline (BMWi, 2019).

In 2020, the state officially approved and legislated the proposed coal phase-out deadline of 2038, accompanied by a compensation plan allocating 40 billion euros to support 'just transitions' in affected communities and companies (German Federal Government, 2020). This timeline may be revised to 2035 or even as early as 2030, as the current coalition government formed in 2021 aims to ideally phase out coal by 2030 to accelerate emission reduction efforts (BMWK, 2022a).

4.2.2 Natural gas

In the 1970s, Germany made significant investments in international gas pipelines to transport natural gas from Western Siberian fields in the Union of Soviet Socialist Republics (USSR) with the main aim of generating electricity and using the resource for industrial as well as heating purposes (Jonathan, 2005).

In the 1980s, however, the use of gas in electricity generation declined in Germany as nuclear power began to develop rapidly. Additionally, the European Commission passed a regulation to restrict gas consumption in electricity generation, which was in force from 1975 until 1991(European Commission, 1975).

In the 1990s and 2000s, following the lifting of EU regulations, the introduction of a series of liberalisation policies as well as advancements in Combined Cycle Gas Turbine (CCGT) technologies made gas power a popular investment throughout Europe, including Germany (Pahle, 2010). However, this growth did not continue in the 2010s, and gas power remained under 15% of the share of electricity due to a more favourable economic environment for coal power during the decade (Lauber and Jacobsson, 2015) (see also Figure 4.1).

In the 2020s, according to the most recent transition projections in Germany, gas power is anticipated to serve as a 'bridge source', replacing coal and supplying electricity until modern renewables become the predominant source for electricity generation (Kemmler et al., 2020; Sprenger and Schäfer, 2022) (Figure 4.1). Following the energy crisis triggered by the Russo-Ukrainian War in 2022, the perception of natural gas as a bridging source was further intensified. As a consequence, the state made significant investments in securing gas supply, including the development of liquefied natural gas terminals with a number of supply contracts spanning multiple decades (Brower et al., 2023).

4.2.3 Nuclear power

Between the mid-1950s and the 1970s, nuclear power, as expected to become the second pillar of energy supply, gained increasing political support in Germany (Renn and Marshall, 2016). By the end of the 1960s, the German nuclear industry had already grown competency in the international market, and Siemens—which constructed almost all nuclear reactors in

Germany—also received two international orders from the Netherlands and Argentina (IAEA, 2022). After the oil crisis in 1973, the deployment of nuclear power was further accelerated (Jacobsson and Lauber, 2006a), which rapidly grew to supply ca. 160 TWh (30% share) in 1989.

Already in the early 1980s, however, the appetite for the further expansion of nuclear power significantly declined primarily due to the anticipated stagnation of electricity demand in the 1990s (Hake et al., 2015). At the same time, the future role of nuclear power became increasingly contested as the political representation of the Greens increased in the federal parliament. Additionally, the Social Democratic Party (SPD) turned against nuclear power following the Chernobyl Disaster in 1986 (Cherp et al., 2017). Furthermore, by the end of the 1980s, the state abandoned the pursuit of establishing a closed nuclear fuel cycle and subsequently divested from associated activities including fuel reprocessing, thereby diminishing the role of nuclear power as a domestic source of energy in Germany (IAEA, 2022).

In the 2000s, with the two anti-nuclear parties assuming political leadership, a nuclear phase-out law was enacted in 2002. This law prohibited the construction of new nuclear power plants and mandated the premature retirement of existing ones at an average age of 32 years (Renn and Marshall, 2016).

In the 2010s, the conservative government took back the political power and extended the phase-out timeline to 2036, allowing the prolonged use of existing nuclear power plants with multiple objectives to: (1) let utilities exploit the assets; (2) raise public revenues through nuclear fuel tax; and (3) secure enough time for developing modern renewables to replace both coal and nuclear power (Renn and Marshall, 2016). However, within a year after the Fukushima nuclear accident, the timeline was reversed back to 2022.

In 2022, after the Russo-Ukrainian War, followed by the subsequent shortage of natural gas to generate electricity, the timeline was moderately adjusted to allow three remaining plants to operate until April 2023 (BASE, 2022).

4.2.4 Modern renewables

The development of modern renewables in Germany has two important aspects: (1) these new technologies were originally developed as part of the country's industrial policy, and (2) their deployment led to a shift in the market structure, with an increasing number of citizens participating as prosumers.

The state's investment in modern renewables as a form of research and development (R&D) funding dates back to the 1970s as a response to the oil crisis in 1973 and the increasing social opposition against nuclear power (Jacobsson and Lauber, 2006a). Initially intended to develop these technologies for export to the international market (Schulz, 2000), however, these they were not deployed within Germany in the 1970s-1980s.

Since the end of the 1980s, on the other hand, modern renewables have increasingly been considered a viable substitute for nuclear power in Germany, particularly in the aftermath of the Chernobyl disaster in 1986 (Jacobsson and Lauber, 2006a). National deployment targets were established for wind (initially set at 100MW, later expanded to 250MW) and solar power (1,000 roofs) in 1989. Alongside the introduction of the Feed-in Law with a fixed feed-in tariff (FiT) in 1991, wind power became an attractive investment (solar power was not as yet), leading to its expansion in the 1990s (Bergek et al., 2008; Jacobsson and Lauber, 2006a). As the 100MW/250MW program was designed to protect domestic wind turbine manufacturers from foreign competitors, a significant portion of this early growth of wind power was supplied by domestic companies such as Siemens and Enercon. These companies soon became global market leaders by the end of the 1990s, forming a strong alliance to promote further development of modern renewables in the country (Cherp et al., 2017).

In the 2000s, the previously relatively limited support for solar power was strengthened by the red-green coalition government through the introduction of the 100,000 Roofs Program and the reinforcement of the FiT scheme and rates. The revised FiT rate was so generous that it led to the explosive growth of solar power which was even more dramatic than wind (Jacobsson and Lauber, 2006b).

The rapid deployment of modern renewables in Germany since the 1990s led to a significant shift in the market structure, with more than 40% of modern renewable projects being developed and owned by citizens, farmers, and collective communities (Baker et al., 2021). These decentralised initiatives accounted for around half of the electricity produced from renewables, constituting ca. 20% of the total electricity supply in the early 2010s (Sutton, 2021). However, as the FiT scheme transitioned into an auctioning system, mega-developers, including conventional utility companies, began increasing their share of renewable energy generation in the late 2010s (Baker et al., 2021; Geels et al., 2016b).

The coalition government formed in 2021 put forward the new renewable energy target to produce 80% of electricity from renewable sources by 2030 as a measure to address the Russo-Ukrainian war and the subsequent energy crisis in Europe in 2022 (BMWK, 2022a). Among various sources, wind and solar power are expected to continue dominating the future growth of modern renewables, with targets set at 245 GW of wind power (including 30 GW offshore wind) and 215 GW of solar power by 2030 (Sprenger and Schäfer, 2022). This marks a significant increase from the current capacities of ca. 69 GW and ca. 82 GW at the end of 2023, respectively (The Federal Network Agency of Germany, 2024).

4.3 Electricity transitions in the UK

The electricity supply in the UK increased from ca. 140 TWh in 1960 to ca. 400 TWh in the mid-2000s, then experienced a decline to ca. 330 TWh in 2021. Initially, coal predominantly supplied electricity until it was largely replaced by natural gas in the 1990s and further substituted by renewables in the 2010s. Nuclear power, at its peak in the 1990s, supplied one-third of electricity but gradually declined afterwards. The UK became a net electricity importer in the late 1980s and expects to maintain this dependence towards 2030, with plans to reduce reliance on gas power and further expand renewables (BEIS, 2022).

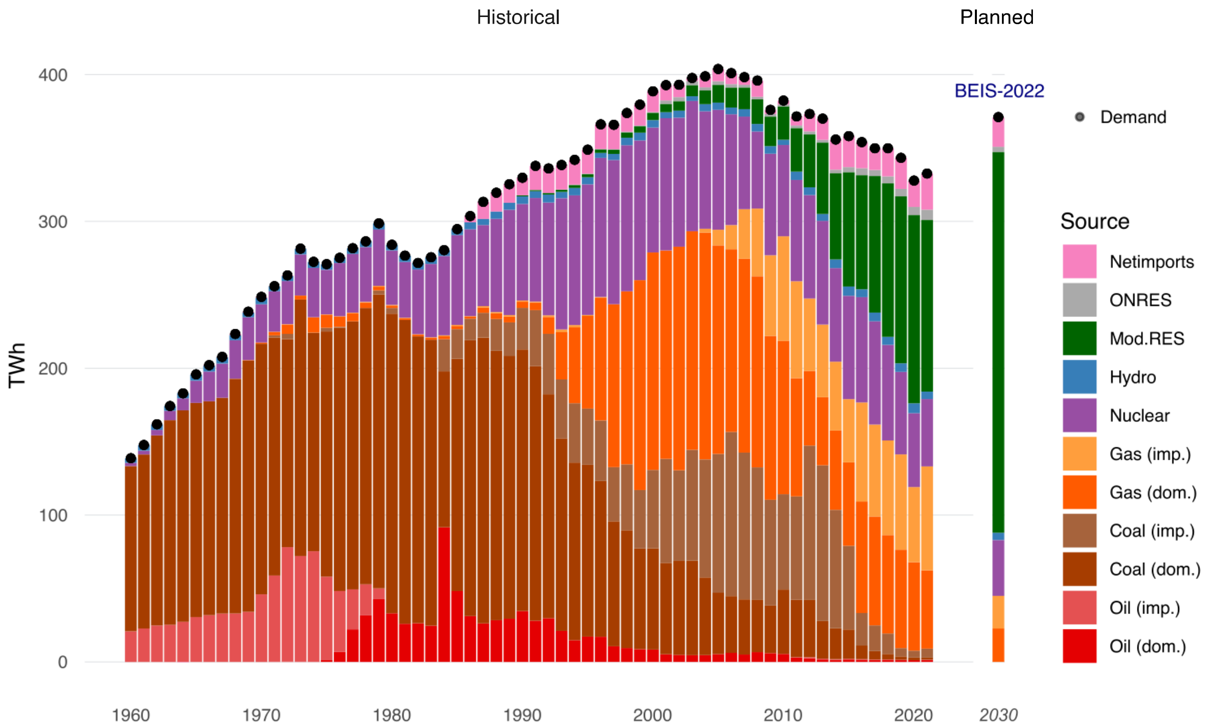


Figure 4.2: Historical and planned electricity supply in the UK in 1960-2030.

Note: Historical data for 1960-2021 are sourced from IEA (2022). The electricity mix in 2030 displays the official projection of the government published in 2022 based on existing and planned policies (BEIS, 2022). In the legend, "imp." stands for "imported", while "dom." refers to "domestic".

There are several notable episodes of technological growth and decline in the UK in 1960-2030 (Table 4.2), particularly in regard to oil, coal, gas, nuclear power, and modern renewables, which are analysed more closely in the following subsections. Same with Germany, since hydropower has been negligible in the UK, it is excluded from further analysis.

Table 4.2: Technological change rates in the UK in 1960-2030, divided into decadal episodes

Source	Annual change rate (%)						
	Historical						Planned
	1960-1970	1970-1980	1980-1990	1990-2000	2000-2010	2010-2020	2020-2030
Oil	1.3	-0.4	-0.2	-0.7	-0.1	-0.1	0.0
Coal	2.7	1.4	0.0	-2.5	-0.4	-2.9	-0.2
Gas	0.1	0.0	0.1	4.0	0.5	-1.2	-2.3
Nuclear	1.3	0.4	1.0	0.6	-0.6	-0.5	-0.4
Mod.RES	0.0	0.0	0.0	0.1	0.5	2.8	4.2

4.3.1 Oil

Unlike in Germany where oil power remained negligible, in the UK it grew to supply ca. 80 TWh (28% share) at its peak in 1974. This growth was led by the state, which pursued a ‘four-fuel economy’ in the 1960s, removing protective measures for coal with the aim of diversifying the energy mix (Turnheim and Geels, 2012). Despite the oil crises in the 1970s, the use of oil for electricity generation did not decrease, mainly due to the increasing availability of domestic oil following the discovery in the North Sea. However, oil power gradually declined to negligible levels towards the end of the 1990s as it was replaced by gas, which also became increasingly available.

4.3.2 Coal

In the 1960s and 1970s, similar to Germany, coal power in the UK experienced continuous growth, supplying ca. 210 TWh at its peak in 1981, accounting for 75% of the total electricity supply. Additionally, like Germany, the state supported the domestic coal industry by mandating utilities to purchase domestic coal for electricity generation. This support aimed to minimise the socio-economic impacts of the ‘controlled rundown’ of the domestic mining industry, initiated after the European coal crisis in 1958 (Turnheim and Geels, 2012).

In the 1980s, state support for coal power sharply declined, particularly after the Thatcher government came into power in 1979. The UK exclusively mined hard coal, which faced increasing international competition, especially after the oil crises in the 1970s. The government viewed the powerful labour union representing the domestic coal sector as a hindrance to progress, labelling the regime a 'sick' industry (Turnheim, 2012). The Central Electricity Generating Board (CEGB), the public institution responsible for electricity generation and transmission, began to strongly oppose the mandatory use of uncompetitive domestic coal. These tensions led to a major strike by coal miners in 1984 and 1985, which was heavily politicised and ultimately crushed by the government. Subsequently, the government closed several mines, removed subsidies, and deregulated the industry, further diminishing its support for the domestic coal sector (Turnheim and Geels, 2012).

In the 1990s, the state implemented a series of privatisation and liberalisation policies to 'modernise' the energy sector by increasingly relying on market forces to decide the fate of energy technologies including coal (Bolton, 2022). As a result, the 'dash for gas' and the 'rush from coal' (Bocse and Gegenbauer, 2017; Parker, 1994; Spooner, 1995) took place where more than 100 gas reactors with a cumulative capacity of 13 GW were built, in contrast to the two small additional coal reactors with a 40 MW capacity built in the 1990s (Platts, 2022). Consequently, as old coal power plants retired, coal power production rapidly declined by half, dropping from ca. 200 TWh in 1990 to ca. 100 TWh in 1999.

In the 2000s, the UK government grew increasingly concerned about the looming energy security challenges stemming from declining domestic oil and gas production (Pearson and Watson, 2012). Simultaneously, worries about the lack of progress towards meeting climate targets intensified. Although coal power was no longer a domestic energy source, it was once again recognised as an affordable and abundant—and thus important—energy source for ensuring energy security. However, its sustained use was contingent upon the availability of

Carbon Capture and Storage (CCS) technologies, prompting the state to support their development progressively (Turnheim, 2012).

Despite investing a total of £168 million, the UK failed to develop CCS technologies and largely abandoned their use for fossil fuel generation in 2015—the same year the government decided to phase out coal power by 2025 (The House of Commons of the United Kingdom, 2017). Throughout the 2000s, coal power production stagnated at around 100 TWh. However, with the introduction of a carbon tax in 2013, coal power rapidly declined once again to less than 10 TWh by the late 2010s. In 2017, the UK, in collaboration with Canada, launched the Powering Past Coal Alliance (PPCA), an international initiative comprising countries, states, cities, and corporations committed to ending the use of unabated coal power (PPCA, 2023).

4.3.3 Natural gas

Similarly to Germany, gas was not widely used for power generation in the UK until the end of the 1980s. However, in the 1990s, gas power underwent considerable growth, resulting in a substantial substitution of coal power. This significant shift in power generation was commonly referred to as the 'dash for gas' and was driven by a combination of factors (Bocse and Gegenbauer, 2017; Parker, 1994; Spooner, 1995), as partially discussed in subsection 4.3.2.

First, domestic oil and natural gas became increasingly available, particularly after the discovery of fossil reserves in the North Sea (Bocse and Gegenbauer, 2017). The privatisation and liberalisation of the electricity sector in the 1990s facilitated new market entry and promoted the diversification of the electricity supply. Although deregulation broke down the CEGB monopoly, the generation market was still largely dominated by its successors, National Power and PowerGen, which inherited the large assets of coal power (Spooner, 1995). In an effort to be independent of this duopoly and encouraged by the regulator whose primary task was to promote competition, new market players sought to develop alternative sources of power (Spooner, 1995). Combined cycle gas turbines (CCGTs) were a particularly attractive option as their capital costs were low, and they could be built relatively quickly. Additionally, the timing was ideal for the growth of gas power, as the EU lifted its ban on the use of gas in electricity generation in 1991, and gas prices were low. National Power and PowerGen, afraid of losing market share, also invested in CCGTs (Parker, 1994). Notably, the ‘dash for gas’ only occurred in England and Wales but not in Scotland, where the vertically integrated structure of the electricity supply was retained (Spooner, 1995).

Already in the early 2000s, however, gas power started to stagnate as domestic production of natural gas began to decline. The government further constrained the use of gas for electricity generation in the 2010s through the introduction of a carbon tax in 2013 and plans to further reduce its role in electricity supply towards 2030 by substituting gas power mainly with renewables (BEIS, 2022).

4.3.4 Nuclear power

In the 1950s, the UK began investing in nuclear power which grew to supply ca. 100 TWh (27% share) at its peak in 1998. This long-term investment was often criticised as “the greatest commercial failure in British history” due to a range of significant technical and financial issues (Collingridge, 1984; Hannah, 1982, p. 285). Nevertheless, the government consistently provided robust support for nuclear power, with the exception of the late 1990s and early 2000s, when the state was temporarily indecisive on the role of nuclear power in the future energy supply (Hannah, 1982; Pearson and Watson, 2012; Taylor, 2007).

In the 2000s and 2010s, the UK’s nuclear power sector experienced a decline, primarily due to the retirement of old reactors and the lack of construction of new plants. However, during this period, the government became increasingly supportive of nuclear power, recognising that "the energy markets alone cannot achieve broader social and environmental objectives" (DTI, 2007, p. 8). Subsequently, a series of supporting measures were implemented over time, including subsidies for new nuclear plant construction, R&D initiatives, particularly for small modular reactors, and the establishment of a governmental institution to facilitate the redevelopment of nuclear power within and beyond the country (Johnstone and Stirling, 2020; The Government of the United Kingdom, 2022)

The UK currently aims to construct 24GW of nuclear power, three times more than the current level, to produce 25% of electricity in 2050 (The Government of the United Kingdom, 2022). According to the official projection published in 2022, nuclear power is expected to supply 11% of electricity in 2030 and 14% of electricity in 2040 (BEIS, 2022).

4.3.5 Modern renewables

Against the backdrop of prevailing market liberalisation policies in the 1980s and the 1990s, state support for modern renewables long remained limited in the UK, favouring the deployment of near-to-market technologies, which only included nuclear power and waste-to-gas generation in the 1990s (Geels et al., 2016b; Mitchell, 1995). As a result, there was almost no expansion of modern renewables such as solar and wind power in the UK in the 1990s.

In the 2000s, as the cost of wind power rapidly declined, the technology increasingly diffused from neighbouring countries such as Denmark, Spain, and Germany into the British market. This was facilitated through the introduction of the Renewable Obligation (RO) policy in 2002. Due to its market-oriented nature favouring large-scale projects and consequently requiring high financial capabilities, conventional utilities, rather than new market actors, predominantly benefited from this policy (Geels et al., 2016b; Wood and Dow, 2011). As local opposition to onshore wind power grew, these actors advocated for more state support towards the development of offshore wind power. Matched also with multiple interests of the government and the Crown Estate, the RO was subsequently revised in 2009 to provide favourable support for offshore wind power development (Kern et al., 2014).

In the 2010s, the UK government continued to provide state support for large-scale renewable projects, such as through the introduction of Contracts for Difference (CfD) in 2014, aimed at facilitating further expansion of wind power, particularly offshore wind. This policy quickly made the UK a global leader in deploying offshore wind technology (Geels et al., 2016b; IEA, 2019). Additionally, with the decreasing cost of solar power during the 2000s, the UK introduced Feed-in Tariffs (FiT) in 2010 to incentivise its deployment. Despite this policy, however, the growth of solar power remained modest compared to wind power throughout the 2010s. To illustrate, wind power experienced rapid growth from 10 TWh to 75 TWh (23% share) in 2020, whereas solar power supplied up to 10 TWh throughout the decade.

In 2022, following the Russo-Ukrainian War and the subsequent energy crisis in Europe, the UK government unveiled the British Energy Security Strategy. This strategy aims to achieve the goal of supplying up to 95% of electricity from low-carbon sources by 2030, with the majority expected to come from modern renewable sources (BEIS, 2022; The Government of the United Kingdom, 2022).

4.4 Comparing Germany and the UK

Table 4.3 summarises the key features of historical and planned technological changes and state interventions in Germany and the UK from 1960 to 2030. It shows that the electricity transitions in these countries were generally similar until the 1980s, with no technological decline, and the state supported various sources to meet the rapidly growing demand for electricity. However, after the 1980s, state actions diverged, with Germany starting to phase out nuclear power and then coal, while the UK started to phase out coal and subsequently natural gas. Moreover, modern renewables started to develop slightly earlier in Germany, involving more actors in their development compared to the UK. The different trajectories of natural gas power largely reflect varying developments in coal, nuclear power and modern renewables, which I will further explain in the following subsections. This section, therefore, primarily focuses on comparing the technological evolutions of coal, nuclear power, and modern renewables with reference to natural gas while examining the similarities and differences in state interventions in the transitions.

Table 4.3: Historical and planned electricity transitions and state interventions in Germany and the UK in 1960-2030.

Notes: The colours indicate the speed of technical changes, with dark blue representing rapid growth (more than 2% growth/year), light blue growth (1-2% growth/year), grey stagnation (less than 1% growth or decline/year), light red decline (1-2% decline/year), and dark red rapid decline (more than 2% decline/year).

		1960-1970	1970-1980	1980-1990	1990-2000	2000-2010	2010-2020	2020-2030
Oil	DE	negligible						
	GB	**Supportive** ‘four-fuel economy’ policy to promote its use	negligible					
Coal	DE	**Supportive** ‘coal penny’ to protect the industry		**Supportive** removal of the ‘coal penny’ in 1995 while introducing a series of supporting policies including nuclear phase-out, tax exemptions, ‘windfall of profits’ through ETS			**Destabilising** gradual phase-out policies with generous compensation schemes	
	GB	**Supportive** ‘controlled rundown’ policy to phase-down the industry while promoting its use for electricity generation		**Destabilising** framing it as a ‘sick industry’ and reducing support	**Neutral/destabilising** liberalisation policies to trigger ‘rush from coal’	**Supportive** investing in CCS to prolong coal power	**Destabilising** phase-out policies incl. carbon tax and PPCA	negligible
Gas	DE	negligible	**Supportive** investing in gas pipelines to support its use	**Supportive** Increasingly supporting gas as a “bridge source”				
	GB	negligible			**Neutral/supportive** liberalisation policies to trigger ‘dash to gas’	**Destabilising** reducing support as domestic reserves depleted	**Destabilising** phase-out policies incl. carbon tax and PPCA	**Destabilising** fossil phase-out
Nuclear	DE	negligible	**Supportive** promoting the development as the ‘second pillar’ of energy		**Destabilising** introducing nuclear phase-out to initiate the decline towards 2022		**Destabilising** re-committing to phase out by 2022 after Fukushima	
	GB	**Supportive** promoting the development despite a number of technical and financial issues			**Supportive** implementing a number of support schemes to prevent the decline			
Mod.RES	DE	negligible	**Supportive** industrial policy to develop strong manufacturing capacity for solar and wind			**Supportive** promoting distributed deployments	**Supportive** increasing commitment and policy support for a 100% renewable energy system	
	GB	negligible				**Supportive** promoting centralised deployments	**Supportive** increasing commitment and policy support while continuing to favour centralised deployments	

4.4.1 State actions and coal

The evolution of coal power in Germany and the UK can be divided into multiple distinct periods, exhibiting remarkable overall similarities but also notable differences between the two countries. Before delving into their divergences, it is important to emphasise the similarities: both nations experienced a peak in coal electricity generation in 1990, followed by periods of relative stagnation and a steady decline that persisted for 20 years (Figure 4.3).

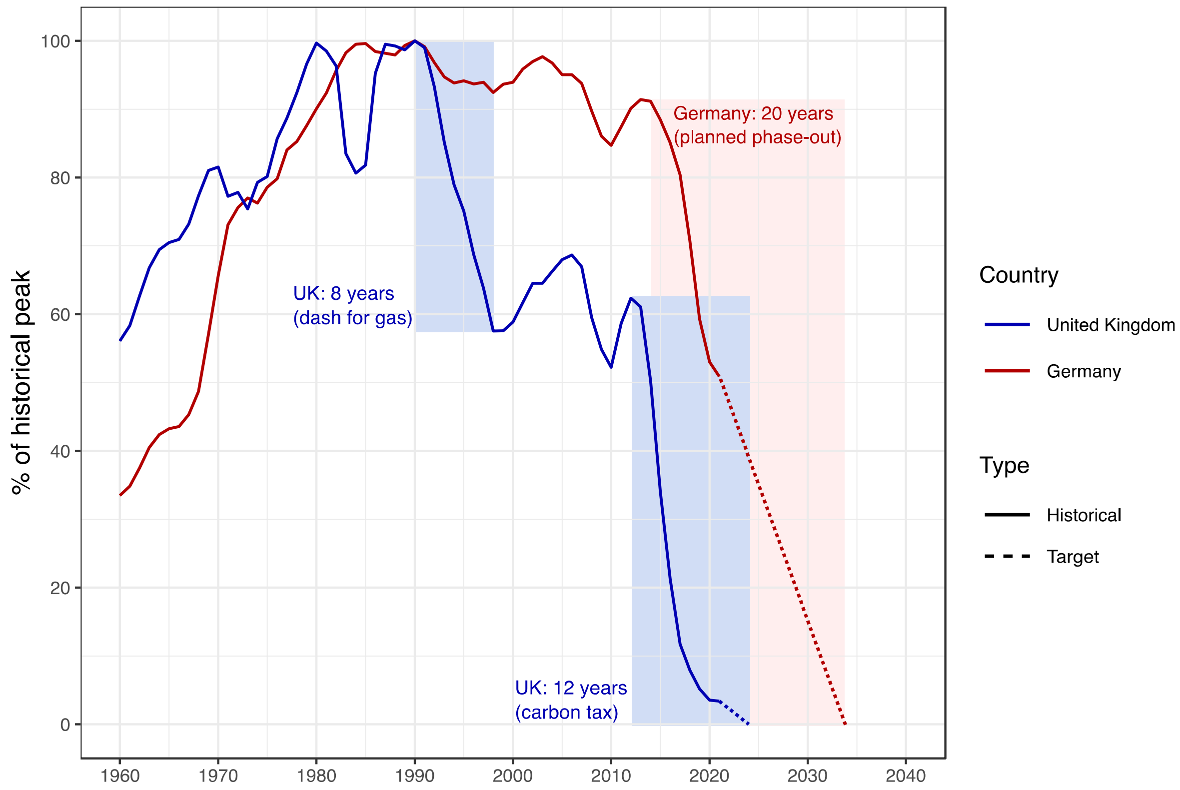


Figure 4.3: Coal power in Germany and the UK as % of the peak value, 1960-2040

The main difference lies in the sequencing of these periods of stagnation. In the UK, a period of stagnation followed the initial steep decline and lasted for about 14 years (1998-2012). In Germany, a longer period of stagnation occurred after the peak, lasting around 24 years (1990-2014). Consequently, Germany will phase out coal electricity 10 years later than the UK due to this longer period of stagnation.

The important question is whether and how the state contributed to these patterns in each country. There are two similar state actions. The first was the liberalisation of electricity markets in the 1990s (including the removal of the 'coal penny' in Germany in 1995), after which coal electricity started to decline, though much more profoundly in the UK. The second similarity has been actively supporting modern renewables over the last decades and politically committing to coal phase-out in the late 2010s.

In two instances, however, it is shown that Germany takes a more active stance on coal by resisting market forces, while the UK leverages these forces to destabilise the industry. The first case relates to the period following the liberalisation of the electricity market in the 1990s. During the eight years following the liberalisation in 1990, coal power in the UK fell by almost half, replaced by domestic gas from the North Sea fields, due to the removal of long-standing policies that had protected the coal industry. In contrast, the use of coal power in Germany remained stable for 19 years, even after the removal of the 'coal penny' in 1995.

If so, one could argue that the stability of coal production in Germany can simply be explained by the lack of an alternative source similar to North Sea gas. This argument is, however, only partially true. There were alternatives to coal in Germany that were at least as viable as in the UK. The production of modern renewable electricity in Germany grew by ca. 140 TWh between 1995 and 2014, while the demand grew by ca. 60 TWh. This almost exactly matches the shifts in the UK, where gas electricity increased by ca. 120 TWh and the demand increased by ca. 40 TWh between 1990 and 1998. However, in the UK, during this period, coal rapidly declined by ca. 85 TWh (almost equal to the difference between gas increase and demand growth). In contrast, in Germany, it declined only marginally, less than 10 TWh, between 1995 and 2014.

This lack of coal decline in Germany between 1995 and 2014 was enabled by the state to politically steer the growth of modern renewables to solely destabilise nuclear power. If modern renewables in Germany were substituting coal rather than nuclear, coal power in Germany in 2014 would be at ca. 50% of the peak value, which is exactly the same as the UK in the same year (Figure 4.3). Instead, the nuclear phase-out policy in Germany, first implemented in 2002 and re-affirmed in 2011 after Fukushima, ensured that the growth of modern renewables would not harm the coal industry (Cherp et al., 2017). In parallel, the state supported the coal industry in preventing its decline through a number of additional policies, including taxing natural gas, another competitor to coal generation. As a result, there was a significant investment in new coal power plants in Germany throughout the 2000s and even the 2010s, something that would complicate its final phase-out in Germany, as I discuss below.

The second case, demonstrating Germany's more active stance on coal, pertains to the coal phase-out policies of both countries. While the UK is primarily retiring old power plants that have exceeded their average lifetime and rely exclusively on imported coal, Germany, in the final phase of its coal exit plan, will need to retire many younger power plants constructed in the 2010s and close domestic lignite coal mines. This endeavour proved to be significantly costly, with the German government allocating over 40 billion Euros to support affected industries and regions (German Federal Government, 2020). Interestingly, while Germany's initial action aimed to slow down the demise of coal, its subsequent action involved accelerating it through substantial state financing. Consequently, the overall trajectories of the decline of coal power in Germany and the UK have been and are planned to remain remarkably similar.

In summary, in the UK, the state removed protective measures over coal generation and let it be ravaged by market forces in the 1990s, relatively sparing it in the 2000s, but decided to phase out the technology in the 2010s. In contrast, Germany, while also removing some protection by abolishing the ‘coal penny’, notably shielded the coal industry between 1990 and 2014 by eliminating one of its main competitors, nuclear power, and taxing the other, natural gas. Both states are currently aiming to phase out coal, but they face different costs and timelines. The UK can achieve this with minimal costs and on an earlier timeline, while Germany would require a more protracted and expensive process. All in all, ca. 35-45 years after reaching peak production, coal generation in both countries will be gone.

4.4.2 State actions and nuclear power

Nuclear power in both countries steadily increased to provide a peak supply of ca. 30% of their electricity around 2000. It subsequently experienced a similar decline throughout the 2000s, but in the following decades, the trajectories of the two countries diverged: Germany continued the decline and completely phased out nuclear power in 2023, while the UK has been politically supporting its preservation and redevelopment, aiming for nuclear power to provide ca. 25% of electricity by 2050 (Figure 4.4).

The reason for the phase-out of nuclear power in Germany, but not in the UK, can be explained by the presence of competitors and varying levels of political support for nuclear power. In Germany, nuclear power faced increasing competition from rapidly growing modern renewables, as well as increasingly hostile political actions against the technology since the 1990s. On the other hand, nuclear power in the UK did not have such competitors because coal power was competing with gas (increasingly imported versus domestic) in the 1990s. Furthermore, there was no political incentive to destabilise nuclear power in the 2000s because it became the only reliable source of (quasi-)domestic energy when domestic gas reserves started to deplete, and modern renewables were not yet available on a large scale.

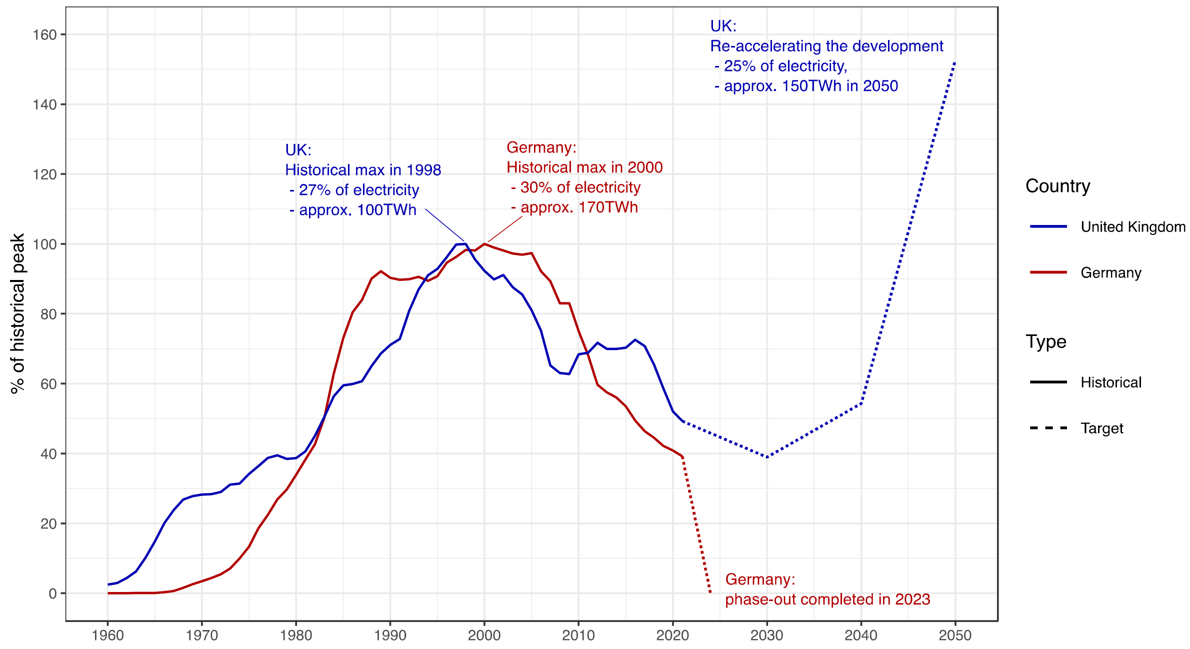


Figure 4.4: Nuclear power generation in Germany and the UK as % of peak value

Notes: Historical data (1960-2021) is sourced from IEA (2022). Germany phased out nuclear power in April 2023. The UK's target data is from BEIS (2022), supplemented by the current governmental target to develop up to 24GW of nuclear power capacity to supply 25% of electricity by 2050. The weighted average load factor in the UK in 1960-2022 was used to calculate the amount of electricity (TWh) produced in 2050.

As a result, nuclear power was entirely phased out in Germany in 2023, prompting the country to expedite investments in natural gas, particularly after the energy crisis following the Russo-Ukrainian War in 2022. In contrast, as modern renewables became more readily available and political motivations to mitigate climate change grew stronger, the UK positioned nuclear power as a pivotal element in decarbonising its energy system by gradually phasing out all fossil fuels, including natural gas, from the electricity supply.

4.4.3 State actions and modern renewables

Germany and the UK have taken different approaches to developing renewable technologies over the last few decades, driven by their distinct national objectives. Germany's initial focus was on developing a robust manufacturing sector with exporting capabilities, and investing in renewables played a crucial role in achieving this goal. On the other hand, the UK's energy policy did not prioritise industrial expansion. Instead, it initially adhered to the mainstream 'free-market paradigm' in the country during the 1990s. Consequently, the UK concentrated on deploying renewable technologies through market-oriented schemes, adopting these technologies as they became commercially viable through the efforts of other countries.

As a result of these varying strategies, Germany took an early lead in the development of solar and wind power compared to the UK (Figure 4.5). However, both countries experienced synchronous growth in low-carbon electricity based on biofuels, particularly waste-to-generation, as it was already cost-competitive in the 1990s.

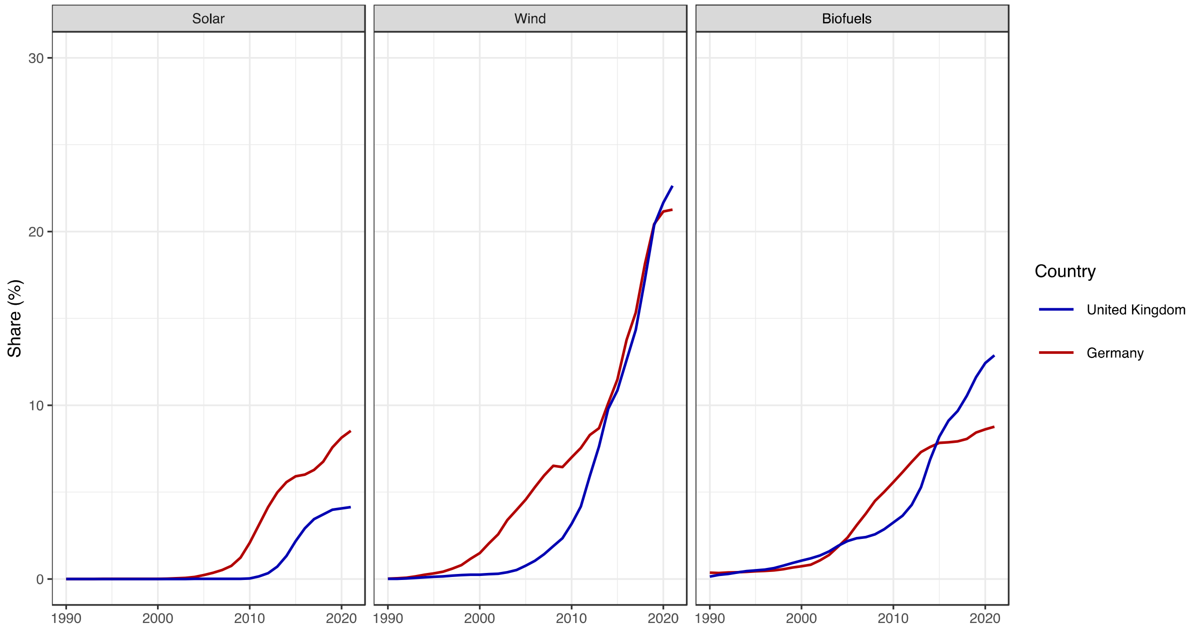


Figure 4.5: Low-carbon electricity growth in Germany, and the UK

Figure 4.5 also demonstrates that the UK caught up with Germany in deploying wind power in the 2010s, contributing to over 20% of its electricity supply in 2020, facilitated by additional support for large-scale offshore wind development. However, the expansion of solar power in the UK still lagged behind Germany. This difference may be attributed to the UK's inclination towards the development of large-scale renewable projects, driven by existing industry actors, as opposed to the more distributed approach involving numerous actors in Germany.

Overall, while both Germany and the UK gradually accelerated the development of renewable energy technologies, their divergent approaches and varying priorities influenced the timing, extent, and type (distributed or concentrated energy systems) of their advancements in specific renewable technologies.

4.5 Comparing the speed of technological growth and decline

In the previous section (4.4), I identified a number of differences in national circumstances and state interventions regarding electricity transitions in Germany and the UK from 1960 to 2030, particularly after 1980. The biggest differences have been:

1. Germany's proactive approach to coal power, shielding it from decline for several decades and subsequently destabilising it with substantial state financing towards the 2030s.
2. The contrasting approach between the two countries for nuclear power, where Germany politically phased it out by 2023, while the UK has increasingly protected and aimed to revitalise the use of the technology in the future.
3. Different national objectives for developing modern renewables, resulting in variations in the timing, extent, and type (distributed or concentrated energy systems) of development of these technologies across the countries.
4. The contrasting policies in the future role of natural gas as a consequence of these diverging interventions on coal, nuclear power, and modern renewables.

Given these differences in national circumstances and policies, one might anticipate a substantial divergence in the pace of energy transitions between the two countries. However, the following subsections will demonstrate that, when aggregated, the speed of technological growth and decline has been and is planned to remain remarkably similar between Germany and the UK.

4.5.1 Comparing the growth of modern renewables

Despite the differences in the objectives, timings, extents, as well as types of state interventions and market developments, the growth speed of modern renewables in Germany and the UK, when all sources are considered together, has been and is planned to remain remarkably similar over the last few decades and in the future (Figure 4.6).

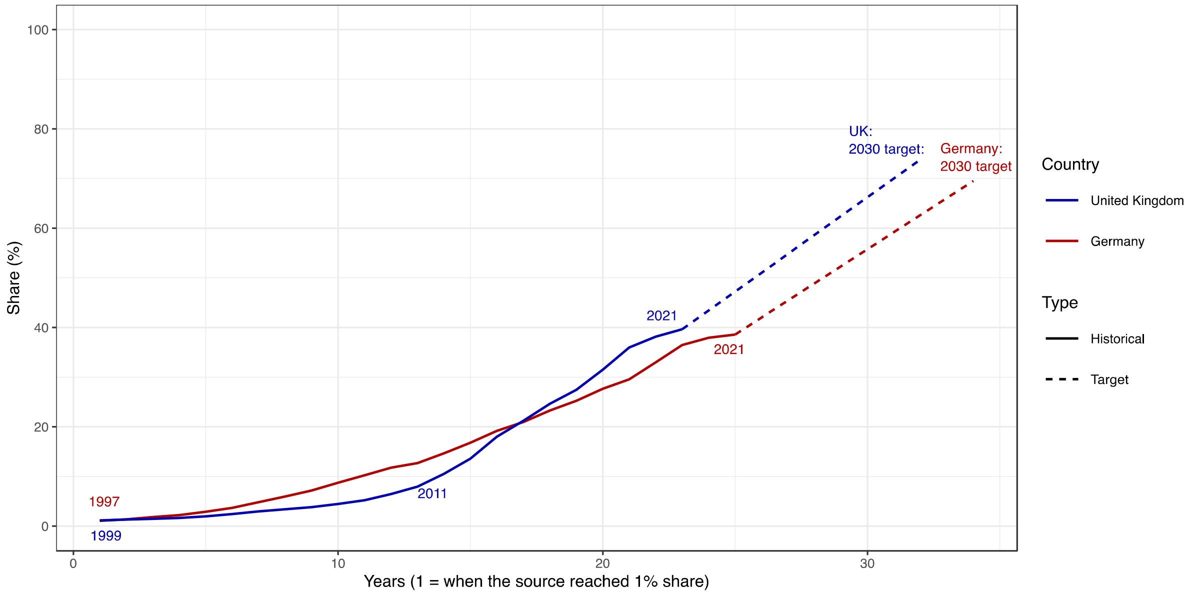


Figure 4.6: Aggregated growth of modern renewables in Germany and the UK

Notes: The Y-axis shows the number of years after the source reached a 1% share of electricity. The 2030 target of Germany is the average of the two recent national projections (Kemmler et al., 2020; Sprenger and Schäfer, 2022), which would best reflect the most recent development in the country to accelerate developing modern renewables, thereby phasing out coal in the early 2030s. The 2030 target of the UK is obtained from the official projection published in 2022 (BEIS, 2022).

After reaching a 1% share of the market in 1997 in Germany and 1999 in the UK, respectively, the growth was initially slightly faster in Germany than in the UK. This difference can be explained by variations in the initial objectives of developing renewable technologies in the two countries (see subsection 4.4.3 for more details). However, after 2011, with the increasing political and financial support provided to offshore wind, the UK started to outpace Germany's growth speed. This may indicate that more centralised development of renewables such as offshore wind farms, can develop faster than distributed deployments such as solar rooftops. Nevertheless, both countries supplied about 40% of electricity from modern renewables in

2021, after 40 to 50 years since the initial investments in the technologies or after 22 to 24 years after reaching a 1% share of electricity supply (slightly less than a 2% share growth per year).

The recent national projections towards 2030 show linear growth in both countries, with the UK slightly outpacing Germany, supplying 70-73% of electricity from modern renewables in 2030.

4.5.2 Comparing the decline of incumbent technologies

Similar to the nearly identical growth speed of modern renewables in recent decades and projected for the future, the decline rate of incumbent technologies in Germany (nuclear power and coal) and the UK (natural gas and coal) also exhibits great similarities, particularly after the late 2000s. On the one hand, the targeted incumbent technologies for decline in Germany had a larger share of electricity generation in 1990, but their decline has progressed more steadily compared to the UK up to today. On the other hand, this also means that the rate of decline has been slightly faster in the UK after the late 2000s (36% drop in the UK vs 29% in Germany) than in Germany, where no technology declined more than 20% per decade throughout the scope of analysis (Figure 4.7).

This later but faster decline of incumbent technologies in the UK compared to Germany may be explained by the fact that it was only after the late 2000s that the UK started to re-intensify its intervention in the energy market, including accelerating the deployment of modern renewables. Another explanation is that electricity demand also began to decline around the same time in the UK, which may have necessitated accelerating the decline of incumbent technologies to make room for the increasingly growing renewables in the shrinking market.

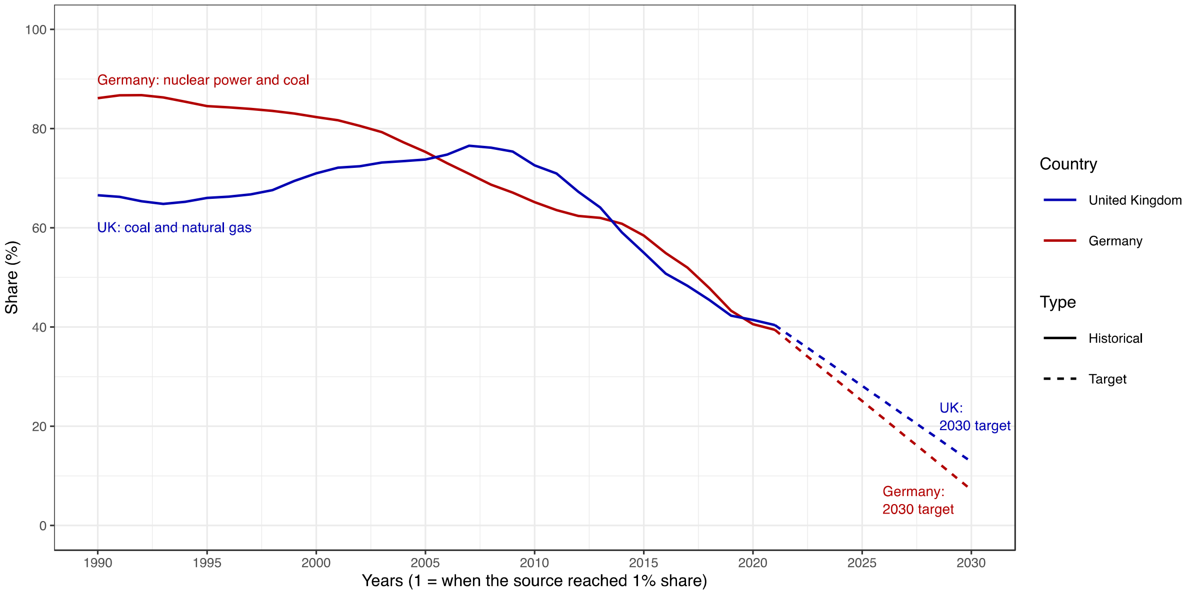


Figure 4.7: Aggregated decline of incumbent technologies in Germany and the UK

Notes: The 2030 target of Germany is the average of the two recent national projections (Kemmler et al., 2020; Sprenger and Schäfer, 2022), which would best reflect the most recent developments in the country to accelerate the development of modern renewables, and thereby phasing out coal in the early 2030s. The 2030 target of the UK is obtained from the most recent projection of the government (BEIS, 2022)

Looking at recent projections, Germany forecasts a continuously steady decline towards 2030, while the UK projects a slightly slower decline.

All in all, the decline speed of incumbent technologies has been and is planned to be remarkably similar between Germany and the UK since the late 2000s. This may indicate that while state policies can influence the choice of energy technologies to be used in the market (renewables and natural gas in Germany, and renewables and nuclear power in the UK), the speed of technological decline cannot be significantly altered. Alternatively, it may be the case that while pursuing different technological transitions through a variety of policies, Germany and the UK could be both operating at the forefront of technological decline speed.

4.6 Summary

This chapter conducted a longitudinal comparative analysis of historical and planned electricity transitions in Germany and the UK with a focus on comparing state interventions and their outcomes including plans between 1960 and 2030. By systematically identifying notable decadal episodes of technological growth and decline and tracing the influence of state policies, I revealed both similarities and differences in their state interventions. The most prominent disparities were found in the extensive state-led developments of coal, natural gas, nuclear power, and modern renewables since the 1980s.

Interestingly, despite these differences in state actions, the speeds of technological growth and decline have been and are planned to remain remarkably similar between Germany and the UK. This raises the question of whether there exists a regularity or limit to the speeds of technological change, or if these countries are at the forefront of politically accelerating these speeds. Moreover, it is important to clarify how these speeds compare to what is necessary to mitigate climate change.

The following chapter will address these inquiries by expanding the analysis to include the other G7 countries and the EU. It will focus on comparing the speeds of historical and required electricity transitions to limit the global temperature increase below 1.5ºC, shedding light on the broader implications for climate change mitigation in the future.

5. Historical and required transitions in the G7 and the EU

5.1 Introduction

The previous chapter (4) finds that while the UK and Germany have pursued different state policies, particularly for coal, natural gas, nuclear power, and modern renewables in recent decades, the speeds of technological growth and decline have shown remarkable similarities. In addition to the comparative analysis across countries, this chapter conducts a comparative analysis across time-periods. By doing so, this chapter investigates whether and how climate policies in recent decades have altered energy transitions beyond historical trends. Furthermore, it examines the implication of this historical analysis for achieving climate targets in the future.

The cases chosen for this chapter are the G7 countries and the EU in the electricity sector, where the majority of climate policies have been implemented in the last decades. As among the largest economies with significant economic, financial, and technological capabilities, these countries have consistently made commitments to mitigating climate change and have faced increasing pressure to lead these efforts over the last decades (Kirton and Kokotsis, 2015). The G7 and the EU also committed to decarbonising electricity "fully or predominantly" in 2022 by 2035 (G7, 2022), which is outlined as a major milestone by the IEA to keep the global temperature increase below 1.5°C. In other words, if this target is not met by the G7 and the EU as well as the rest of the developed countries, achieving the global 1.5°C temperature goal would be extremely challenging, if not impossible.

The following main research question will guide the rest of the chapter:

- Have climate policies altered energy transitions beyond historical trends, if so, how in light of climate target requirements?

To operationalise the analysis, this question is further divided into the following subset of questions.

- How has the energy sector evolved in the G7 and the EU over the last six decades?
- Is there any evidence that climate policies have significantly altered the nature and speed of energy transitions beyond historically observed trends?
- What are the implications of the observed trends and the effects of climate policies for achieving climate targets?

5.2 Historical and required evolution of the electricity sector

5.2.1 Electricity generation in 1960-2035

Electricity generation in the G7 countries and the EU steadily increased over five times from 1960 to 2005, after which the growth stagnated (Figure 5.1). Fossil fuels had been the main source of electricity; however, their share decreased from its peak of 76% in 1970 to 52% in 2020. In absolute terms, fossil fuel-based electricity increased from ca. 1100 TWh in 1960 to its peak in 2005 at ca. 5700 TWh and declined thereafter to ca. 4800 TWh in 2020. Among low-carbon sources, hydropower stagnated after 1995 at ca. 1100 TWh, nuclear power peaked in 2005 at ca. 2200 TWh and gradually declined thereafter, and modern renewables (all renewable sources excluding hydro) grew progressively faster after 1990 from 100 TWh to ca. 1500 TWh in 2020. Combined, low-carbon electricity grew from ca. 500 TWh (30%) in 1960 to ca. 4400 TWh (48%) in 2020.

In the future, according to the IEA 1.5°C pathway, electricity generation in the G7 and the EU needs to grow by 40% from 2020 to 2035 to reach ca. 13000 TWh in order to decarbonise other sectors through electrification (IEA, 2021a). Historically, such level of demand growth in the G7 and the EU always entailed the growth of all supply technologies. In contrast, following the IEA 1.5°C pathway requires only low-carbon sources to grow and fossil fuels to decline.

In particular, modern renewables are expected to produce most of the electricity (ca. 8300 TWh) in 2035, almost equivalent to the total electricity generation in 2020.

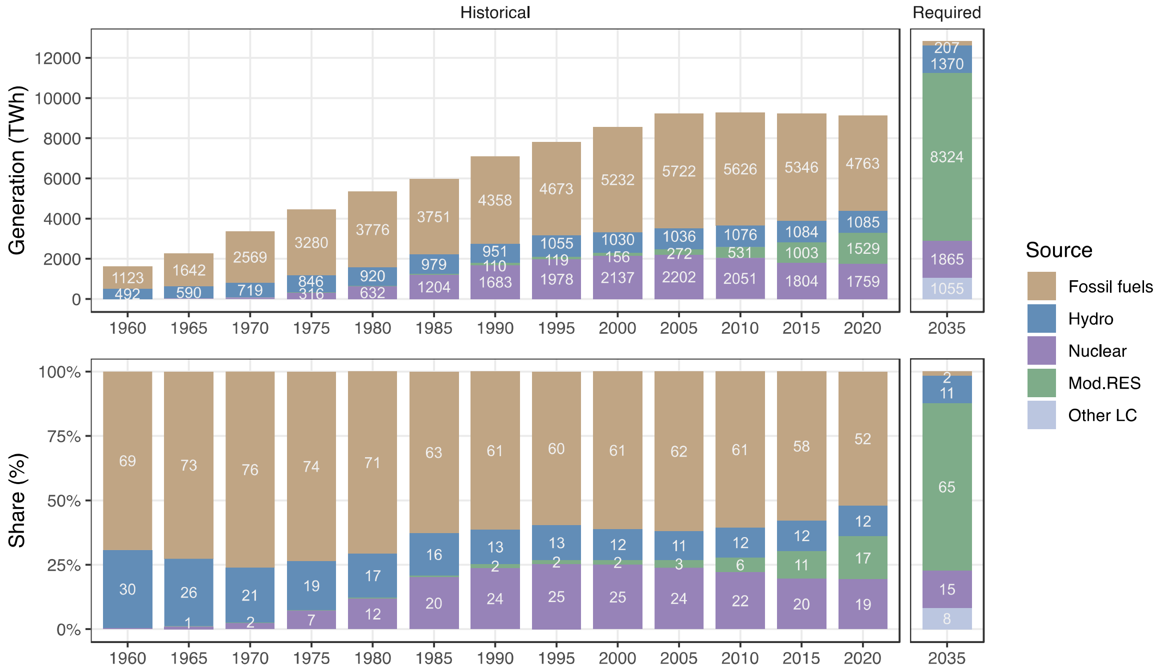


Figure 5.1: Historical and required electricity generation to limit the temperature increase below 1.5°C in the G7 and the EU in 1960-2035.

Note: Mod.RES refers to modern renewables which include all renewable sources excluding hydro (See Table 3.1 for source categories). Other LC includes ammonia, hydrogen, and fossil fuel with carbon capture, utilisation, and storage (CCUS). The data of some EU member states are only available and were included later than 1960 (see Table A2 for the first year of available data for the EU member states).

5.2.2 Speed of technological changes and climate policies

Between 1960 and 2020, electricity sources generally grew progressively slower over time in the G7 and the EU on average: fossil fuels achieved the highest growth rate among all sources at 6.6% per year in 1965–1970, followed by nuclear power at 2% in 1980–1985, and modern renewables at 1.1% in 2015–2020 (Figure 5.2A).

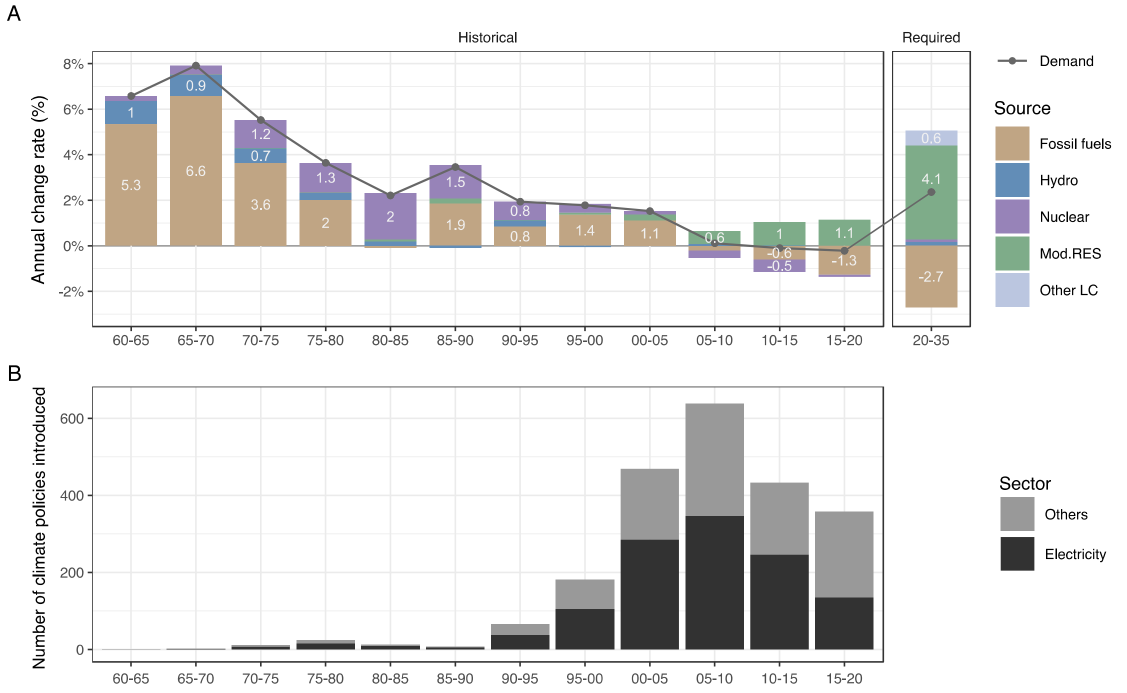


Figure 5.2: Speed of historical and required electricity transitions (A), and the number of climate policies introduced in 1960-2035 in the G7 and the EU (B).

Notes: Years are expressed in two digits (60-65 refers to 1960-1965). Mod.RES refers to modern renewables which include all renewable sources excluding hydro. Other LC includes low-carbon electricity produced from ammonia, hydrogen, and fossil fuels with CCUS. Despite the increase in the number of climate policies particularly after 1990, the growth rate of low-carbon technologies has remained lower than the pre-1990 rates (e.g. 1.1% in 15-20 in comparison to 2.3% in 80-85), and significantly lower than the required rate (i.e. 5.1% in 20-35) to achieve climate targets.

In contrast, the number of climate policies introduced increased particularly after 1990, reaching its peak in 2005–2010 and starting to decrease thereafter (Figure 5.2B). It is important to note that while the number of climate policies introduced serves as an indicator of political activity aimed at mitigating climate change, it does not necessarily reflect the strength of climate governance, as policies introduced earlier may still be in effect. Additionally, a higher number of policies introduced does not necessarily indicate stronger climate governance, as the stringency of each policy is not extensively analysed in the Climate Policy Database (NewClimate Institute et al., 2023). Recent research, however, does argue that the cumulative number of policies in force, often referred to as “policy density” and understood as the level of political ambition, has increased over time globally (Schaub et al., 2022). I also see this phenomenon in the G7 and the EU as a whole as well as individually (Figure 5.3).

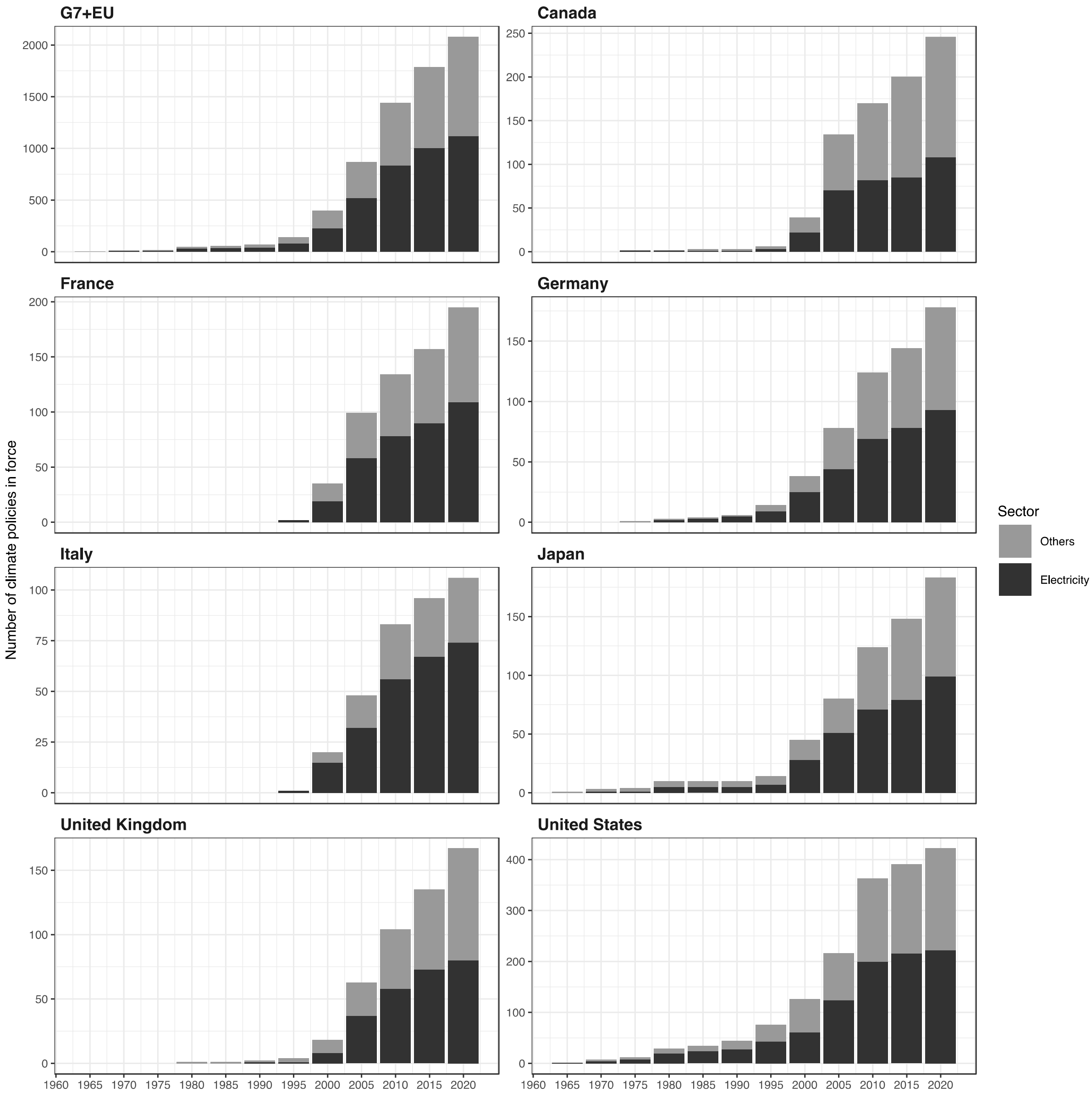
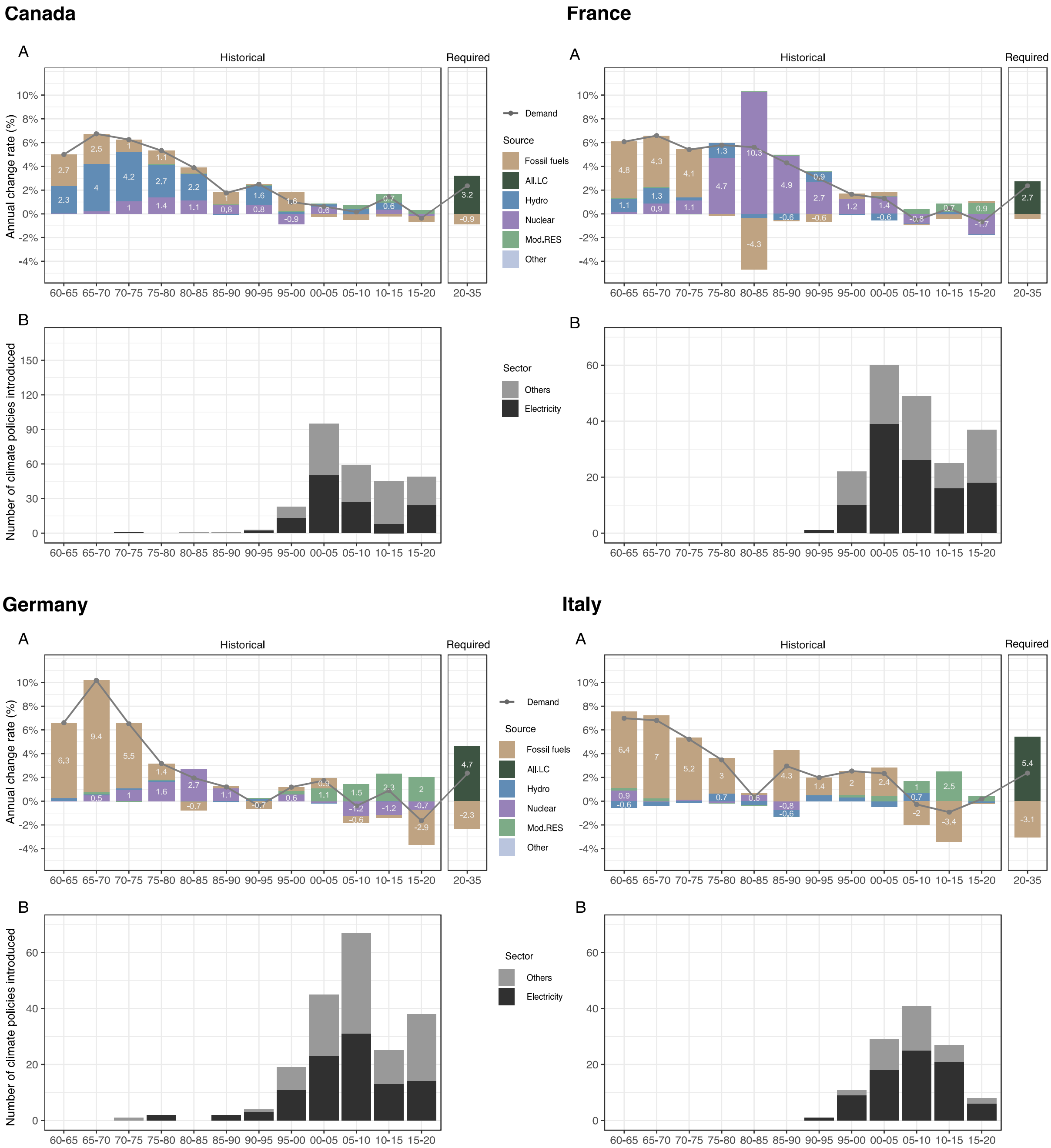


Figure 5.3: Number of climate policies in force in the G7 and the EU as a whole and individually in 1960-2020

Note: To calculate the number of climate policies in force each year, I aggregate the count of policies introduced in that year or earlier, excluding those that were terminated by that year. However, it should be noted that the end year of policies registered in the Climate Policy Database is rarely recorded, presumably due to the difficulty of tracking policy terminations compared to their introductions. Consequently, the total number of policies in force may be overestimated.

Most of these policies have been targeted at the electricity sector, except in 2015-2020 (Figure 5.2B). It is also notable that fossil fuels experienced a progressive decline, accelerating after 2005 when the demand started to stagnate and decline. In the period of 2015-2020, fossil fuels recorded an annual decline rate of -1.3%.

The negative correlation between the increasing number of climate policies introduced and the slower growth of new energy technologies, as well as the phenomenon that fossil fuels decline only under the stagnating demand, can also be generally observed in the G7 member states individually (Figure 5.4).



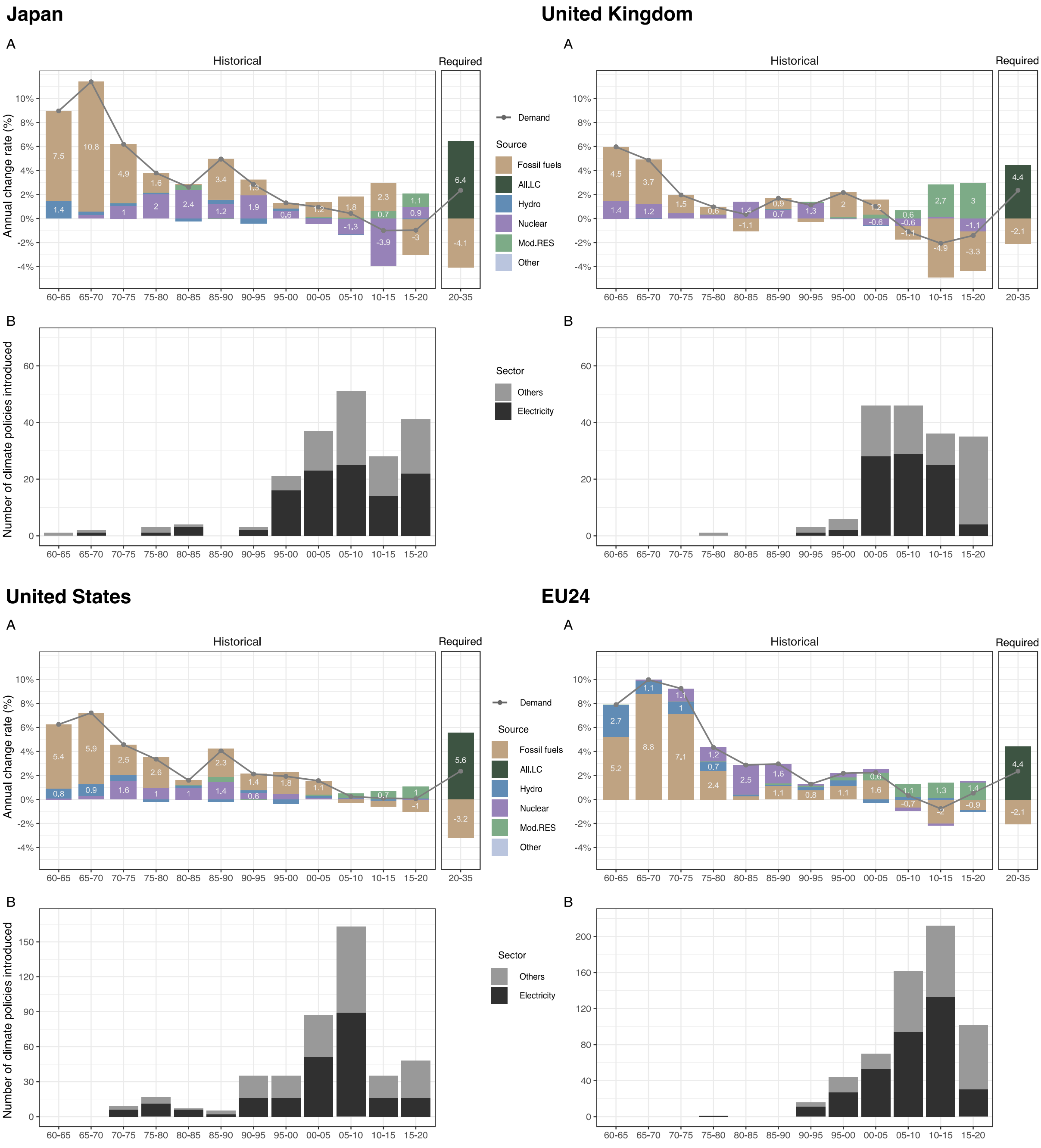


Figure 5.4: Speed of historical electricity transitions in 1960-2020 in the G7 main member states

Note: To account for the limited availability of data regarding the targeted share of each low-carbon source in individual countries in 2035, a new category called "All.LC" is introduced in the figure which includes all low-carbon sources (i.e. other than fossil fuels). The required rates of "All.LC" growth and "Fossil fuels" decline for individual countries in 2020-2035 are calculated based on the assumption that the level of decarbonisation targeted by the IEA for the G7+EU countries as a whole (i.e. 98% low-carbon) would also be achieved individually. Consequently, countries with a lower share of low-carbon electricity today would need to achieve a higher growth rate in 2020-2035. All change rates are calculated based on the same method described in Section 3.3.1.

It is important to point out that while modern renewables started to develop particularly after 1990 (Figure 5.2A), its previously steady acceleration in the growth rate began to stagnate in the 2010s: the rate during 2015-2020 was only 0.1% higher compared to the rate observed in

2010-2015. This occurred despite the continuous decrease in costs for solar, onshore and offshore wind technologies, as shown in Figure 5.5.

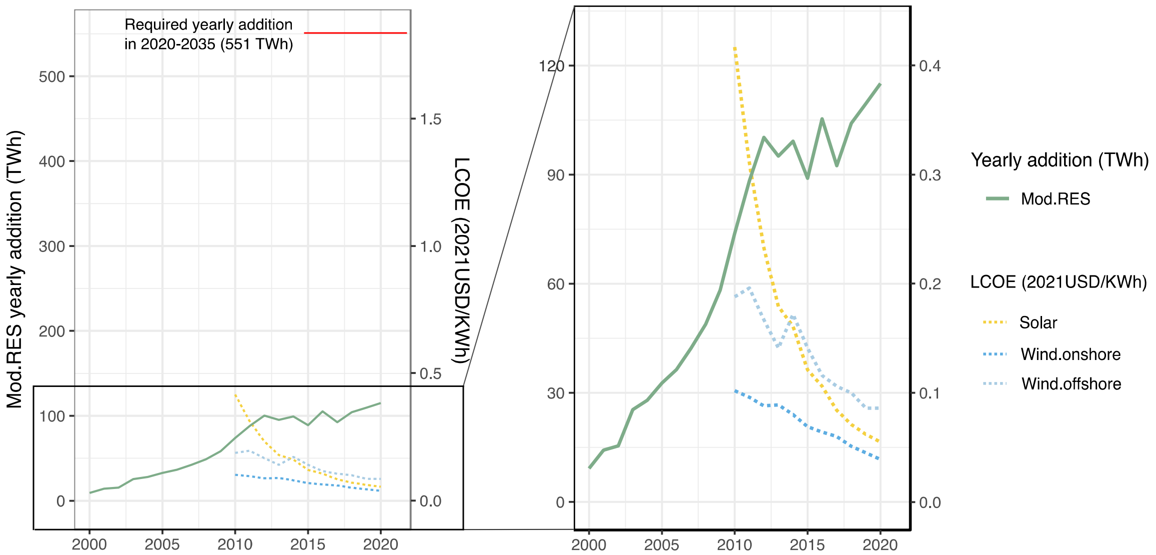


Figure 5.5: Costs of solar, onshore, and offshore wind in comparison to yearly addition of modern renewables in the G7 and the EU in 2000-2020 and the required addition in 2020-2035

Note: The costs represent the global weighted average costs of these technologies obtained from IRENA (IRENA, 2022).

Achieving the IEA 1.5°C pathway in the G7 and the EU requires significant acceleration to develop low-carbon sources at an annual rate of 5.1% in 2020-2035, with modern renewables growing at 4.1%, which is more than twice as fast as the rate of nuclear power deployment in 1980-1985. In contrast, fossil fuels need to decline at an annual rate of -2.7% during the same period, and the overall electricity supply needs to grow at 2.4%, which is higher than all periods after 1990 (Figure 5.2A).

5.2.3 Evolution of the type and speed of electricity transitions

Figure 5.6 synthesises the findings from Sections 5.2.1 and 5.2.2, illustrating the evolution of the type and speed of electricity transitions in the G7 and the EU in 1960-2035 based on the typology of energy transitions developed in this dissertation (see Figure 3.2).

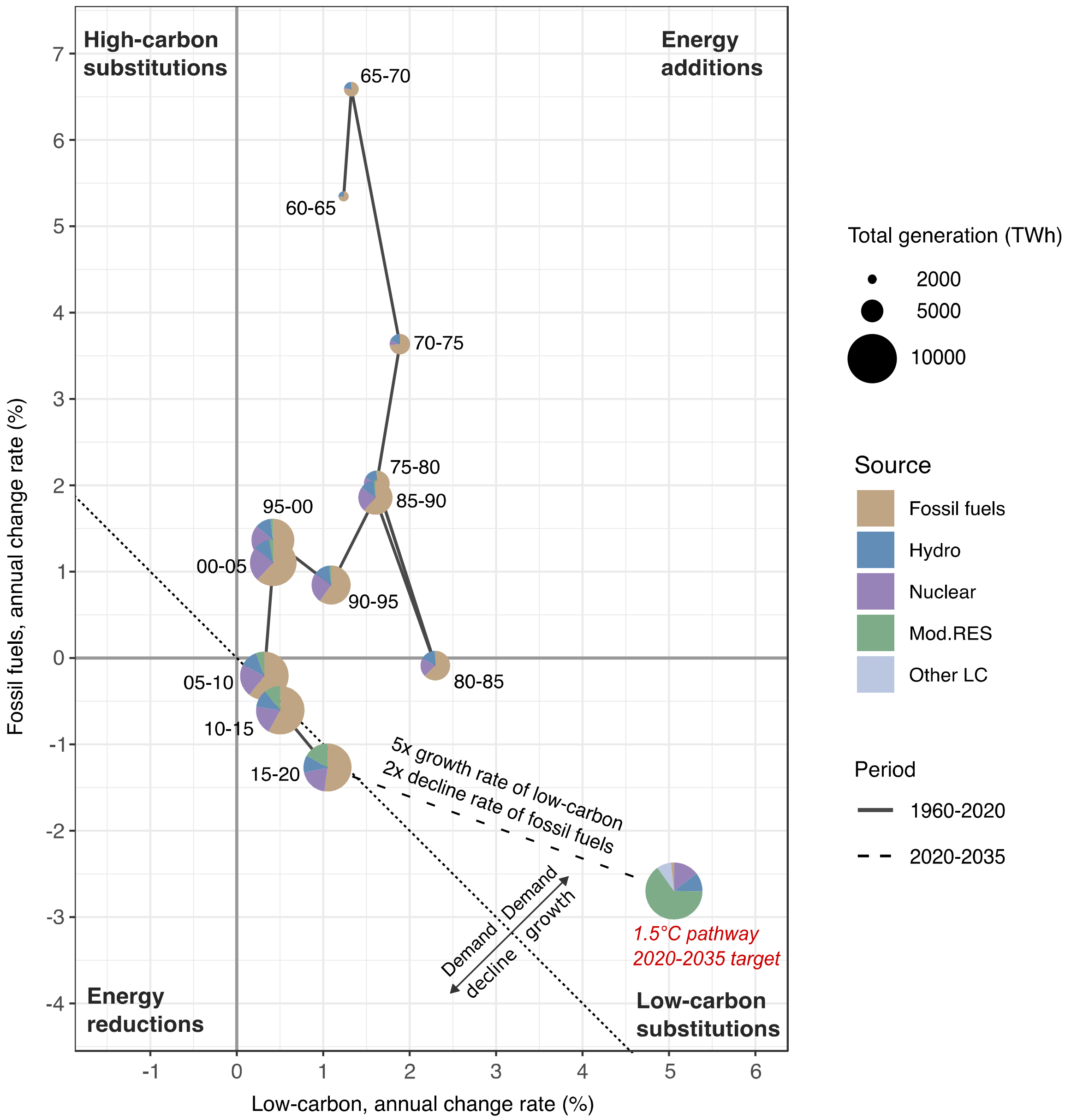


Figure 5.6: Historical and required electricity transitions in the G7 and the EU in 1960-2035.

Notes: The pies show the electricity mix at the end of the five-year episodes in the G7 and the EU in 1960-2020 and the required mix in 2035 to keep the global temperature increase below 1.5°C. The size of pies indicates total generation, while colours represent sources. Texts next to pies refer to years (e.g. 15-20 is the episode in 2015-2020).

Between 1960 and 1980, the electricity sector in the G7 and the EU experienced significant growth through energy additions. This period was characterised by a rapid increase in electricity demand, which was supplied by various technologies, with fossil fuels playing a predominant role. However, a notable shift towards low-carbon substitutions occurred in the subsequent period of 1980–1985. This shift was made possible by the rapid expansion of nuclear power following the oil crises in the 1970s, resulting in the historically highest annual growth of low-carbon electricity up to today, reaching 2.3% (also see Figure 5.2). On the other hand, this progress towards decarbonisation was not sustained, as the growth of nuclear power soon stagnated, resulting in a re-emergence of reliance on fossil fuels. Consequently, the G7 and the EU reverted to undergoing energy additions in 1985–1990.

While the number of climate policies introduced increased particularly after 1990 (Figure 5.2B and Figure 5.3), the G7 and the EU continued to undergo energy additions between 1990 and 2005. During this period, the resurgence of energy additions was once again predominantly fuelled by fossil fuels, although the growth rate was modest compared to the preceding decades. This slower growth can be attributed to the limited increase in electricity demand.

However, starting in 2005, the G7 and the EU entered a new period of low-carbon substitutions, characterised by the increasing adoption of modern renewables (Figure 5.1). Unlike the first period of low-carbon substitutions in 1980–1985, this second period was facilitated by a decline in electricity demand, which made it possible for the moderately growing low-carbon electricity at 1% (i.e. half of the speed achieved in 1980–1985, despite the increasing number of climate policies introduced) to replace fossil fuels (see Figure 5.2).

The individual historical trajectories of the G7 main member states generally show a similar trend observed in the G7 and the EU as a whole (Figure 5.7).

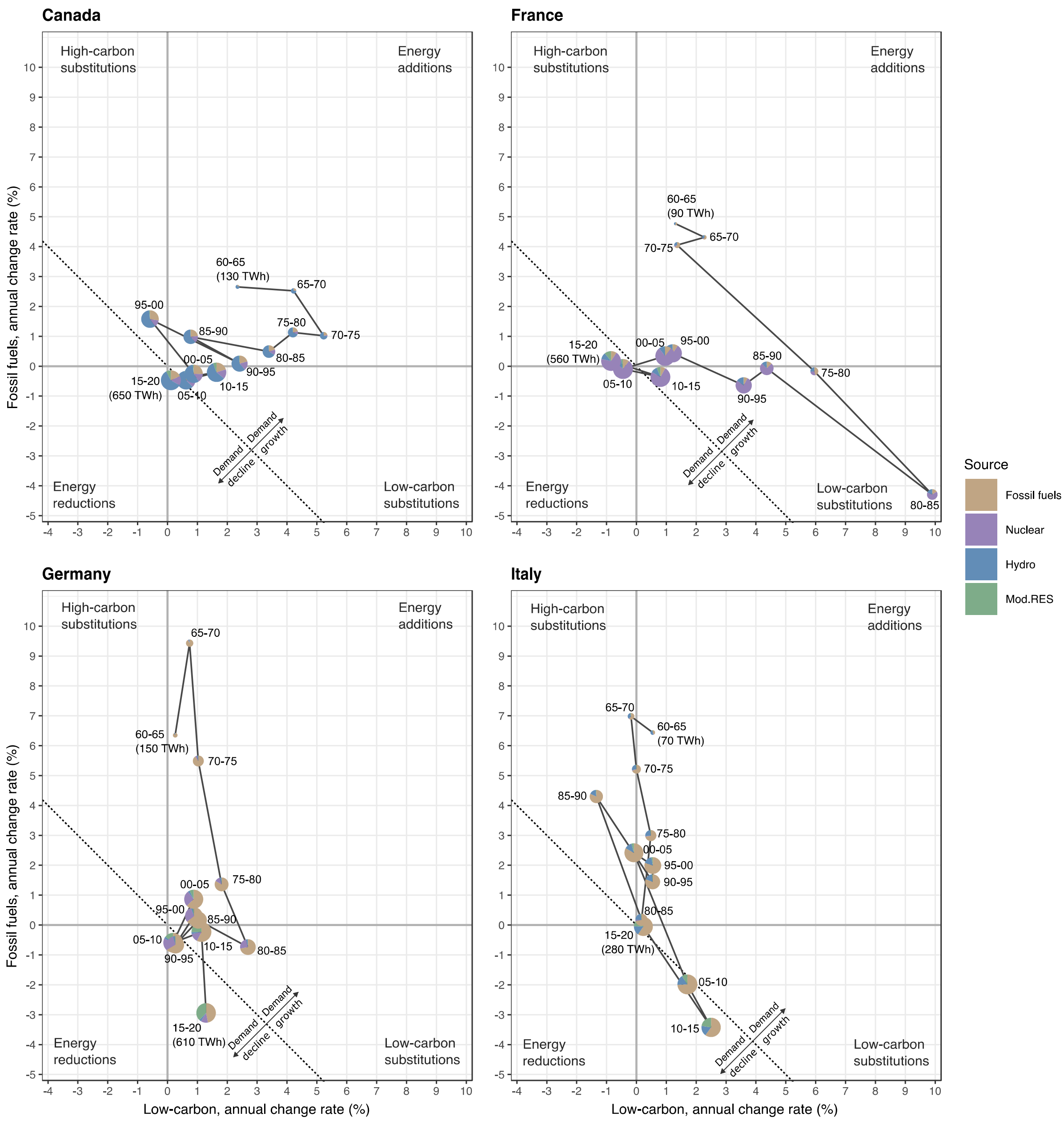


Figure 5.7: Historical developments of the electricity sector in the G7 main member states in 1960-2035.

Notes: The pies show the electricity mix at the end of the five-year episodes in the G7 in 1960-2020 and the required mix in 2035 to achieve 1.5°C. The size of pies indicates total generation, while colours represent sources. Texts next to pies refer to years (e.g. 15-20 is the episode in 2015-2020).

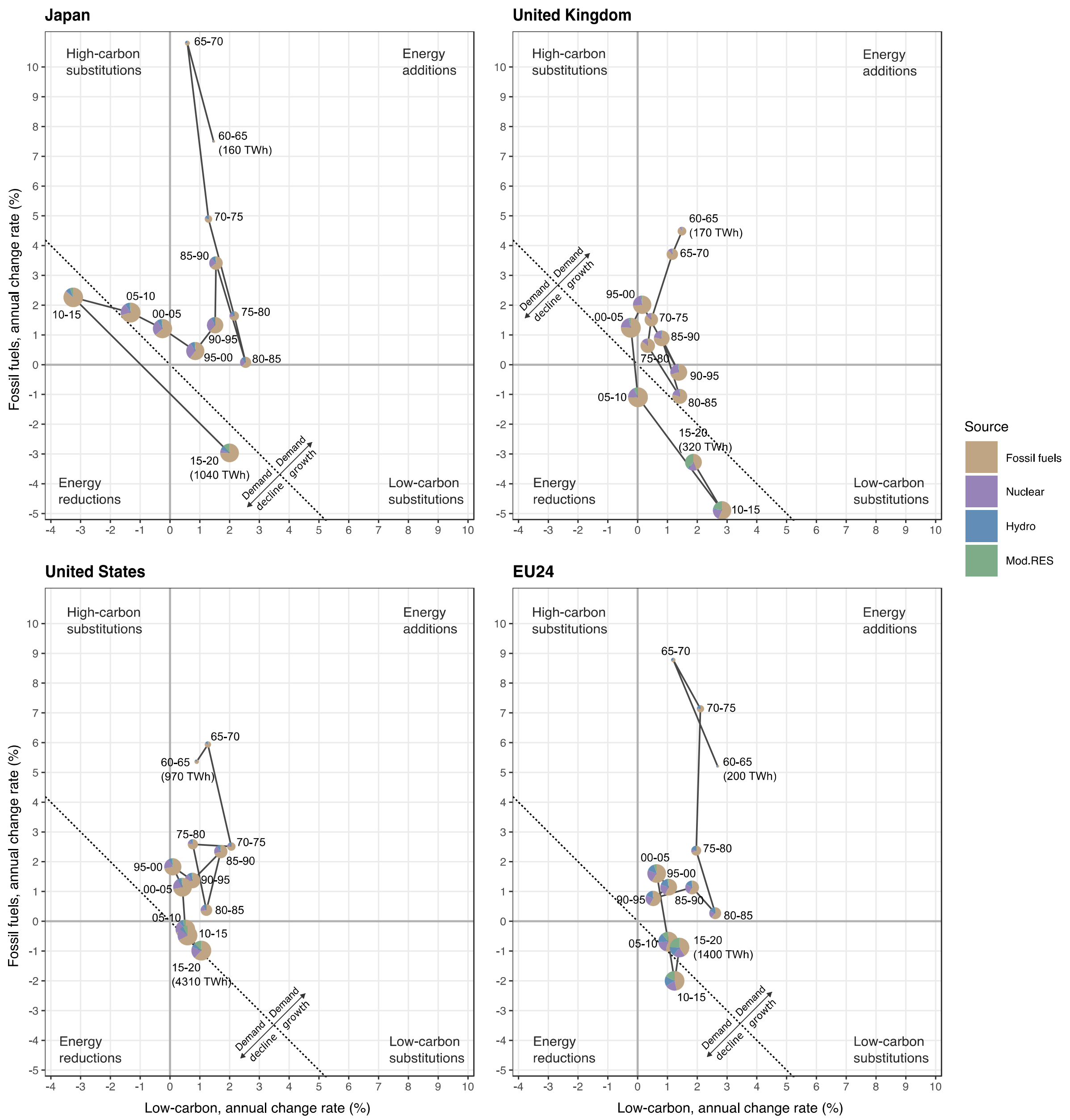


Figure 5.7 (continued).

In contrast to the incremental progress of low-carbon substitutions observed from 2005 to 2020, following the IEA 1.5°C pathway requires immediate and significant acceleration to develop low-carbon electricity five times faster and reduce fossil fuels two times faster than what was observed in 2015–2020 in the G7 and the EU.

5.2.4 Frontier speed of national low-carbon substitutions in 2020

Figure 5.8 illustrates the fastest five-year low-carbon substitution episodes in 1960–2020 in the G7 and the EU as well as comparable countries, and the empirically grounded speed zones delineated by their density, as outlined in Figure 3.3 (see also subsection 3.3.3 for detailed methods). The required low-carbon substitutions under the IEA 1.5°C pathway for the G7 and the EU fall within the fastest 5% speed zone. This means that all the G7 countries and the EU would need to replicate the historical top 5% fastest low-carbon substitutions achieved at the individual country level[5], and sustain such speed for 15 years in 2020–2035.

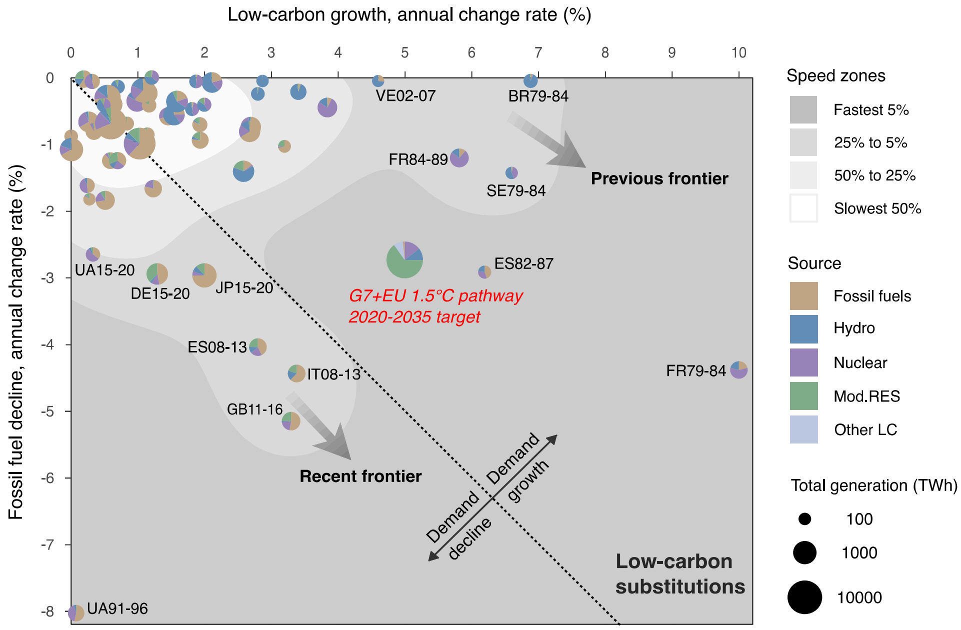


Figure 5.8: Speed zones, and historical, required and frontiers of low-carbon energy transitions

Notes: Speed zones are defined by the density of historical episodes, which are divided into bands based on the frequency of observation (see subsections 3.2.3 and 3.3.3 for detailed framework and methods). Pies are the fastest five-year episodes of low-carbon substitutions in countries with more than 100 TWh at the time of the episodes in 1960–2020. The pie size indicates the total generation, while the colours represent the electricity mix at the end of the episodes. The number of observations in each speed zone does not necessarily perfectly match the indicated proportion due to the smoothing effect of the density estimation function. See Table A1 for country codes and Table 3.3 for the details of the episodes.

5 Note that this "top 5% fastest" is the proportion out of the total number of low-carbon substitution episodes, which represents around one-fourth of all episodes including the other energy transition types. In other words, this top 5% of low-carbon substitution episodes is equal to 1.25% of all historical episodes analysed.

Three out of 56 low-carbon substitution episodes achieved this top 5% speed in 1960–2020: FR79-84, ES82-87 and UA91-96. Table 5.1 shows that these three episodes, along with the 10 episodes that achieved above the top 25% speed, generally exhibit similar characteristics to those observed in the transitions of the G7 and the EU as a whole (Figure 5.6). During the previous low-carbon substitution episodes primarily driven by nuclear power before 1990, low-carbon electricity experienced faster growth, but fossil fuels did not decline significantly. Contrastingly in the more recent low-carbon substitution episodes instead primarily driven by modern renewables, fossil fuels exhibited a faster decline under the declining demand for electricity, but low-carbon electricity did not show substantial growth.

Table 5.1: Fastest 25% episodes of low-carbon substitutions in the G7 and the EU and comparable countries in 1960-2020 in comparison to the required transition of the G7 and the EU in 2020-2035.

Episode	Country	Year		Annual change rate					
		Start	End	Demand	Transition speed	Fossil fuels	Low-carbon	major source	
FR79-84	**France**	**1979**	**1984**	**5.6%**	**14.4%**	**-4.4%**	**10.0%**	**Nuclear**	**10.2%**
SE79-84	**Sweden**	**1979**	**1984**	**5.2%**	**8.0%**	**-1.4%**	**6.6%**	**Nuclear**	**4.9%**
BR79-84	Brazil	1979	1984	6.9%	6.9%	0.0%	6.9%	Hydro	6.5%
ES82-87	**Spain**	**1982**	**1987**	**3.3%**	**9.1%**	**-2.9%**	**6.2%**	**Nuclear**	**5.4%**
FR84-89	France	1984	1989	4.6%	7.0%	-1.2%	5.8%	Nuclear	6.2%
UA91-96	Ukraine	1991	1996	-7.9%	8.1%	-8.0%	0.1%	Nuclear	0.1%
VE02-07	Venezuela	2002	2007	4.5%	4.7%	-0.1%	4.6%	Hydro	4.6%
IT08-13	Italy	2008	2013	-1.1%	7.8%	-4.4%	3.4%	Mod.RES	2.7%
ES08-13	Spain	2008	2013	-1.2%	6.8%	-4.0%	2.8%	Mod.RES	2.2%
GB11-16	United Kingdom	2011	2016	-1.9%	8.4%	-5.1%	3.3%	Mod.RES	3.0%
JP15-20	Japan	2015	2020	-1.0%	5.0%	-3.0%	2.0%	Mod.RES	1.1%
DE15-20	Germany	2015	2020	-1.6%	4.2%	-2.9%	1.3%	Mod.RES	2.0%
UA15-20	Ukraine	2015	2020	-2.3%	3.0%	-2.6%	0.3%	Mod.RES	0.7%
G7_20-35	**G7+EU**	**2020**	**2035**	**2.4%**	**7.8%**	**-2.7%**	**5.1%**	**Mod.RES**	**4.1%**

Note: The required transition for the G7 and the EU and the historical episodes with compatible speeds are bolded.

These distinct characteristics observed in the previous and more recent low-carbon substitution episodes produce two distinct speed frontiers (Figure 5.8). As a result, there are a few precedents that can be directly compared to the transition necessary for the G7 and the EU in the future, where both the growth of low-carbon electricity and the decline of fossil fuels must occur rapidly at the same time. Only France in 1979–1984 and Spain in 1982–1987 exceeded the required rates, although these high speeds were sustained only for five years.

No country has sustained the required transition speeds for a continuous period of 15 years, although there have been some notable episodes that have come close (Figure 5.9). Four episodes achieved the fastest 25 to 5% speed: France in 1972–1987, Sweden in 1971–1986, the UK in 2005–2020, and Ukraine in 1990–2005. These episodes once again demonstrate the same distinct characteristics of the previous and more recent low-carbon substitution episodes, leaving no precedent directly comparable to the required transition in the G7 and the EU in 2020–2035.

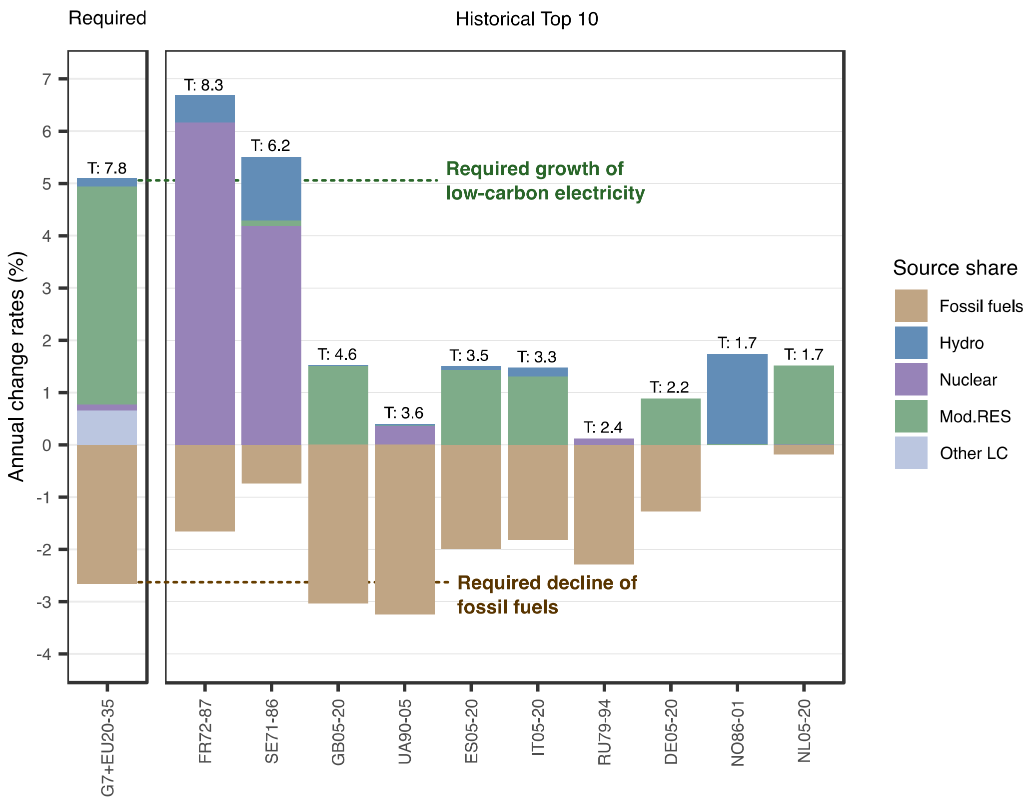


Figure 5.9: Required speed of low-carbon substitutions in 2020-2035, compared to the historically top 10 fastest episodes of low-carbon substitutions for 15 years in all case countries.

Notes: Bars depict the growth of low-carbon electricity (above 0) and the decline of fossil fuels (below 0), while colours represent the shares of energy sources within. Texts at the top of the bars indicate transition speeds, which are the aggregated rates of fossil decline and low-carbon growth (this is calculated using the same approach described in 3.3.1, but for 15 years instead of five years). See Table A1 for country codes.

5.2.5 Latest developments

In 2020-2022, none of the G7 countries and the EU achieved or made significant progress towards the required rate of low-carbon substitutions, as shown in Figure 5.10. Apart from Japan, all member states increased their reliance on fossil fuels for electricity generation. Specifically, the UK, Germany, and Italy experienced a stagnation or significant decline in low-carbon electricity, with Germany and Italy undergoing a notable shift towards high-carbon substitutions. Although Japan underwent low-carbon substitutions in 2020-2022, its rate remained at the slowest 50% speed, far from the required fastest 5% speed to follow the IEA 1.5°C pathway.

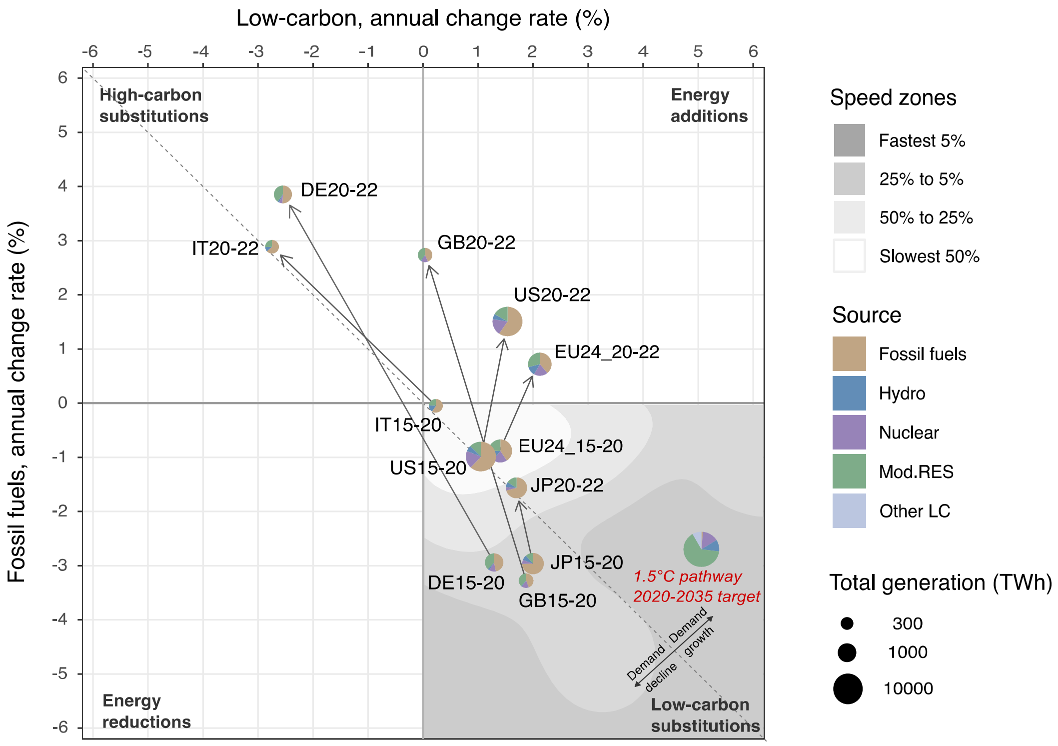


Figure 5.10: Latest developments in the G7 countries and the EU.

Notes: EU24 countries are EU member states excluding France, Germany, and Italy. Canada and France are excluded as their electricity generation is almost fully decarbonised. However, they would still need to accelerate the development of low-carbon sources to be compatible with the IEA 1.5°C pathway.

5.3 Comparing the historical and required electricity transitions

This section comes back to the three questions asked in this paper: (1) How has the energy sector evolved in the G7 and the EU over the last six decades?; (2) Is there any evidence that climate policies have significantly altered the nature and speed of energy transitions beyond historically observed trends?; and (3) What are the implications of the observed trends and the impacts of climate policies for achieving climate targets in the future?

5.3.1 Evolution of the electricity sector in the G7 and the EU

Table 5.2 summarises the key features of electricity transitions in the G7 and the EU in 1960-2035. The overarching historical trend is that technological changes in the electricity sector in the G7 and the EU have strongly correlated with changes in electricity demand. As the demand for electricity grew, all energy technologies tended to grow, but as demand declined, some of the technologies declined (Table 5.2 and Figure 5.2A).

Table 5.2: Historical and required electricity transitions in the G7 and the EU in 1960-2035.

Period		Number of climate policies introduced	Demand	Supply: technological changes and speed		Types of energy transitions and speed
				Fossil fuels	Low-carbon (main growing source)	
Historical	1960-1975	14 (8)	Rapid growth (> 4%)	Rapid growth: max 6.6%	Growth: max 1.9% (Nuclear power)	Rapid energy additions (marginal low-carbon substitutions in 1980-1985)
	1975-1990	44 (28)	Growth (> 2%)	Growth: max 2% (marginally declined in 1980-1985)	Growth: max 2.3% (Nuclear power)	
	1990-2005	718 (427)	Stagnation (< 2%)	Growth: max 1.4%	Growth: max 1.1% (Modern renewables)	Slow energy additions
	2005-2020	1435 (728)	Decline (< 0%)	Decline: max -1.3%	Growth: max 1.0% (Modern renewables)	Slow low-carbon substitutions
Required	2020-2035	NA	Growth (2.5%)	Decline: - 2.7%	Rapid growth: 5.1%	Rapid low-carbon substitutions

Notes: In the column "# of climate policies introduced", the top number represents the total count of policies introduced, while the number in brackets indicates the subset of policies introduced specifically targeting the electricity sector. In the column "Supply: technological changes and speed", the term "max (speed)" refers to the highest rate of technological changes observed within each timeframe. For example, the entry "Growth: max 2.3%" in 1975-1990 was achieved during 1980-1985, mainly through the adoption of nuclear power.

It is thus more common to observe rapidly growing technologies under increasing demand or declining technologies under stagnating demand, though such demand conditions are often neglected in the literature (see, for example, Cherp et al. (2017) on the impacts of different demand conditions for the development of modern renewables and nuclear power in Germany and Japan).

5.3.2 Effects of climate policies

In parallel with these changes in electricity demand and the use of various technologies, the number of climate policies introduced progressively increased in the G7 and the EU particularly after 1990 (Table 5.2). Have these policies significantly altered the historically demand-led technological changes, and if so, how? One clear influence is the recent growth of modern renewables particularly after 2005 (Table 5.2 and Figure 5.2A) which took place under the stagnating and declining demand for electricity. Since there are no past analogies to demand decline, it is difficult to say whether the growth of a new technology under such conditions is historically unique. Still, it is very likely that climate policies have contributed to this phenomenon and thereby facilitated low-carbon substitutions between 2005 and 2020.

However, climate policies have not accelerated the growth of modern renewables beyond the historical rates of other technologies (Figure 5.2A). Here, nuclear power serves as a particularly relevant benchmark, as it was also accelerated by policies following the oil crises in the 1970s (Brutschin et al., 2021; Cherp et al., 2017; Ikenberry, 1986), leading to the first but limited period of low-carbon substitutions in 1980–1985 in the G7 and the EU (Figure 5.6). Interestingly, the growth of nuclear power in the 1970s–80s outpaced the recent growth of all modern renewables combined (Figure 5.11) (also see Fig. A1 for comparison in terms of generation). This contradicts the commonly held view that distributed renewable technologies grow faster than conventional technologies because of their faster learning effects and acceleration due to climate policies (Kern and Rogge, 2016; Wilson et al., 2020).

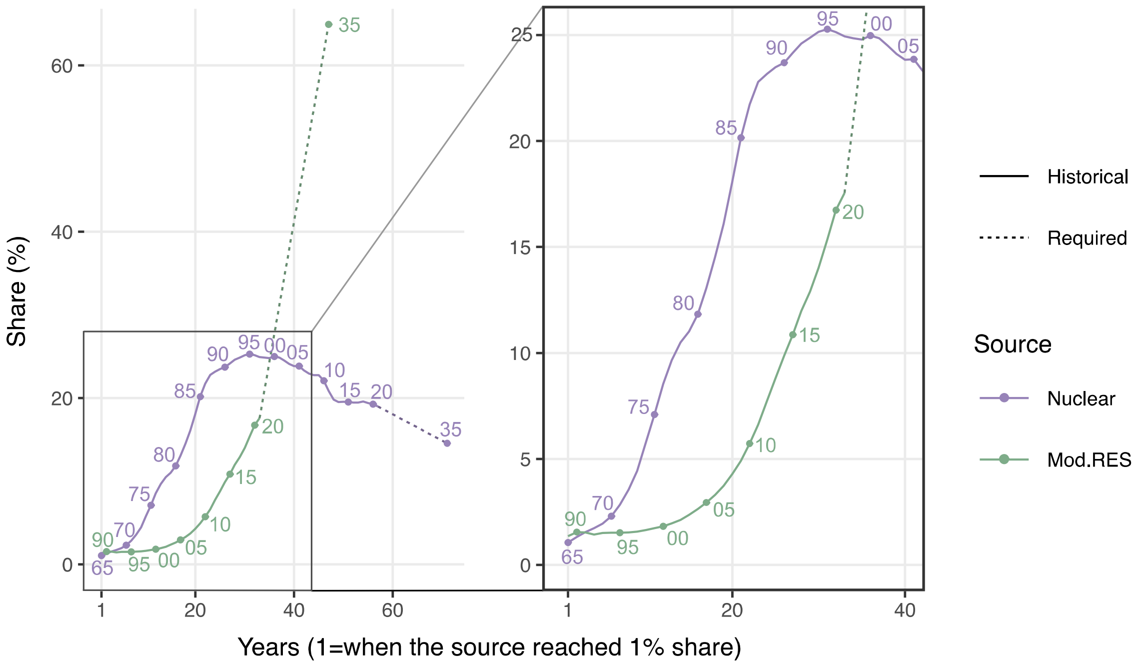


Figure 5.11: Growth of nuclear power and modern renewables in the share of electricity generation after reaching a 1% market share in the G7 and the EU.

Notes: The x-axis represents the number of years after each source supplying 1% of electricity.

Nuclear power has so far also grown faster in individual G7 countries and the EU except for Germany (where it grew at the same speed) and the UK and Italy (where it grew slower) (Figure 5.12). Nevertheless, even the fastest growth of modern renewables in the UK still falls short of the rate required by the IEA 1.5°C pathway. The growth of modern renewables, therefore, needs to be significantly accelerated in all the G7 countries and the EU to keep the global temperature increase to 1.5°C. However, the acceleration in their growth stagnated in the 2010s despite their continuously decreasing costs (Figure 5.5), indicating that re-accelerating the growth would need much stronger policies than historically observed.

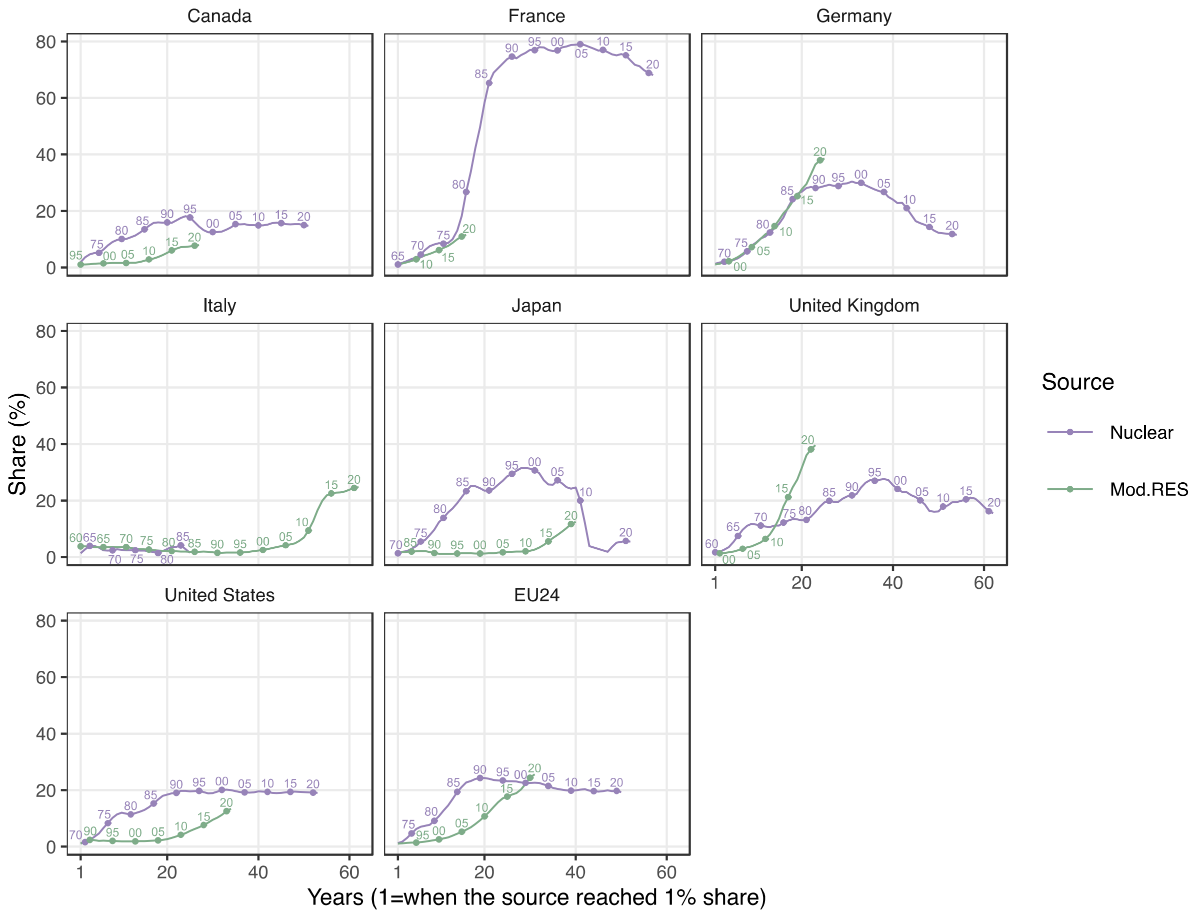


Figure 5.12: Growth speed of nuclear power and modern renewables in the share of electricity generation after reaching a 1% market share in the G7 main member states.

Notes: The x-axis represents the number of years after each source supplying 1% of electricity.

The progress towards decarbonisation in the G7 and the EU has been, therefore, derailed after the first period of low-carbon substitutions in 1980–1985 and slowed down by the limited availability of low-carbon electricity due to the stagnation and decline of nuclear power and the relatively slow growth of modern renewables to compensate for the shortfall (Figure 5.6). As a result, the historical annual maximum growth rate of low-carbon electricity in the G7 and the EU on average remains the record achieved predominantly by nuclear power in 1980–1985 at 2.3%, compared to the most recent rate at 1.0% led by modern renewables in 2015–2020 (Table 5.2).

Since the changes in the use of energy technologies have correlated with the changes in electricity demand, it is logical to ask whether climate policies have impacted the electricity demand dynamics. The increase in climate policies did take place when the electricity demand stagnated and declined, particularly after 1990 (Figure 5.3). However, climate policies did not accelerate demand reduction compared to the past, as a more pronounced reduction occurred between 1970 and 1985 when climate policies were largely absent (Figure 5.3). Looking at individual countries, however, at least a similar speed of demand reduction to the past was recently observed in the UK, Germany and Italy, where a rapid decline of fossil fuels was accompanied (Figure 5.2A). Climate policies in these countries may have played a role in restricting the use of fossil fuels under declining demand, although not accelerating the process compared to the past. Among these countries, only the UK so far maintained a decline in fossil fuels at a pace and duration sufficient to achieve the IEA 1.5°C pathway (Figure 5.9).

In summary, the impacts of climate policies on energy transitions have been limited: while they may have influenced the choice of deployed technologies and thereby affected the type of transitions in the G7 and the EU, they have not accelerated transitions either by expediting the growth of low-carbon technologies or hastening the decline of fossil fuels compared to historically observed trends or rates.

5.3.3 Implications for achieving the IEA 1.5°C pathway in the G7 and the EU

The IEA 1.5°C pathway in the G7 and the EU requires immediate and dramatic acceleration to develop low-carbon electricity five times faster and reduce fossil fuels two times faster on average than the rates observed in 2015–2020. This transition must occur alongside growing electricity demand, a context where fossil fuels historically rarely declined in the G7 and the EU (Figure 5.6). Such high speeds of low-carbon substitutions were historically achieved only for five years in France and Spain in the 1980s (Figure 5.8). Furthermore, there is no historical precedent of sustaining such speeds for a continuous period of 15 years (Figure 5.9). While the sufficiency of the recent growth of low-carbon technologies or the decline of fossil fuels to meet climate targets is debated in the literature (Cherp et al., 2017; Grubb et al., 2020; Muttitt et al., 2023; Odenweller et al., 2022; Smil, 2010; Vinichenko et al., 2023a, 2021; Wilson et al., 2013), this chapter reveals that there has been no instance in the last six decades where the sufficient rates of both technological growth and decline were achieved simultaneously, even in countries with the highest economic, financial, and technological capabilities.

On the other hand, this chapter shows that there are some precedents that achieved either the necessary level of low-carbon technology growth or fossil fuel decline for five years (Figure 5.8) and 15 years (Figure 5.9), producing two distinct speed frontiers in low-carbon substitutions.[6] For example, France in 1972–1987 and Sweden in 1971–1986 achieved an exceptionally high growth (>5%) of low-carbon electricity primarily by nuclear power. Existing literature identifies factors behind such acceleration as the extreme orchestration of resources into a single technology, led by a limited number of actors (Finon and Staropoli, 2001; Grubler, 2010; Hecht, 2000; Kaijser, 1992). Such experiences may not be directly applicable to the challenges we face today not only because such concentrated power "may not be replicable…even in France in the new Millennium" (Grubler, 2010, p. 5174), but also because future transitions are likely to require a combination of multiple technologies and supporting infrastructures (i.e. various renewable technologies, energy storage systems, larger and smarter grid connections, etc.) involving a multitude of actors. Re-accelerating the deployment of nuclear power may be another option. However, this would also face numerous challenges including increasing cost and construction time overruns, rising opposition against the technology for perceived risks, as well as the eroding industry base which has already taken place for decades (Markard et al., 2020). Additionally, deploying such a capital-intensive and

[6] Interestingly, despite being the most well-studied country for energy transitions, Germany has never so far achieved the required technological growth or decline over 15 years (Figure 5.9).

controversial technology may be more difficult in today's increasingly liberalised market (Brutschin et al., 2021).

In terms of the precedents for the necessary decline of fossil fuels, the UK in 2005–2020 and Ukraine[7] in 1990–2005 achieved a rapid decline (faster than -3%) which was primarily driven by the declining demand for electricity (Vinichenko et al., 2021). However, such demand-driven transitions are not compatible with any climate mitigation pathway published by the Intergovernmental Panel on Climate Change (IPCC) for 1.5 or even 2°C because more electricity is necessary in the future to decarbonise other sectors through electrification (Riahi et al., 2022; Rogelj et al., 2018).

Following the IEA 1.5°C pathway thus requires the G7 and the EU to develop low-carbon sources at a similar speed to the development of nuclear power, historically only observable in France or Sweden before 1990, while at the same time replicating the fastest decline of fossil fuels recently occurred in the UK, but instead under growing demand for electricity. The greatest challenge may be that such an unprecedented supply-centred transition must occur across all the G7 countries and the EU simultaneously, requiring a pace and level of coherence never observed in history. Unfortunately, there was no observable trend in this direction during 2020–2022. On the contrary, more fossil fuels were added, and low-carbon electricity generation stagnated and even declined in most countries (Figure 5.10), necessitating even faster transitions by 2035. On the one hand, multiple intertwined causes are contributing to this deviation including the post-COVID 19 economic recovery, the recent energy crisis induced by the Russo-Ukrainian War, and unfavourable weather for renewables in Europe (IEA, 2023c). On the other hand, achieving the decarbonised electricity target by 2035 requires an

[7] Although Ukraine also achieved a compatible decline speed of fossil fuels in 1990-2005, this was primarily caused by the post-Soviet crisis and subsequent economic recessions, which is hardly a model for sustainable transitions (Vinichenko et al., 2021).

unprecedented effort to withstand and overcome disruptions including unexpected challenges, which may also arise in the future.

5.4 Summary

This chapter examined whether and how climate policies have so far altered the nature and speed of energy transitions beyond historical trends and analysed the implications for future transitions. I focused on the G7 countries and the EU in the electricity sector as they have spearheaded the implementation of climate policies, particularly in the sector, and have made repeated commitments to lead the global efforts to mitigate climate change including by committing to decarbonise electricity by 2035.

I find that although climate policies may have influenced the choice of deployed technologies and thereby affected the type of transitions, they have not accelerated the speed of transitions beyond historical trends in the G7 and the EU. Instead, electricity transitions have strongly correlated with the changes in electricity demand in the last six decades. The recent growth of low-carbon electricity through the development of modern renewables remains 50% slower than the historically fastest speed achieved in 1980-1985 when climate policies were largely absent. The recent decline of fossil fuels in the G7 and the EU has, therefore, been facilitated by the overall decrease in electricity demand, allowing the substitution by relatively slowly growing renewables.

Meeting the decarbonised electricity target in the G7 and the EU by 2035 is extremely challenging. It requires achieving immediate and unprecedented supply-driven transitions, with rates of technological growth and decline that have rarely, if ever, been observed in history. None of these countries achieved such transitions in 2020-2022; in fact, in most of the G7 countries and the EU, more fossil fuels were added, and the growth of low-carbon electricity stagnated and declined. Counteracting this trend and meeting the target, therefore, requires drastically different policies rather than incremental changes including finding and enforcing new mechanisms to develop low-carbon electricity and to facilitate a more rapid and continuous decline of fossil fuels.

However, do countries politically target such radically different transitions compared to the past? The next chapter investigates this question by analysing the evolution of energy transition policies in the G7 member states over the last decades.

6. Evolution of energy transition policies in the G7

6.1 Introduction

The previous chapter (5) demonstrates that despite the increasing adoption of climate policies in recent decades, the rate of technological change has remained primarily correlated with changes in energy demand. This observation raises the question of whether the quantity of policies serves as a reliable indicator of political acceleration, though existing studies often call for more policies (Eskander and Fankhauser, 2020; Knill et al., 2012; Schaub et al., 2022).

While the overall stringency of policies is arguably more crucial, the presence of both enabling and hindering factors for political acceleration introduces ambiguity regarding how policy stringency empirically escalates (see the relevant theoretical discussions in the literature in subsection 2.2.2, empirical observations of political acceleration in subsection 2.3.3, and political deceleration in subsection 2.3.4). Therefore, this chapter delves into the evolving stringency of national policies to mitigate climate change in recent decades. Here, I use energy transition projections directly developed or commissioned by national governments as proxies to estimate the changing stringency of policies over time (the limitations of this analysis are described in subsection 3.3.4, and further discussed in subsection 7.5.2).

Applying the same selection criteria as in Chapter 5, I continue to analyse the G7 countries that position themselves as leaders in decarbonisation. However, the focus of this chapter's analysis shifts more towards the national level, given that energy transition policies are formulated and implemented by national governments. This investigation focuses on the developments since 2000, as my findings in Chapter 5 reveal that transitions towards decarbonising the energy sector, as I coin as 'low-carbon substitutions', started to take place after this period in the G7.

The following question will guide the analysis of this chapter:

- How has the stringency of national energy transition policies changed over the last decades, and how does this evolution align with achieving climate targets?

The rest of this chapter is organised as follows. I first present the national transition projections developed in the G7 countries since 2000 in Section 6.2. The evolutions of these projections are then analysed by country in comparison to the required transition to mitigate climate change in Section 6.3. Section 6.4 shows the result of the comparative analyses among the G7 countries. Additionally, the correlation between these projections and actual transitions is analysed in Section 6.5. Lastly, Section 6.6 provides the summary of this chapter.

6.2 Overview of national transition projections analysed

Following the method described in subsection 3.3.4, I identified and analysed 42 national transition projections (75 data points in total as some projections contain multiple end years) in the G7 countries, which were developed between 2000 and 2023 reflecting the existing and planned national policies at the time of projection development. I explain how these projections were developed and justify their use for analysing the evolving stringency of transition policies in the following subsections. The summary of these projections and the major relevant policies is provided at the end of this section in Table 6.1.

6.2.1 Germany

In Germany, the Federal Ministry for Economic Affairs and Energy (BMWi) and its previous predecessors, such as BMWT and BMWA, periodically commission external research organisations to develop transition projections, evaluating existing and planned policies to inform further policymaking. Notably, BMWi has regularly commissioned Prognos, an economic research institute headquartered in Switzerland, to develop projections between 2000 and 2023. Prognos often collaborated with other organisations, most notably the Institute of

Energy Economics at the University of Cologne, Germany (EWi), and the Economic Research Institute in Osnabrück, Germany (gws).

The major projections I identified as best reflecting the changing national policies in Germany towards decarbonisation between 2000 and 2023 are as follows:

- DE1 (2000) (see "ID" in Table 6.1) reflects perhaps one of the most significant events in Germany's energy policy, where the 'red-green' coalition government of the Greens and SPD made a political decision to phase out nuclear power by 2022. This projection development was commissioned by the Greens to align with this policy (Matthes and Cames, 2000).
- DE2 (2005) corresponds to the formalised nuclear phase-out policy (Vorwerk, 2002) as well as Germany's commitment to reduce emissions under the Kyoto Protocol and the EU Emissions Trading Scheme (ETS) in 2005 (Schulz et al., 2005).
- DE3 (2010) informed the decision in 2010 to extend the nuclear phase-out timeline to 2036 as part of the Energy Concept to achieve Germany's newly set long-term climate targets to reduce emissions by 40% by 2020, 55% by 2030, 80-95% by 2050 relative to 1990 levels and to generate electricity from renewable sources by 35% by 2020, 50% by 2030, 80% by 2050 (BMWi, 2010).
- DE4 (2014) reflects the re-commitment to the original nuclear phase-out deadline of 2022 in 2011, following the Fukushima nuclear accident, while keeping the other long-term emission reductions as well as renewable deployment targets (BMWi, 2010).
- DE5 (2020) reflects Germany's strengthened policies after the adoption of the Paris Agreement, encapsulated as the Climate Protection Programme 2030 introduced in 2019, which echoes the amended Federal Climate Change Act (Klimaschutzgesetz) to reduce emissions by 65%, from the previous 55%, by 2030 relative to 1990 levels

(BMU, 2019). Furthermore, the renewable target was increased to supply 65% of electricity, from the previous 50%, by 2030. Additionally, Germany committed to phasing out coal power by 2038, the latest (Kohleausstiegsgesetz) in 2020 (The Federal Parliament of Germany, 2020).

- DE6 (2022) mirrors the coalition agreement of the SPD, the Free Democratic Party (FDP) and the Greens in 2021, which was further strengthened and introduced as the 'Easter Package' after the Russo-Ukrainian War in 2022 to accelerate the phasing-out of coal ("ideally" by 2030) and the development of renewable electricity (85% by 2030, from the previous 65% target) (BMWK, 2022b).

6.2.2 United Kingdom

In the UK, energy transition policies have been outlined in the Energy (White) Paper and similar documents. Additionally, after introducing the Climate Change Act in 2008, the Department for Energy Security and Net Zero (DESNZ) and its predecessors, such as BEIS, DTI and DECC, have been publishing annual Energy and Emissions Projections to monitor the progress towards the decarbonisation target set by the act. These updates are founded on the country's evolving energy and climate policies, which, in turn, are informed by scenarios and recommendations from various research organisations. For example, the University College London developed and maintains the UK's integrated assessment model (UK TIMES) to inform national energy and climate policies. Furthermore, the Climate Change Committee (CCC) plays a significant role in advising the government on climate and energy policies in the UK.

The major projections I identified as best reflecting the changing national policies in the UK towards decarbonisation between 2000 and 2023 are as follows:

- GB1 (2000) reflects the country's target in 2000 to supply 10% of electricity from renewable sources by 2010, which was set in line with the UK's commitment to reduce emissions by 20% by 2010 relative to 1990 levels (DTI, 2000).
- GB2 (2007) reflects the UK's policy in the late-2000s to re-intervene in the energy market to address climate change through developing a "trinity" of energy sources, namely nuclear power, CCS, and modern renewables, in response to the depletion of domestic gas reserves (DTI, 2007). In particular, the government started to actively promote the re-development of nuclear power, as written in White Paper 2007: "The Government's role is therefore to provide a policy framework that encourages the development of a wide range of low carbon technologies… it is in the public interest to give the private sector the option of investing in new nuclear power stations" (DTI, 2007, pp. 16–17).
- GB3 (2011) corresponds to the Climate Change Act in 2008 (The Parliament of the United Kingdom, 2008) and the subsequent Low-carbon Transition Plan in 2009 (The Government of the United Kingdom, 2009), wherein the UK committed to achieving 80% emissions reductions relative to 1990 levels by 2050. The government projected that to achieve this long-term target, the UK needs to largely decarbonise electricity within the 2030s. To achieve this, a number of policies including FiT and Contracts for Difference were introduced to accelerate long-term investments into low-carbon generation technologies (DECC, 2011a).
- GB4 (2014) reflects the further interventions of the government to accelerate the phasing out of fossil fuels and developing low-carbon technologies, particularly by the introduction of the Carbon Price Floor in 2013 to tax fossil generation as well as the introduction of the Electricity Market Reform Delivery Plan in the same year (David, 2018; DECC, 2013). The Capacity Market policy was additionally introduced to ensure

the security of supply through the transition into the new system, which was increasingly supplied by renewable sources (DECC, 2013).

- GB5 (2017) corresponds to the UK Clean Growth Strategy, the country's first long-term strategy aligned with the Paris Agreement, developed in 2017 (BEIS, 2017a). Prior to developing the strategy, the UK became the first country to politically commit to phasing out the unabated use of coal power by 2025 (BEIS, 2017a). Furthermore, together with Canada, the UK initiated the international coalition, Powering Past Coal Alliance (PPCA), to spearhead the global phase-out of coal power in 2017 (PPCA, 2023).
- GB6 (2020) and GB7 (2022) reflect the increased target of the UK set in 2019, following the recommendation of the CCC, to achieve net-zero emissions by 2050 compared to the previous 80% reductions by 2050 below 1990 levels, initially set by Climate Change Act in 2008 (BEIS, 2020a). Additionally, the government established the Nuclear Sector Deal as well as the Offshore Wind Sector Deal with the relevant industries to jointly commit to ensure the accelerated development of the technologies to meet the country's climate targets (BEIS, 2020b, 2018). More detailed strategies on how to achieve the targets were developed as the UK Net-zero Strategy in 2021.
- GB8 (2023) reflects the package of policies in the UK, titled Powering up Britain in 2023 (The Government of the United Kingdom, 2023). This comprehensive set of strengthened policies aims to enhance the country's energy security through various measures. These include increased investment in nuclear power, renewables, hydrogen, and improvements in energy efficiency. Formulated in response to the Russian-Ukrainian War in 2022, the UK has notably raised its offshore wind target to 50GW (compared to the previous 40GW set in 2021). Additionally, there is a fivefold increase targeted for solar power, aiming to reach 70GW by 2030.

It is important to note that, following the establishment of the CCC in 2008, the UK's transition targets have progressively become more normative, as the government is obligated to adopt the CCC's recommendations on 'carbon budgets' set for five-year periods. Nonetheless, a growing gap has emerged between these transition targets and the annual emission and energy projections reported by BEIS in the last decade. This indicates that existing and planned policies have increasingly lagged in their efforts to achieve the targets.

6.2.3 France

In France, Electricity Transmission Network (le Réseau de Transport d'Électricité - RTE), a 100% subsidiary of Electricity of France (Électricité de France - EDF)—the French state-owned electricity monopoly—has been mandated by law since 2000 to periodically provide national energy transition projections based on the country's existing and planned policies.

It is important to point out that the electricity system in France has already been largely decarbonised after the rapid development of nuclear power in the 1970s and 1980s. However, the country still needs to develop more low-carbon sources and phase out fossil fuels to be in line with 1.5°C compatible pathways.

Compared to Germany and the UK, France tends to develop transition policies by following rather than spearheading European directives.

The major projections I identified as best reflecting the changing national policies in France towards decarbonisation between 2000 and 2023 are as follows:

- FR1 (2005) reflects France's response to European Directive 2001/77/EC to promote the use of renewable sources in electricity generation, supplying 22.1% on average in 2010 across the EU member states. France accordingly introduced the POPE (loi Programme fixant les Orientations de Politique Energétique: Law on Energy Policy

Guidelines) in 2005 to supply 21% of electricity from renewable sources including hydro (The Government of France, 2005)

- FR2 (2009) corresponds to France's response to the 2009 EU Energy Directive to mandate EU member states to supply at least 20% of primary energy from renewable sources by 2020. France accordingly targeted to supply min. 23% of primary energy from renewable sources by 2020 by accelerating the development of renewable technologies, particularly hydro, solar, and wind, through the Grenelle Environment Plan in 2009 and its relevant laws (The Government of France, 2010).
- FR3 (2015) mirrors a turning point in France's energy policy where the government, following the Fukushima nuclear accident in 2011, planned to reduce reliance on nuclear power from the then 75% share of electricity in 2012 to 50% in 2025 while filling the gap with renewable sources supplying 40% of electricity in 2025 (The Government of France, 2015)
- FR5 (2021) echoes France's efforts to comply with the EU mandate of developing National Energy and Climate Plans (NECPs) to reduce emissions by 80-95% by 2050 relative to 1990 levels in the EU. France accordingly committed to reduce emissions by 40% by 2030 and 85% by 2050 in its Climate and Energy Law in 2019 (The Government of France, 2019). Additionally, France delayed the timeline of reducing reliance on nuclear power to the year 2035 from the previously set year 2025. This reduction target, however, was abandoned in 2023.

6.2.4 Italy

In Italy, various governmental organisations develop projections as well as other scenarios including the National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), the Ministry of Enterprises and Made in Italy (MIMIT, and its previous predecessors such as MISE) which is the supervisory authority of ENEA, the Ministry for

Environment, Land and Sea Protection (MATTM), and the Regulatory Authority for Energy, Networks and Environment (ARERA).

Similar to France, compared to Germany and the UK, Italy tends to develop transition targets and policies by following rather than spearheading European directives.

The major projections I identified as best reflecting the changing national policies in Italy towards decarbonisation between 2000 and 2023 are as follows:

- IT1 (2010) corresponds to the country's target to supply 17% of final energy consumption from renewable sources in 2020 as mandated by the 2009 EU Renewable Energy Directive. The projection refers to the Position Paper on renewables developed by the government, which estimated the maximum potential of renewable-based electricity for Italy in 2020 (The Ministerial Committee for European Affairs of Italy, 2007).
- IT2 (2012) reflects Italy's compliance with the EU 2050 Roadmap Scenario to reduce emissions by 80-95% by 2050 relative to 1990 levels in the EU. ENEA accordingly developed projections based on the existing policies and additional policies necessary to achieve an interim target of 40% emissions reductions by 2030 relative to 1990 levels in Italy (ENEA, 2012).
- IT3 (2017) reflects Italy's compliance with the EU-wide target to supply 27% of final energy consumption from renewable sources in 2030. National Energy Strategy was subsequently developed in 2017, and Italy planned to supply 30% of primary energy and 55% of electricity from renewable sources by 2030 (MISE and MATTM, 2017).
- IT4 (2021) corresponds to Italy's efforts to further detail its long-term transition plans in line with the EU mandate of developing/updating NECPs in the member states to

achieve the EU target to reduce emissions by 80-95% by 2050 relative to 1990 levels (MISE et al., 2019).

- IT5 (2023) reflects Italy's strengthened plan to accelerate the development of renewable technologies to supply 65% of electricity by 2030 from the previous target of 55% set in 2017 (MISE, 2023).

6.2.5 Japan

In Japan, two central policy documents outline the country's energy transition policies: the Strategic Energy Plan and the Long-term Energy Demand and Supply Outlook. The Japanese Ministry of Economy, Trade, and Industry (METI) have taken the lead in drafting both documents, which typically takes around three years and involves inputs from research organisations such as the Research Institute of Innovative Technology for the Earth (RITE) and expert meetings. Subsequently, these drafts have been approved by the cabinet as governmental decisions. While the Strategic Energy Plan provides an overview of Japan's energy policy objectives, the Long-term Energy Demand and Supply Outlook defines specific energy mix targets to achieve those objectives, making these documents de-facto energy transition policies.

The major projections I identified as best reflecting the changing national policies in Japan towards decarbonisation between 2000 and 2023 are as follows:

- JP1 (2001) reflects Japan's efforts to comply with the emission reduction target set by the Kyoto Protocol and the country's plan to accelerate the development of nuclear power in addition to supplying 1% of electricity from renewable sources by 2010 (METI, 2001).
- JP2 (2005) corresponds to the introduction of the Basic Act on Energy Policy in 2002 (The National Diet of Japan, 2002), and the subsequently developed Strategic Energy Plan, aiming to achieve three primary objectives in Japan's energy policy coined as

"3Es": Energy security; Environment; and Economic efficiency. In this plan, nuclear power was emphasised as the most important technology for Japan's energy future to achieve these overarching objectives (METI, 2005).

- JP3 (2008) and JP4 (2010) echo progressively increased low-carbon electricity generation targets and corresponding policies, primarily through the accelerated development of nuclear power as stipulated in the 2nd Strategic Energy Plan in 2007 and the 3rd Strategic Energy Plan in 2010. In JP4, nuclear power and renewables were expected to supply 50% and 20% of electricity respectively in 2030 in Japan.
- JP5 (2015) marks a significant turning point in Japan's energy policy, formulated as the 4th Strategic Energy Plan in 2015 (METI, 2015), in response to the Fukushima nuclear accident in 2011. This plan places increasing emphasis on the promotion of modern renewables, aiming to supply 22-24% of electricity in 2030. Simultaneously, the projected reliance on nuclear power was subsequently reduced to 22-24% in the envisaged electricity mix in 2030.
- JP6 (2018) aligns with Japan's long-term objectives, as outlined in the 5th Strategic Energy Plan in 2018 (METI, 2018), aimed at reducing emissions by 80% relative to 2013 levels by 2050. The electricity mix target set in 2015 for the year 2030, however, remained unchanged.
- JP7 (2021) reflects Japan's strengthened policy to achieve carbon neutrality by 2050, along with an increased interim target to reduce emissions by 46% relative to 2013 levels by 2030, compared to the previous target to reduce emissions by 26% by 2030. Consequently, the electricity mix target was revised to supply 36-38% from renewables and 20-22% from nuclear power in 2030, marking the first time that Japan targeted a higher share of electricity from renewable sources compared to nuclear power (METI, 2021).

6.2.6 Canada

In Canada, the Canada Energy Regulator (CER) and its predecessor, the National Energy Board (NEB), have annually published projections called Canada's Energy Future, reflecting the existing and planned transition policies in the country since 2007. This centralised annual projection practice has also been observed in the UK (since 2008) and in the US (since 1979).

Similar to France, it is important to point out that the electricity system in Canada has already been largely decarbonised, primarily due to the abundant hydropower resources. Nevertheless, the country still needs to develop more low-carbon sources and phase out fossil fuels to be in line with 1.5°C compatible pathways.

The major projections I identified as best reflecting the changing national policies in Canada towards decarbonisation between 2000 and 2023 are as follows:

- CA1 (2007) reflects Canada's first international commitment in 2007 to reduce emissions by 20% relative to 2006 levels by 2020, coined as the "Turning the Corner" policy (The Government of Canada, 2007). Additionally, the government also committed to reducing emissions by 60-70% relative to 2006 levels by 2050.
- CA2 (2011) corresponds to the country's weakened commitment in 2009, compared to the one in 2007, to reduce emissions by 17% relative to 2005 levels by 2020 under the Copenhagen Accord (Office of the Auditor General of Canada, 2021). Furthermore, in 2011, Canada withdrew from the Kyoto Protocol, where the country previously committed to reducing emissions by 6% below the 1990 levels on average between 2008 and 2012.
- CA3 (2016) is based on Canada's commitment in 2015 under the Paris Agreement to reduce emissions by 30% relative to 2005 levels by 2030. Canada also published the

Pan-Canadian Framework on Clean Growth and Climate Change in 2016, which is the country's first comprehensive transition plan to mitigate climate change (ECCC, 2016).

- CA4 (2021) echoes the series of policies implemented since 2016, most particularly the coal phase-out policy by 2030 in 2018. Additionally, Canada updated the 2016 Pan-Canadian Framework with A Healthy Environment and a Healthy Economy Plan, which introduced a number of new measures to accelerate transitions (ECCC, 2020).
- CA5 (2023) reflect the country's strengthened commitment to reduce emissions by 40-45% relative to 2005 levels by 2030. Canada accordingly introduced the 2030 Emissions Reduction Plan: Clean Air, Strong Economy to outline measures to achieve the reduction target (The Government of Canada, 2023).

6.2.7 United States

In the US, the Energy Information Administration (EIA) of the US Department of Energy has annually published energy transition projections since 1979, the longest history of such centralised analyses among the G7 countries. These projections are based on the use of the National Energy Modeling System (NEMS), an integrated energy-economy-environment model, first developed in 1993 by the EIA (EIA, 2019).

The major projections I identified as best reflecting the changing national policies in the US towards decarbonisation between 2000 and 2023 are as follows:

- US1 (2000) reflects the Climate Change Action Plan of the Clinton Administration in 1994, which aimed to reduce emissions to the 1990 levels by 2000 with a number of voluntary measures.
- US2 (2006) reflects the Federal Energy Policy Act of 2005 which introduced, among other things, energy efficiency standards for various appliances used in the residential and commercial sectors, renewable fuel standards and tax benefits for various low-

carbon energy sources including nuclear power and renewables (The Federal Government of the United States, 2005). Renewable Portfolio Standards were also introduced in multiple states, most notably in California.

- US3 (2010) reflects the American Recovery and Reinvestment Act of 2009 (The Federal Government of the United States, 2009), which was introduced following the financial crisis in 2008, as “the largest single investment in clean energy in history” under the Obama Administration providing more than 90 billion USD and further mobilising 150 billion USD for clean energy investments (The White House, 2016).
- US4 (2016) reflects the Clean Power Plan under the Obama Administration, marking the inaugural federal-level initiative mandating emission reductions in the country. Specifically targeting the electricity sector, the policy aimed to reduce emissions by 32% relative to 2005 levels by 2030, accomplished through carbon emission limits imposed on both existing and new power plants. This plan was designed particularly to reduce the use of coal and accelerate the development of renewable sources (EPA, 2015).
- US5 (2018) reflects President Trump’s executive order in 2017 to repeal the Clean Power Plan. The Trump Administration additionally decided to withdraw from the Paris Agreement in 2017 and suspended other climate change policies developed by the Obama Administration.
- US6 (2021) incorporates the Affordable Clean Energy rule in 2019 (EPA, 2019), which replaced the Clean Power Plan and aimed to increase the energy efficiency of existing and new power plans without mandating emissions reductions.
- US7 (2023) reflects the turn-around of the US to re-join the Paris Agreement and address climate change under the leadership of President Biden, where the US committed to decarbonise electricity by 2035 and achieve net zero emissions by 2050

(The White House, 2021). The Biden Administration has also introduced a series of 'grand-breaking' policies, including the Infrastructure Investment and Jobs Act in 2021 and the Inflation Reduction Act in 2022, together accounting for more than 1.5 trillion USD to accelerate climate change mitigation and adaptation actions in the country.

Table 6.1: Major energy transition projections of the G7 countries between 2000 and 2023

Notes: One projection may encompass several forecasted years, particularly when presenting detailed projections for the distant future, as seen in the UK, Canada, and the US. In such cases, forecasted years in bold are selected for the comparative analyses of this chapter, where * indicates that data is extrapolated from the last available data point and ** shows that data is interpolated between available data points. Furthermore, in cases where multiple projections are available for the same year, including those with specific assumptions alongside reference scenarios, the ones that best reflect the policies during projection development are selected. The “case chosen” column shows the outcomes of these selections, and the rationale for each choice is explained in Section 6.2. The “authority” column indicates governmental institutions responsible for either developing or commissioning the development of each projection.

Country	ID	Year		Projection name	Case chosen	Major relevant policies	Authority	Reference
		Published	Forecasted					
Germany	DE1	2000	**2010/ 2020/ 2035***	Energiewende 2020: The path to a sustainable energy industry	Reference	1998 Red-green coalition to phase out nuclear by 2022	Greens	(Matthes and Cames, 2000)
	DE2	2005	**2010/ 2020/** 2030/ **2035***	The development of the Energy markets up to the year 2030	Reference	2002 Atomgesetz, 2005 Kyoto Protocol, 2005 EU ETS	BMWA	(Schulz et al., 2005)
	DE3	2010	**2020/** 2030/ **2035**/** 2040	Energy scenarios for an energy concept of the federal government	SIIA	2010 Energy Concept to extend the nuclear phase-out to 2036	BMWT	(Schlesinger et al., 2010)
	DE4	2014	**2020/** 2030/ **2035**/** 2040	Development of the energy markets - Energy reference forecast	Reference	2011 Recommitment to the original nuclear phase-out by 2022	BMWT	(Schlesinger et al., 2014)
	DE5	2020	2030/ **2035***	Energy Industry Projections and Impact Assessments 2030/2050	Climate	2019 Climate Action Programme (65% RES electricity by 2030)	BMWi	(Kemmler et al., 2020)
	DE6	2022	2030/ **2035***	Implications of the planned expansion of renewable energies according to the Easter package and EEG 2023	OP	2021 Coalition Agreement (80% RES electricity by 2030), 2022 Easter Package (i.e. Erneuerbare-Energien-Gesetz - EEG 2023)	N/A	(Sprenger and Schäfer, 2022)
United Kingdom	GB1	2000	**2010/ 2035***	Energy paper 68 Energy Projections for the UK	Central	2000 RES 10% electricity target by 2010	DTI	(DTI, 2000)
	GB2	2007	**2010/ 2020/ 2035***	Meeting the Energy Challenge: A White Paper on Energy	High (new nuclear)	2007 Support for “Trinity”: RES, nuclear, and CCS, 2009: Renewable Obligation	DTI	(DTI, 2007)
	GB3	2011	**2020/** 2030/ **2035***	Updated energy and emissions projections 2011	Central	2008 Climate Change Act (80% emission reductions relative to 1990 levels), 2009 Low-carbon Transition Plan, 4th Carbon Budget	DECC	(DECC, 2011b)
	GB4	2014	**2020/ 2035**	Updated energy and emissions projections 2014	Reference	2013 Carbon tax, Electricity Market Reform Delivery Plan	DECC	(DECC, 2014)
	GB5	2017	**2020/ 2035**	Updated energy and emissions projections 2016	Reference	2015 Coal phase out by 2025, 2017 UK Clean Growth Strategy, 5th Carbon Budget	BEIS	(BEIS, 2017b)

Country	ID	Year		Projection name	Case chosen	Major relevant policies	Authority	Reference
		Published	Forecasted					
	GB6	2020	**2035**	Updated energy and emissions projections 2019	Reference	2019 Commitment to carbon neutrality (100% emission reductions relative to 1990 levels) by 2050	BEIS	(BEIS, 2020c)
	GB7	2022	**2035**	Updated energy and emissions projections 2021 to 2040	Reference	2021 Revised Climate Change Act, 2021 Net-zero Strategy by 2050, 6th Carbon Budget	BEIS	(BEIS, 2022)
	GB8	2023	**2035**	Updated energy and emissions projections 2022 to 2040	Reference	2023 Powering Up Britain	DESNZ	(DESNZ, 2023)
France	FR1	2005	**2010/ 2016/ 2035***	Generation Adequacy Report on the electricity supply-demand balance in France 2005	High-RES	2005 RES 21% electricity target by 2010	CRE	(RTE, 2005)
	FR2	2009	**2020/** 2025/ **2035***	Generation Adequacy Report on the electricity supply-demand balance in France 2009	High-RES	2008 Grenelle Environnement Plan to further accelerate the development of modern renewables while increasing energy efficiency	CRE	(RTE, 2009)
	FR3	2015	**2020/** 2030/ **2035***	Generation Adequacy Report on the electricity supply-demand balance in France 2015	New-mix	2012 Plan to reduce nuclear dependence to 50% by 2025, which was legalised as 2015 The Energy Transition for Green Growth Act	CRE	(RTE, 2015)
	FR4	2021	2030/ **2035***	Generation Adequacy Report on the electricity supply-demand balance in France 2020	PPE	2019 Energy and Climate Law (carbon neutrality by 2050), 2020 Revised National Low-carbon Strategy, which delayed the reliance reduction target of nuclear power to 2035	CRE	(RTE, 2020)
Italy	IT1	2010	2020/ **2035***	Renewable Sources 2010: Research and innovation for a low-carbon future	Act+	2005 Position Paper on Renewables, 2009 EU Renewable Energy Directive, setting 17% RES PE target for Italy in 2020	ENEA	(ENEA, 2010)
	IT2	2012	**2020/** 2030/ **2035***	Energy and Environment Report 2009-2010	Pol-Corr	2011 EU target to reduce 80-95% GHG below 1990 levels by 2050	ENEA	(ENEA, 2012)
	IT3	2017	**2020**/** 2025/ 2030/ **2035***	National Energy Strategy 2017	SEN	2016 EU Clean Energy Package (27% RES PE within EU by 2030), 2017 National Energy Strategy (accordingly supply 55% of renewable based-electricity by 2030)	MISE-MATTM	(MISE and MATTM, 2017)
	IT4	2021	2030/ **2035**/** 2040	Scenario National Trend Italy	New-Trebd	2018 EU Mandate the member states to develop National Energy and Climate Plan, which was developed and published in 2019	ARERA	(Snam and Terna, 2021)
	IT5	2023	2030/ **2035**/** 2040	Revised Integrated National Energy and Climate Plan (PNIEC)	PNIEC	2023 RES electricity 65% target by 2030	MISE	(MISE, 2023)
Japan	JP1	2001	**2010/ 2035***	Long-term energy demand and supply outlook 2001	Additional measure	1997 Kyoto Protocol, 2001 RES electricity 1% target by 2010	METI	(METI, 2001)
	JP2	2005	**2010/** 2030/ **2035***	Long-term energy demand and supply outlook 2005	Max-Nuclear	2003 1st Strategic Energy Plan	METI	(METI, 2005)
	JP3	2008	**2020/** 2030/ **2035***	Long-term energy demand and supply outlook 2008	Best-effort	2007 2nd Strategic Energy Plan	METI	(METI, 2008)

Country	ID	Year: Published	Year: Forecasted	Projection name	Case chosen	Major relevant policies	Authority	Reference
	JP4	2010	2030/ **2035***	3rd Strategic Energy Plan	3rd SEP	2010 3rd Strategic Energy Plan (nuclear power and renewables to supply 50% and 20% of electricity respectively by 2030)	METI	(METI, 2010)
	JP5	2015	2030/ **2035***	Long-term energy demand and supply outlook 2015	4th SEP	2014 4th Strategic Energy Plan after the Fukushima nuclear accident in 2011	METI	(METI, 2015)
	JP6	2018	2030/ **2035***	5th Strategic Energy Plan	5th SEP	2018 5th Strategic Energy Plan	METI	(METI, 2018)
	JP7	2021	2030/ **2035***	6th Strategic Energy Plan	6th SEP	2021 6th Strategic Energy Plan	METI	(METI, 2021)
Canada	CA1	2007	**2020/** 2030/ **2035***	Canada's Energy Future: Reference Case and Scenarios to 2030	Reference	2005 Kyoto Protocol, 2007 "Turning the corner plan": 20% GHG below 2006 levels by 2020	NEB	(The Government of Canada, 2007)
	CA2	2011	**2020/ 2035**	Canada's Energy Future: Energy supply and demand projections to 2035	Reference	2009 Copenhagen Accord: 17% GHG below 2005 levels by 2020, 2011 Withdrawal from Kyoto Protocol	NEB	(The Government of Canada, 2011)
	CA3	2016	**2020/ 2035**	Canada's Energy Future 2016: Energy supply and demand projections to 2040	Reference	2016 30% GHG below 2005 levels by 2030 under the Paris Agreement, 2016 Pan-Canadian Framework on Clean Growth and Climate Change	NEB	(The Government of Canada, 2016)
	CA4	2021	**2020/ 2035**	Canada's Energy Future 2021	Current Policies	2018 Phasing out coal by 2030, 2020 A Healthy Environment and a Healthy Economy plan, 2021 Canadian Net-Zero Emissions Accountability Act	CER	(The Government of Canada, 2021)
	CA5	2023	**2020/ 2035**	Canada's Energy Future 2023	Current Policies	2022 Canada's 2030 Emissions Reduction Plan to reduce emissions by 40-45% below 2005 levels by 2030	CER	(The Government of Canada, 2023)
United States	US1	2000	**2010/ 2020/ 2035***	Annual Energy Outlook 2000 with projections to 2020	Reference	1993 Climate Change Action Plan to reduce emissions to the 1990 levels by 2000	DOE/EIA	(EIA, 2000)
	US2	2006	**2010/ 2020/** 2030/ **2035***	Annual Energy Outlook 2006 with projections to 2030	Reference	2002 State renewable portfolio standard (RPS) programs, 2005 Energy Policy Act of 2005,	DOE/EIA	(EIA, 2006)
	US3	2010	**2020/ 2035**	Annual Energy Outlook 2010 with projections to 2035	Reference	2009 American Recovery and Reinvestment Act, "largest single investment in clean energy in history"	DOE/EIA	(EIA, 2010)
	US4	2016	**2020/ 2035**	Annual Energy Outlook 2016 with projections to 2040	Reference	2015 Clean Power Plan to target 32% emissions reduction in electricity generation below 2005 levels	DOE/EIA	(EIA, 2016)
	US5	2018	**2020/ 2035**	Annual Energy Outlook 2018 with projections to 2050	Reference	2017 Trump Administration to withdraw from Paris agreement and repeal Clean Power Plan	DOE/EIA	(EIA, 2018)
	US6	2021	**2035**	Annual Energy Outlook 2021 with projections to 2050	Reference	2020 Affordable Clean Energy, replacing Clean Power Plan	DOE/EIA	(EIA, 2021)
	US7	2023	**2035**	Annual Energy Outlook 2022 with projections to 2050	Reference	2021 Netzero target by 2050, 2021 Infrastructure Investment and Jobs Act, 2022 Inflation Reduction Act	DOE/EIA	(EIA, 2023)

6.3 Ratcheting up of policies reflected in projections towards 2035

This section provides analyses of the evolving stringency of transition policies in the G7 countries separately. Comparative analyses across the countries are provided in the following section (6.4).

6.3.1 Germany

Overall, energy transition projections in Germany developed between 2000 and 2023 towards 2035 indicate a ratcheting-up in transition policies to accelerate the growth of low-carbon technologies and the decline of fossil fuels for electricity supply (Figure 6.1). A notable shift can be observed around 2010: Germany initially projected to decrease total electricity generation until 2010 (see the 2035 projections developed in 2000 and 2005 in Figure 6.1) but subsequently shifted to increase thereafter (see the 2035 projections developed in and after 2010), aligning better with the IEA 1.5°C pathway. As a result, the most recent projection in 2022 comes closest to what is required for Germany to achieve the 1.5°C target under the IEA net-zero pathway by 2035.

Taking a closer look, it is interesting to see that Germany did not project significant development of renewables until 2010 (see the 2035 projections developed in 2000 and 2005 in Figure 6.1B. This implies that Germany started to aim for substantial restructuring of its energy system only after 2010, while the existing literature portrays the country as actively pursuing the state-led transition (‘Energiewende’) from conventional fossil and nuclear technologies to renewables since the 1980s (Hirschhausen, 2014; Jacobs, 2012). On the contrary, while it is true that Germany began introducing support for developing renewables well before 2010 (see subsection 6.2.1, also subsection 4.2.4), the intent and stringency of these policies remained relatively low to almost negligible until 2010 in comparison to the magnitude of transitions necessary for climate change mitigation.

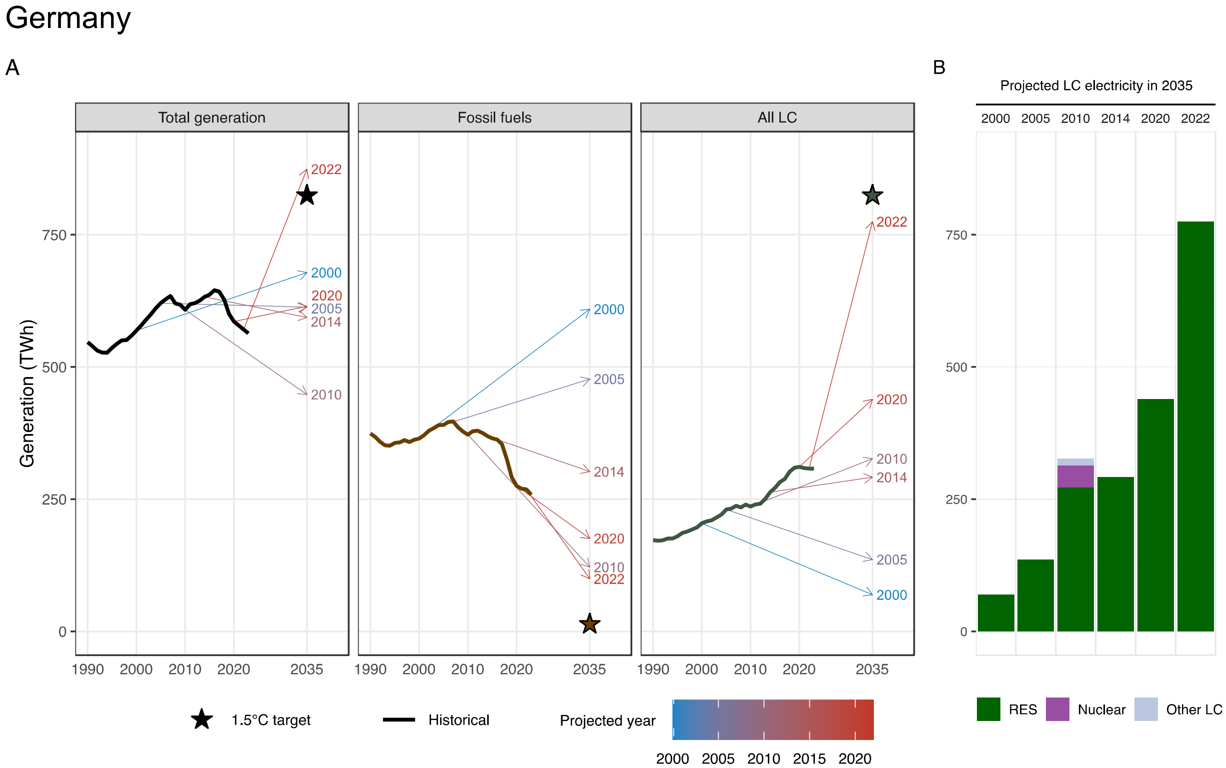


Figure 6.1: Germany - historical evolution of transition projections towards 2035 (A) and the sources of projected low-carbon electricity in 2035 (B)

Notes: In Panel A, “All LC” refers to all low-carbon sources including RES, Nuclear, and “Other LC”. Other LC in Panel B refers to fossil fuels with CCS in Germany. Detailed information on the projections used for this analysis can be found in Section 6.2, in particular Table 6.1.

The later aim for low-carbon substitutions in Germany than commonly assumed is likely due to the fact that Germany prioritised phasing out nuclear power, a low-carbon energy source, rather than utilising the technology to mitigate climate change. Even in 2014, Germany’s primary focus remained on renewables replacing nuclear power, not fossil fuels, resulting in a projected consistent supply of low-carbon electricity of around 250 TWh between 2014 and 2035 (see the actual supply in 2014 and the 2035 projection developed in the same year in Figure 6.1A). It was only in the late 2010s that Germany began to accelerate the substitution of fossil fuels with renewables, as shown in the projections developed in 2020 and further in 2022.

This recently planned acceleration in low-carbon substitutions in Germany, following the Russo-Ukrainian War in 2022, sets the latest projection apart from both other projections and historical transition rates in the country (Figure 6.2).

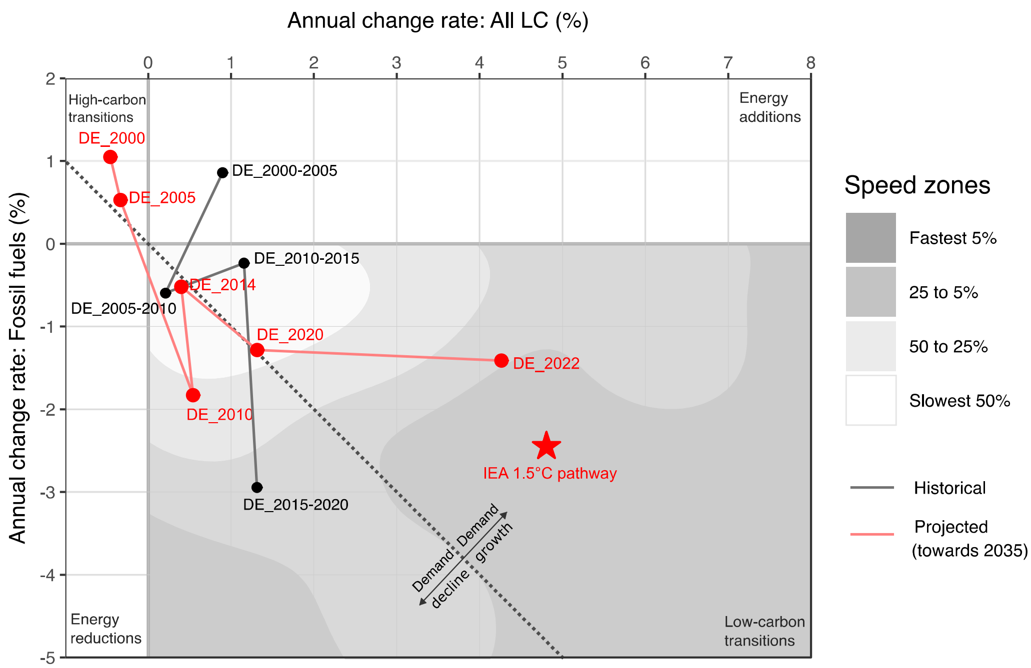


Figure 6.2: Germany - speed zones and historical, projected, and required rates of low-carbon substitutions

Notes: The speed zones in this figure are identical to those in Figure 5.8, which are constructed by the density of relevant national historical episodes observed over five years between 1960 and 2020 where the total generation was more than 100 TWh (see subsections 3.2.3 and 3.3.4 for the detailed framework and methods).

In contrast to the marginal increase of low-carbon electricity in the 2010s, following the IEA 1.5°C pathway would require Germany to accelerate its expansion by five times compared to its historical rate in 2015-2020 (Figure 6.2). While the latest projection developed in 2022 reflecting the 'Easter Package' comes very close to this rate, the authors of this projection signal a feasibility concern (Sprenger and Schäfer, 2022) indicating that this projection includes the political commitments and targets made after the Russian-Ukrainian War in 2022, which have not materialised in policy instruments yet.

On the one hand, both historical and projected rates have generally evolved towards swifter low-carbon substitutions in Germany. On the other hand, both the most recent historical rate (DE_2015-2020) and projected rate (DE_2022) still fall within the top 25-5% speed zones, remaining distant from the fastest 5% speed necessary to meet the 1.5°C pathway. Should Germany further expedite its reduction of fossil fuels, such as committing to a coal phase-out by 2030 or earlier, the country would for the first time enter the fastest 5% speed zone and could then be acknowledged as a leading country in low-carbon substitutions.

6.3.2 United Kingdom

In contrast to Germany, transition projections in the UK developed between 2000 and 2023 towards 2035 do not indicate a continuous ratcheting-up in the stringency of policies to accelerate the growth of low-carbon electricity or the decline of fossil fuels (Figure 6.3). The highest supply of low-carbon electricity was projected in 2014, with subsequent years showing lower supplies. However, the latest projection in 2023, developed after the Russo-Ukrainian War, indicates generating a comparable amount of low-carbon electricity with an accelerated speed of development. This updated projection also reflects the intention to almost completely phase out fossil fuels in the electricity supply by 2035.

Similar to Germany, the UK did not project rapid low-carbon substitutions in the 2000s (Figure 6.3). Differing from Germany, however, the UK subsequently aimed for considerably faster low-carbon substitutions, incorporating renewables, nuclear power, and other low-carbon technologies (specifically, CCS in the UK) in the early 2010s. Conversely, these projected rates towards 2035 decelerated in the late 2010s and the early 2020s, due to the progressively reduced supply projected from nuclear power. This is interesting because the UK has been increasingly supportive of nuclear power in its future energy supply since the mid-2000s (see subsection 4.3.4). Therefore, this shift could be interpreted as a downward revision of previously ambitious nuclear power targets due to mounting challenges despite the growing political backing.

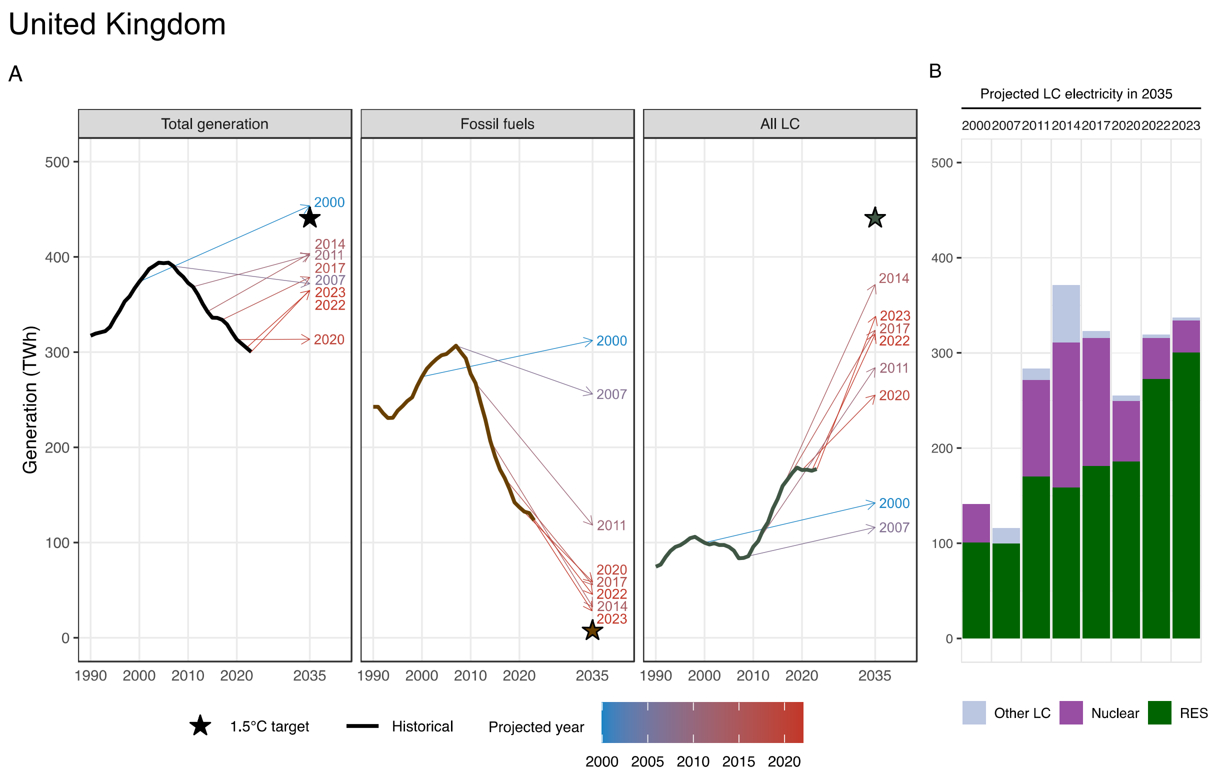


Figure 6.3: UK - historical evolution of transition projections towards 2035 (A) and the sources of projected low-carbon electricity in 2035 (B).

Notes: In Panel A, "All LC" refers to all low-carbon sources including RES, Nuclear, and "Other LC". Other LC in Panel B refers to fossil fuels with CCS in the UK. Detailed information on the projections used for this analysis can be found in Section 6.2, in particular Table 6.1.

It is also interesting that the UK projected a similar level of electricity generation required under the 1.5°C pathway in 2000 but not in the subsequent years, including the latest projection in 2023. This may be due to the fact that electricity generation decreased consistently in the UK between 2005 and 2022. Additionally, it may be the case that the increasing attention to the need for more electricity to meet climate targets through electrifying other energy sectors is a relatively recent development, emerging in the late 2010s.

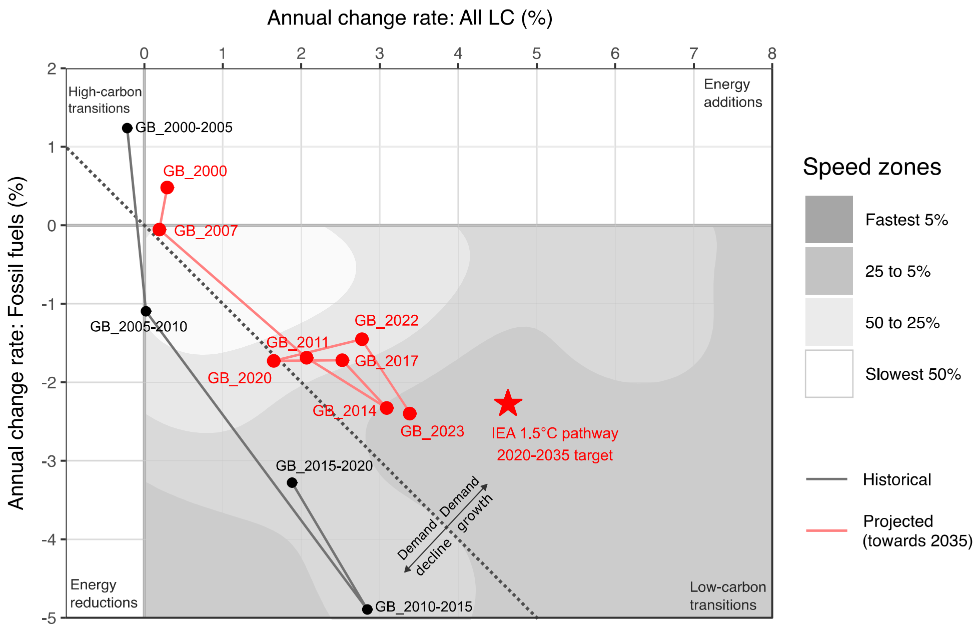


Figure 6.4: UK - speed zones and historical, projected, and required rates of low-carbon substitutions

Notes: The speed zones in this figure are identical to those in Figure 5.8, which are constructed by the density of relevant national historical episodes observed over five years between 1960 and 2020 where the total generation was more than 100 TWh (see subsections 3.2.3 and 3.3.4 for the detailed framework and methods).

In contrast to the historical decline in electricity generation in the UK between 2005 and 2023, achieving the IEA 1.5°C pathway requires the country to accelerate the development of low-carbon electricity by 1.5 times the rate observed in 2010 and 2015 (or twice the rate in 2015-2020) to achieve a 2.4% yearly increase in electricity generation from 2020 to 2035 (i.e. ca. 35% overall increase during the period) (Figure 6.4). The nearest rate was projected in 2023, which, while falling short of low-carbon electricity supply, would meet the required rate of fossil fuel decline. The pivotal determinant for achieving this necessary pace thus hinges on whether nuclear power can be revitalised as initially envisioned in the early 2010s or if renewables and other technologies like CCS can be developed several times faster than historical rates in the country.

6.3.3 France

France's electricity system underwent significant decarbonisation during the 1970s and 1980s, driven by the rapid expansion of nuclear power (see Figure 5.9). However, in recent decades, the role of nuclear power has gradually decreased due to the increasing contribution of modern renewables (Figure 6.5). While France projected a substantial decrease in nuclear power in 2015 towards the future, following the political decision to reduce the reliance on the technology after Fukushima, this trend was quickly reversed by 2020.

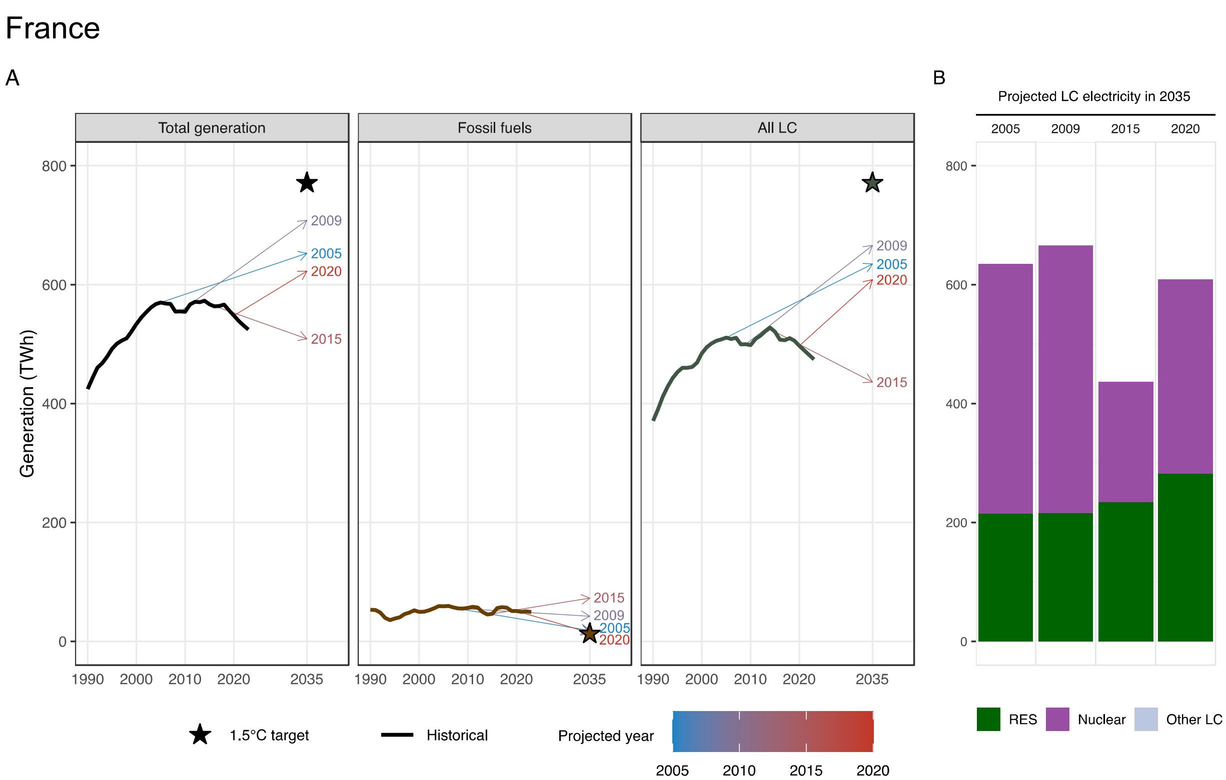


Figure 6.5: France - historical evolution of transition projections towards 2035 (A) and the sources of projected low-carbon electricity in 2035 (B)

Notes: In Panel A, "All LC" refers to all low-carbon sources including RES, Nuclear, and "Other LC". There was no energy source considered as "Other LC" in the projections analysed for France. Detailed information on the projections used for this analysis can be found in Section 6.2, in particular Table 6.1.

Compared to the other G7 countries, achieving the IEA 1.5°C pathway in France would be relatively more attainable as it only requires the country to develop low-carbon electricity at a rate historically achieved by many countries (Figure 6.6). However, none of the historical or projected transitions in France between 2000 and 2023 is compatible with this pathway.

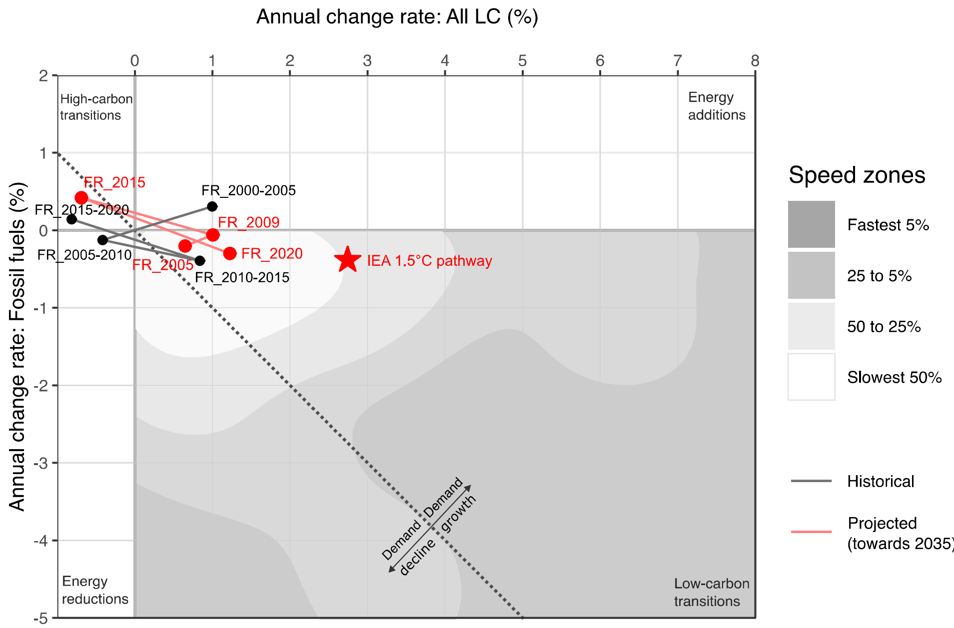


Figure 6.6: France - speed zones and historical, projected, and required rates of low-carbon substitutions

Notes: The speed zones in this figure are identical to those in Figure 5.8, which are constructed by the density of relevant national historical episodes observed over five years between 1960 and 2020 where the total generation was more than 100 TWh (see subsections 3.2.3 and 3.3.4 for the detailed framework and methods).

6.3.4 Italy

The evolution of energy transition projections in Italy indicates a distinct shift in transition policies in the mid-2010s (compare the 2035 projections developed in 2012 and 2017 in Figure 6.7), leading to the faster decline of fossil fuels and the growth of low-carbon electricity (100% renewables as Italy phased out nuclear power in the 1990s) projected towards 2035. Notably, the projections for total generation have been progressively adjusted downward, in line with the historical trend between 2010 and 2023 in the country.

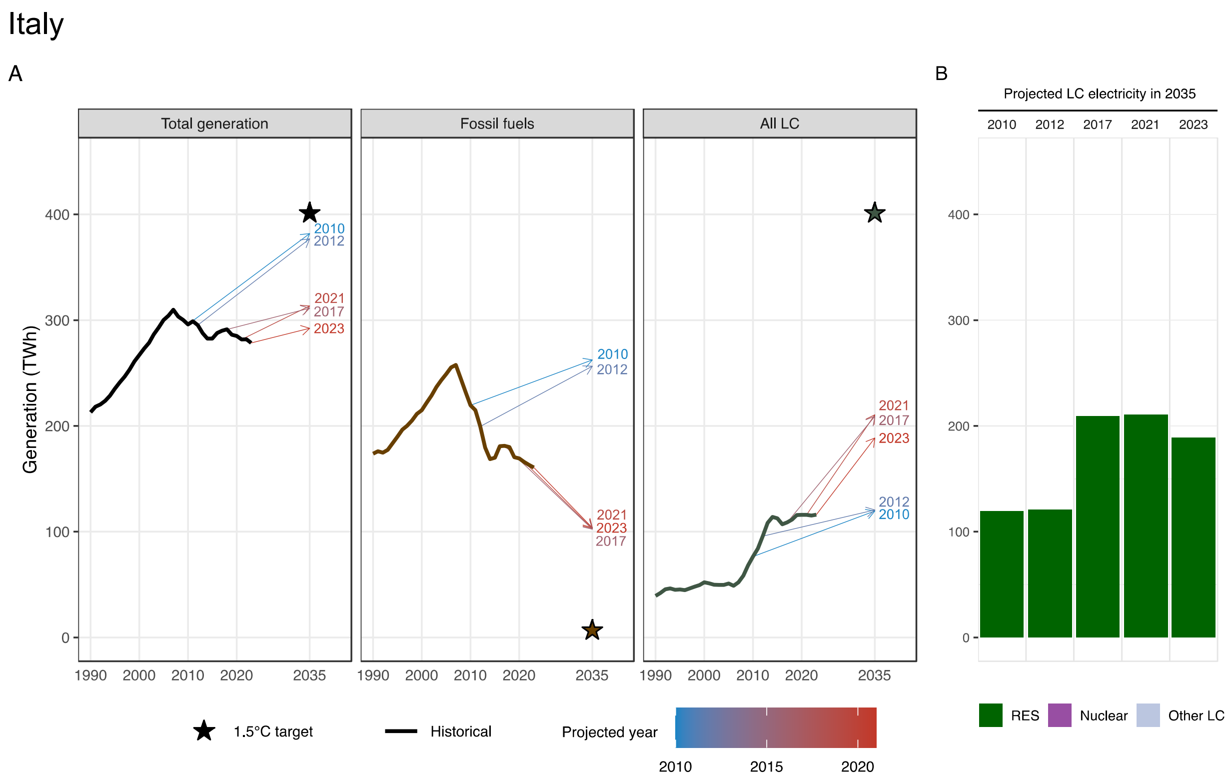


Figure 6.7: Italy - historical evolution of transition projections towards 2035 (A) and the sources of projected low-carbon electricity in 2035 (B)

Notes: In Panel A, "All LC" refers to all low-carbon sources including RES, Nuclear, and "Other LC". There was no energy source considered as "Other LC" in the projections analysed for Italy. Detailed information on the projections used for this analysis can be found in Section 6.2, in particular Table 6.1.

To align with the IEA 1.5°C pathway, Italy would need to more than double the speed of low-carbon substitutions towards 2035 compared to the rates projected in 2023. This involves significantly strengthening the country's efforts to supply ca. 400 TWh of electricity from low-carbon sources in 2035, marking a fourfold increase compared to ca. 100 TWh supplied in 2023.

Interestingly, Italy projected a further expansion of fossil fuels in electricity supply in the early 2010s, a trajectory that contradicts the EU target established during that period to reduce emissions by 80-95% below 1990 levels by 2050. A similar growth of fossil fuels was observed only in the G7 countries endowed with substantial fossil resources, namely Canada and the US, but not in other G7 countries.

Additionally, it is worth noting that Italy's recent projections show the stagnation of modern renewables' growth towards 2035 since 2017 (Figure 6.7B), significantly diverging from the other G7 countries. While there is an indication that Italy may re-develop nuclear power in the future (Pascale, 2023), its contribution to the energy mix by 2035 would likely be limited, considering the lengthy construction time required for new nuclear power plants.

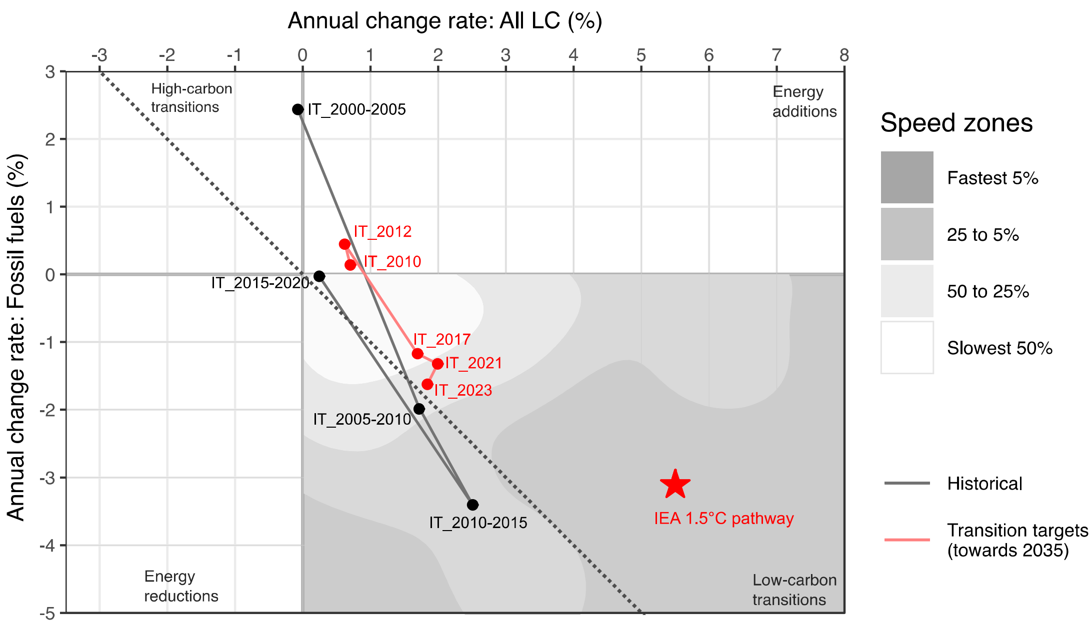


Figure 6.8: Italy - speed zones and historical, projected, and required rates of low-carbon substitutions

Notes: The speed zones in this figure are identical to those in Figure 5.8, which are constructed by the density of relevant national historical episodes observed over five years between 1960 and 2020 where the total generation was more than 100 TWh (see subsections 3.2.3 and 3.3.4 for the detailed framework and methods).

In contrast to the accelerated growth of low-carbon electricity projected during the 2010s, Italy actually witnessed a marked deceleration in the expansion of low-carbon electricity, entering a state of near-stagnation throughout the same decade (Figure 6.8). Achieving the IEA 1.5°C pathway would thus be extremely challenging, requiring Italy to reverse the trend completely to immediately develop low-carbon electricity by ca. 24 times faster in 2020-2035 than the historical rate between 2015 and 2020 (or ca. two times faster than the rate in 2010-2015). Such a dramatic shift has not taken place; on the contrary, the electricity supply from renewables decreased in recent years in Italy (see Figure 5.10).

6.3.5 Japan

The evolution of Japan's energy transition projections from 2000 to 2023 towards 2035 exhibits similarities with those of the UK, indicating that transition policies regarding future low-carbon electricity supply were most ambitious in the early 2010s. In order to meet the IEA 1.5°C pathway, Japan would need to supply ca. 1400 TWh of low-carbon electricity by 2035, representing a five-fold increase compared to the actual generation in 2021 (ca. 250 TWh) or a two-fold increase compared to the latest projection developed in the same year for 2035 (ca. 700 TWh) (Figure 6.9).

On the one hand, the substantial gap among the present, projected, and required supply of low-carbon electricity in 2035 can partly be attributed to the decline of nuclear power in the country, both in actual electricity supply and in the projections towards 2035 following the Fukushima nuclear accident in 2011. Before Fukushima, nuclear power was expected to dominate Japan's future electricity supply, but this ambition was scaled down by over 50% after Fukushima. On the other hand, the rapid growth of renewables, which outpaced the decline of nuclear power in Germany and the UK in the 2010s, did not occur in Japan. Proportionally, this translates to renewables constituting only 20% of the electricity supply in Japan in 2021, compared to ca. 40% in Germany and the UK in the same year. [8]

[8] However, in absolute terms, Japan supplied more electricity from renewable sources at around 200 TWh than the UK (ca. 130 TWh), but less than Germany (ca. 240 TWh) in 2021.

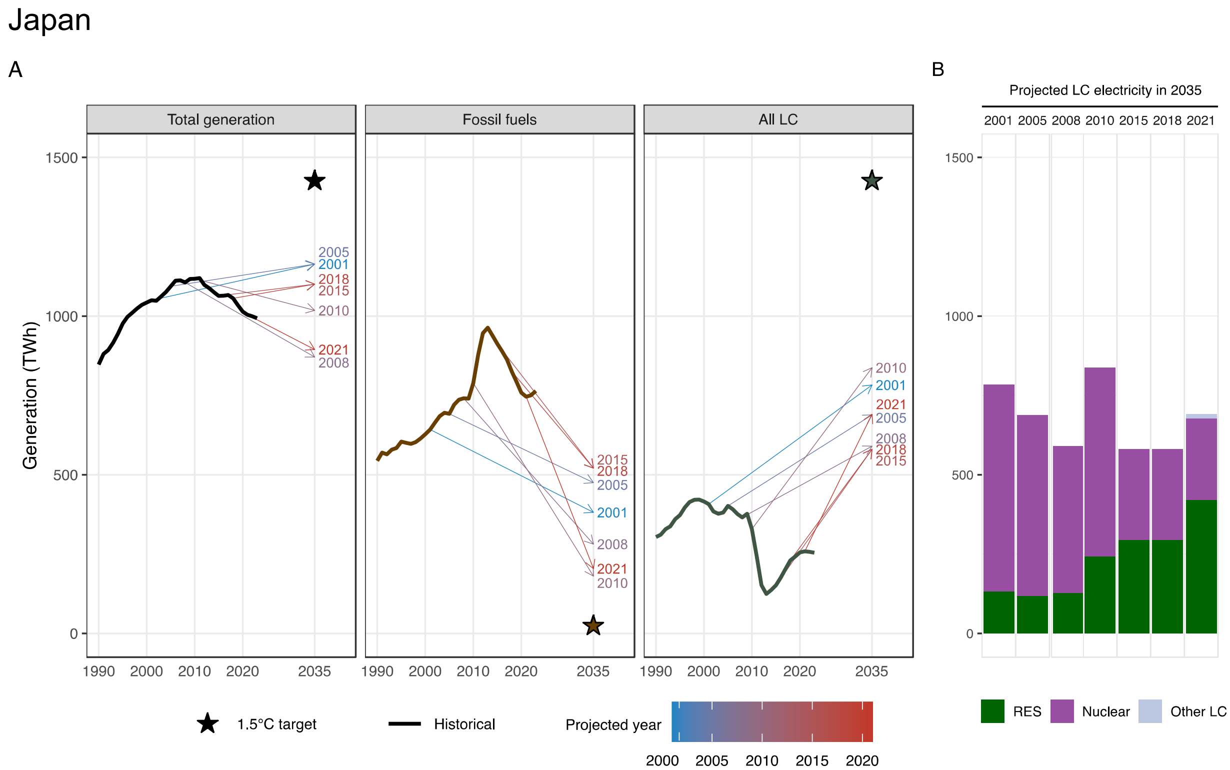


Figure 6.9: Japan - historical evolution of transition projections towards 2035 (A) and the sources of projected low-carbon electricity in 2035 (B)

Notes: In Panel A, "All LC" refers to all low-carbon sources including RES, Nuclear, and "Other LC". "Other LC" in Panel B refers to hydrogen and ammonia in Japan, which appeared only in the most recent projection developed in 2021. Detailed information on the projections used for this analysis can be found in Section 6.2, in particular Table 6.1.

While projecting progressively accelerated low-carbon substitutions in the future between 2000 and 2023, Japan did not historically experience such transitions until 2015-2020 (Figure 6.10). On the contrary, Japan underwent more than 10 years of high-carbon substitutions due to the continuous decline of nuclear power even before Fukushima. Similar to the situation in the UK where an increasing political push has not led to the revival of nuclear power, reversing the declining trajectory of nuclear power seems to be extremely challenging, particularly after Fukushima.

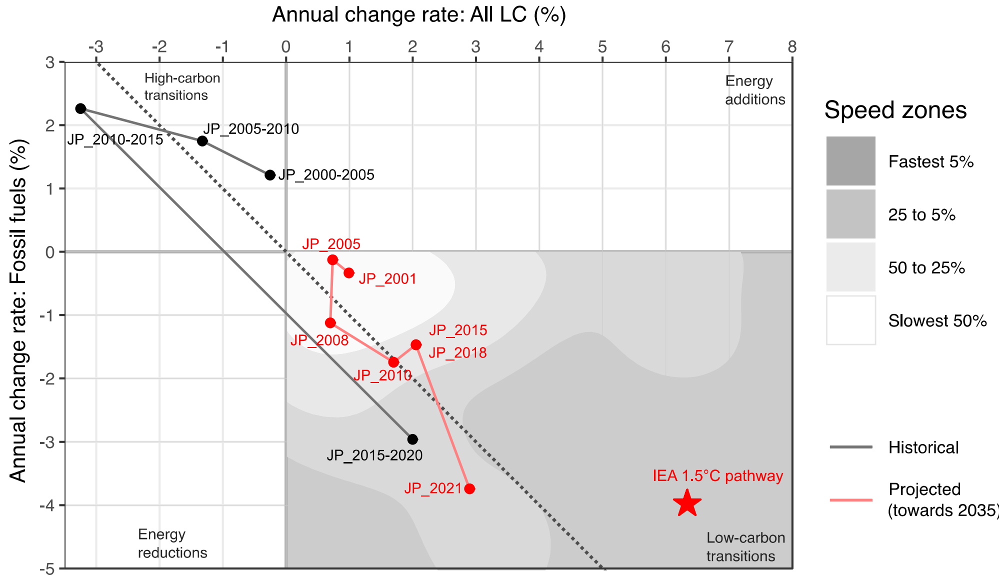


Figure 6.10: Japan - speed zones and historical, projected, and required rates of low-carbon substitutions

Notes: The speed zones in this figure are identical to those in Figure 5.8, which are constructed by the density of relevant national historical episodes observed over five years between 1960 and 2020 where the total generation was more than 100 TWh (see subsections 3.2.3 and 3.3.4 for the detailed framework and methods).

Considering the modest growth of renewables in Japan during the 2000s and 2010s, achieving the IEA 1.5°C pathway may therefore demand a substantial reorientation of energy transition policy in the country, shifting focus away from nuclear power to instead prioritise the development of other low-carbon technologies including modern renewables or providing unprecedented measures to revitalise nuclear power.

6.3.6 Canada

Similar to France, Canada's electricity system has already been largely decarbonised, thanks to the country's abundant hydropower resources. However, the use of fossil fuels in electricity supply has decreased only marginally over the past few decades (Figure 6.11). In fact, Canada even projected to expand the use of fossil fuels in 2016 towards 2035, while the country's focus shifted to maintaining their use rather than reducing them in the subsequent years. As for developing low-carbon electricity, the projections show that Canada does not seem to be interested in accelerating its growth, except in the latest target set in 2023 exceeding the linear trend.

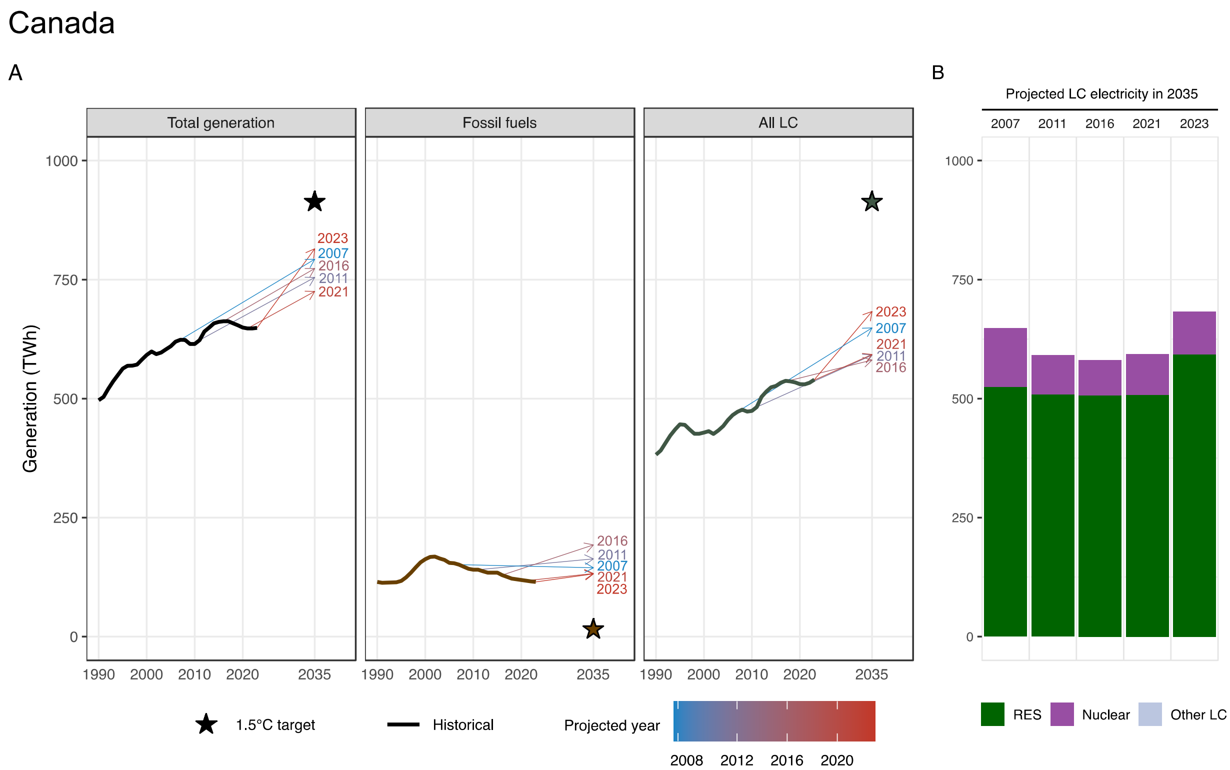


Figure 6.11: Canada - historical evolution of transition projections towards 2035 (A) and the source of projected low-carbon electricity in 2035 (B)

Notes: In Panel A, "All LC" refers to all low-carbon sources including RES, Nuclear, and "Other LC". There was no energy source considered as "Other LC" in the projections analysed for Canada. Detailed information on the projections used for this analysis can be found in Section 6.2, in particular Table 6.1.

Just like France, achieving the IEA 1.5°C pathway in Canada would be relatively more attainable compared to the other G7 countries as it only requires the country to achieve the speed of low-carbon substitutions historically observed in many countries (Figure 6.12). It does require, on the other hand, Canada to reverse the recent trend of stagnant growth in low-carbon electricity and accelerate its growth by two times faster than the rate historically observed in 2010-2015. This accelerated growth would then need to result in an expedited decline of fossil fuels by 2035. This also signifies that Canada would need to discontinue the pursuit of maintaining or expanding fossil fuel growth in the future, as consistently projected based on the existing and planned policies between 2000 and 2023.

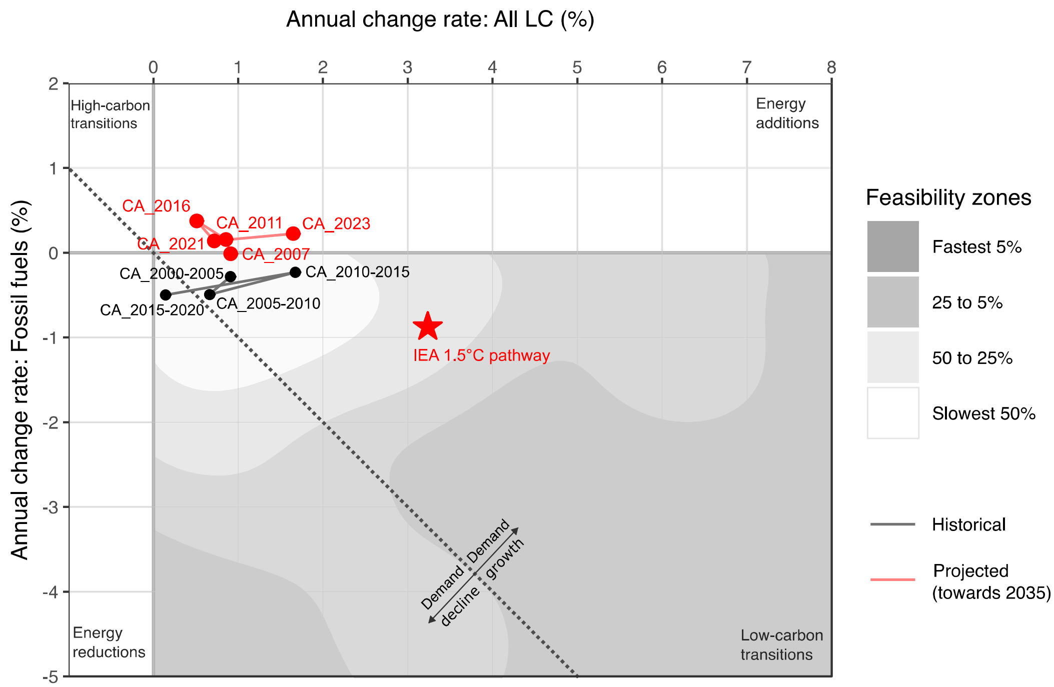


Figure 6.12: Canada - speed zones and historical, projected, and required rates of low-carbon substitutions

Notes: The speed zones in this figure are identical to those in Figure 5.8, which are constructed by the density of relevant national historical episodes observed over five years between 1960 and 2020 where the total generation was more than 100 TWh (see subsections 3.2.3 and 3.3.4 for detailed framework and methods).

6.3.7 United States

The evolution of energy transition projections in the US developed between 2000 and 2023 towards 2035 indicates a clear ratcheting-up in transition policies to progressively accelerate the growth of low-carbon electricity and the decline of fossil fuels over time. However, even the most recent projected rates still fall significantly short of meeting the requirements of the IEA 1.5°C pathway (Figure 6.13).

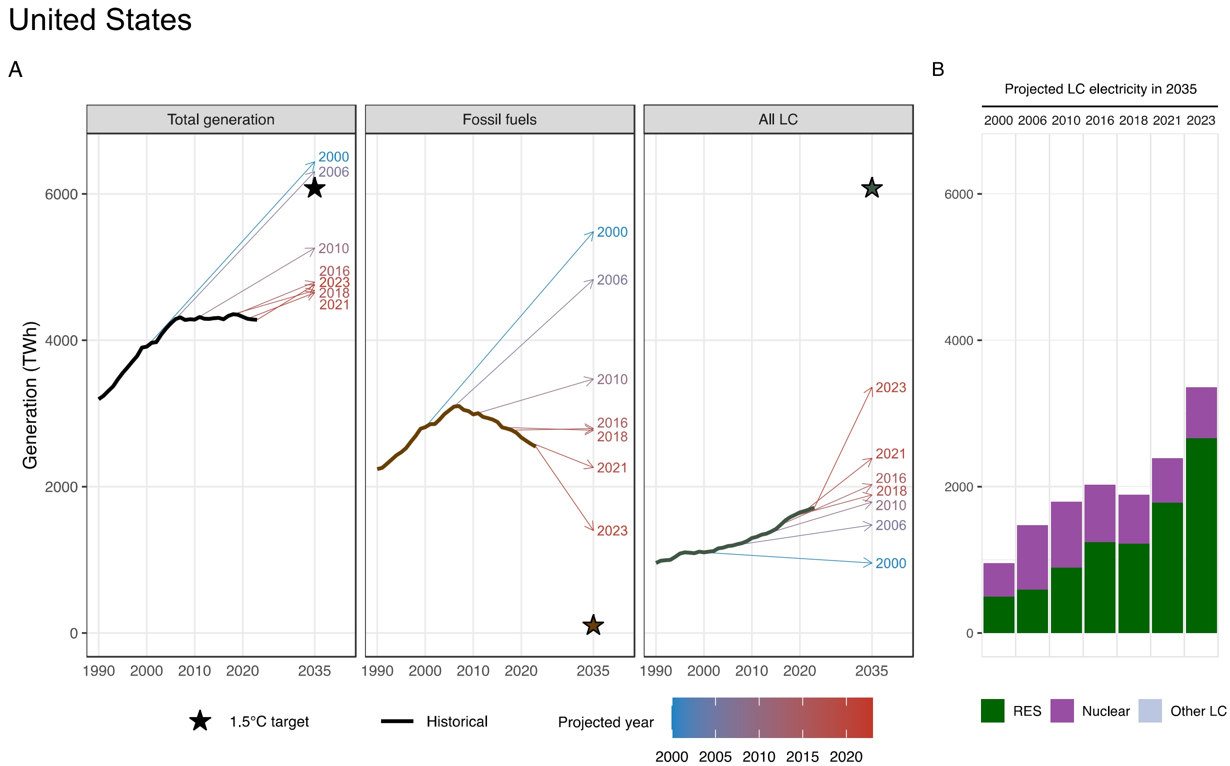


Figure 6.13: US - historical evolution of transition projections towards 2035 (A) and the sources of projected low-carbon electricity in 2035 (B)

Notes: In Panel A, "All LC" refers to all low-carbon sources including RES, Nuclear, and "Other LC". There was no energy source considered as "Other LC" in the projections analysed for the US. Detailed information on the projections used for this analysis can be found in Section 6.2, in particular Table 6.1.

It is interesting that the climate policies under the Obama Administration, as reflected in the 2010 and 2016 projections—commonly perceived as impactful—did not alter the gradual ratcheting up observed in the overall evolution of transition projections in the US. Similarly, what is often considered as 'anti-climate' policies under the Trump Administration, reflected in the 2018 and 2021 projections, also did not shift this overarching trajectory. Nonetheless, it could be argued that the transition projected in 2023, reflecting the Inflation Reduction Act introduced in 2022, indicates a more substantial ratchet-up in transition policies to achieve faster low-carbon substitutions (Figure 6.14).

Similar to several other G7 countries, the US progressively projected a diminishing growth in total electricity supply in the future. In the projections developed after 2016, the US consistently forecasted that the country would generate ca. 4600 TWh of electricity in 2035, slightly surpassing the current supply level of ca. 4300 TWh (Figure 6.13A).

Following the IEA 1.5°C pathway would be extremely challenging for the US. This requires the US to achieve levels of technological growth and decline that have never been observed in the country before, starting immediately and sustaining such rates until 2035 (Figure 6.14). This translates to a two-fold increase in the acceleration of low-carbon substitutions projected in 2023.

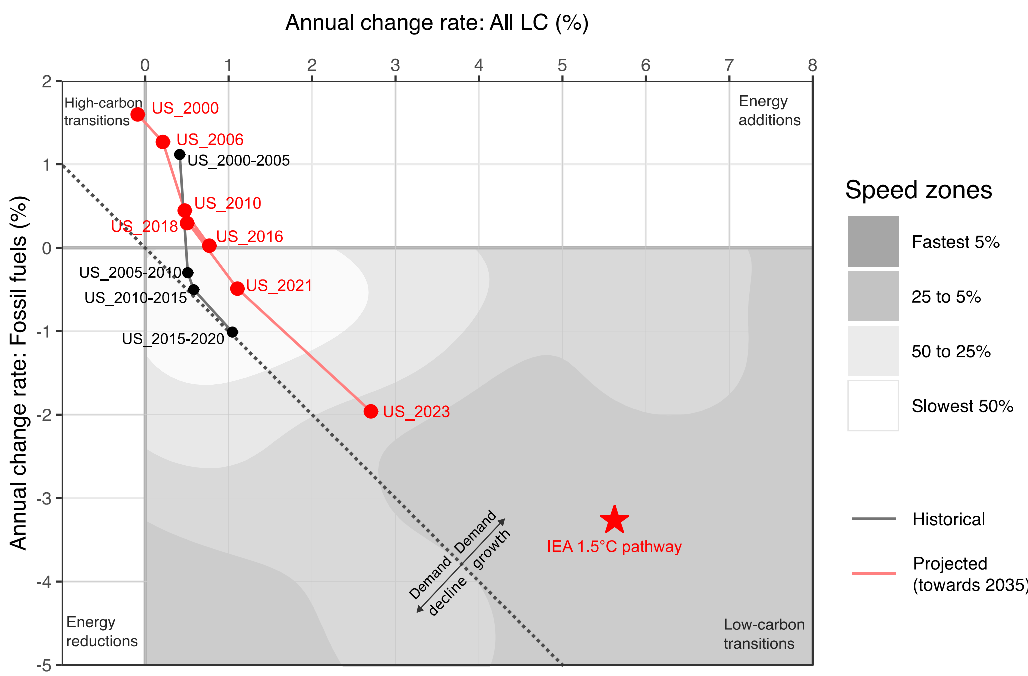


Figure 6.14: US - speed zones and historical, projected, and required rates of low-carbon substitutions

Notes: The speed zones in this figure are identical to those in Figure 5.8, which are constructed by the density of relevant national historical episodes observed over five years between 1960 and 2020 where the total generation was more than 100 TWh (see subsections 3.2.3 and 3.3.4 for the detailed framework and methods).

6.4 Cross-country comparison of energy transition projections

No single projection, developed between 2000 and 2023 across the G7 countries, indicates the stringency of transition policies compatible with the IEA 1.5°C pathway (Figure 6.15). This means that none of the G7 countries has yet demonstrated the level of 'ambition' in their policies necessary to keep the global temperature increase below 1.5°C.

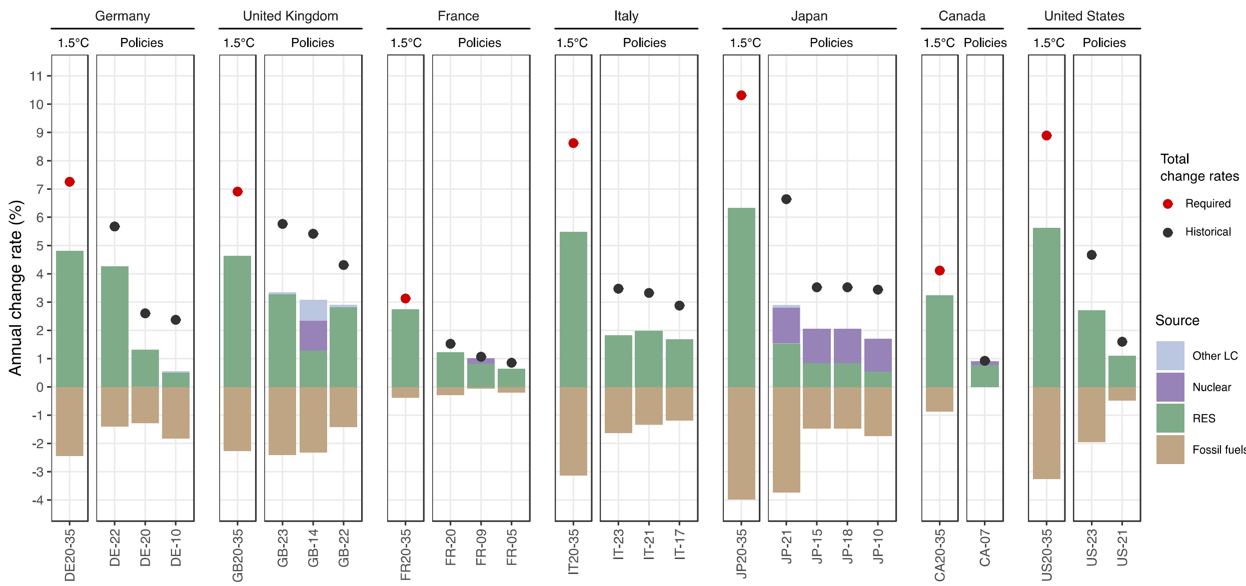


Figure 6.15: The required rates of low-carbon substitutions compared to up to three of the highest projected rates by the G7 countries developed after 2000 towards 2035.

Notes: The panel under "1.5°C" shows the required rates of low-carbon substitutions in the G7 countries (see subsection 3.3.4 for methods) while the panel under "Policies" show the projected transition rates. Here, the x-axis labels comprise the country code and the last two digits of the year when the respective projection was developed (for example, a projection developed in Germany in 2022 would be labelled as "DE-22"). Further details regarding the projections used in this analysis can be found in Section 6.2, particularly in Table 6.1. Dots at the top of the bars indicate total change rates. The source "Other LC" includes fossil fuels with CCS, hydrogen, and ammonia.

The fastest transition to date has been projected by Japan at 6.6% total change rate per year (Figure 6.15), which is surprising since the country is often considered a 'laggard' in climate actions by adhering to the use of fossil fuels (Burck et al., 2022). However, this does not necessarily imply that Japan is a leading country in decarbonising electricity for two distinct reasons. First, the rapid decline in fossil fuels and the simultaneous growth in low-carbon electricity currently projected in

Japan can largely be attributed to the planned restart of nuclear power plants. These plants had been deactivated for safety inspections following the Fukushima nuclear disaster in 2011. Re-starting these plants should be relatively easy compared to accelerating the development of new installations of low-carbon technologies. Secondly, Japan's electricity system still predominantly relies on fossil fuels, signifying a considerable journey ahead compared to other G7 countries on the path towards decarbonisation.

Another noteworthy point is that the UK's two projections in 2014 and 2023 stand out as exceptions among all projections developed by the G7 and analysed in this dissertation, where the required speed of fossil fuel decline was expected to be achieved (Figure 6.15). While the UK planned to decelerate this decline in the years following 2014, the Russo-Ukrainian War in 2022 motivated the country to re-accelerate the phase-out of fossil fuels to enhance energy security. A similar trend is observed in Germany, showing a significant political acceleration in the development of renewables following the war. However, this has not expedited the decline of fossil fuels in Germany, most likely due to the already established coal phase-out timeline in the mid to late 2030s.

The speed zones delineated by historical observations of low-carbon substitutions generally well capture the projected transition rates of the G7 countries (Figure 6.16): only two (GB-14 and GB23) projections out of a total of 27 (7%) are located in the fastest 5% zone; three (11%) are located in the 25-5% zone, nine (33%) are located in the 50-25% zone; and the rest 12 projections (44%) are located in the slowest 50% zones. Having more projections in the 50-25% zone compared to the 25-5% zone indicates that transition policies in the G7 countries have been slightly more conservative (i.e. less ‘ambitious’) than the historical speed of low-carbon substitutions observed in the G7 as well as comparable countries.

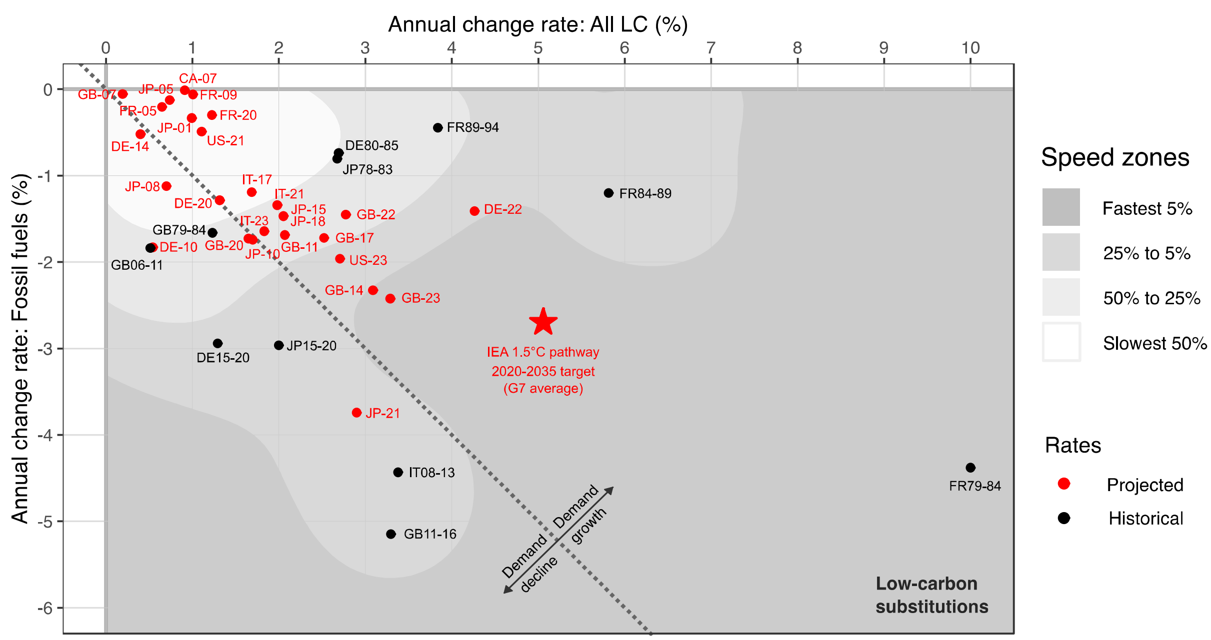


Figure 6.16: Speed zones and historical, projected, and required rates of low-carbon substitutions in comparison to the IEA 1.5°C pathway for the G7.

Notes: The IEA 1.5°C pathway depicts the required rates of low-carbon substitutions for the G7 countries on average. For individual rates, see the country-specific analyses in 6.3. The speed zones in this figure are identical to those in Figure 5.8, which are constructed by the density of relevant national historical episodes observed over five years between 1960 and 2020 (see 3.2.3 and 3.3.4 for the detailed framework and methods). Historical rates that are located faster than the slowest 50% zone are shown in the figure (i.e. the rates located in the slowest 50% are removed to avoid overlapping with the projected rates).

6.5 Transition projections vs actual transitions

Projecting a faster speed of transitions does not necessarily guarantee their realisation in the real world. On the other hand, actual transitions may also outpace projected rates. In other words, to what extent are national projections reliable in forecasting the future development of the energy sector?

Figure 6.17 illustrates the correlation between projected annual change rates and actual change rates in the same geographical scope during the same timeframe. For instance, if Germany projected a 2% growth of renewables in 2014 between 2012 and 2020, and the actual growth turned out to be 3% during that period, the data point would be positioned above the dotted line, indicating an overachievement in reality. In other words, future growth was underestimated. Notably, three panels exhibit statistically significant correlation, with *p*-values < 0.001: All projections for total generation and all projections as well as short-term projections for renewables (RES).

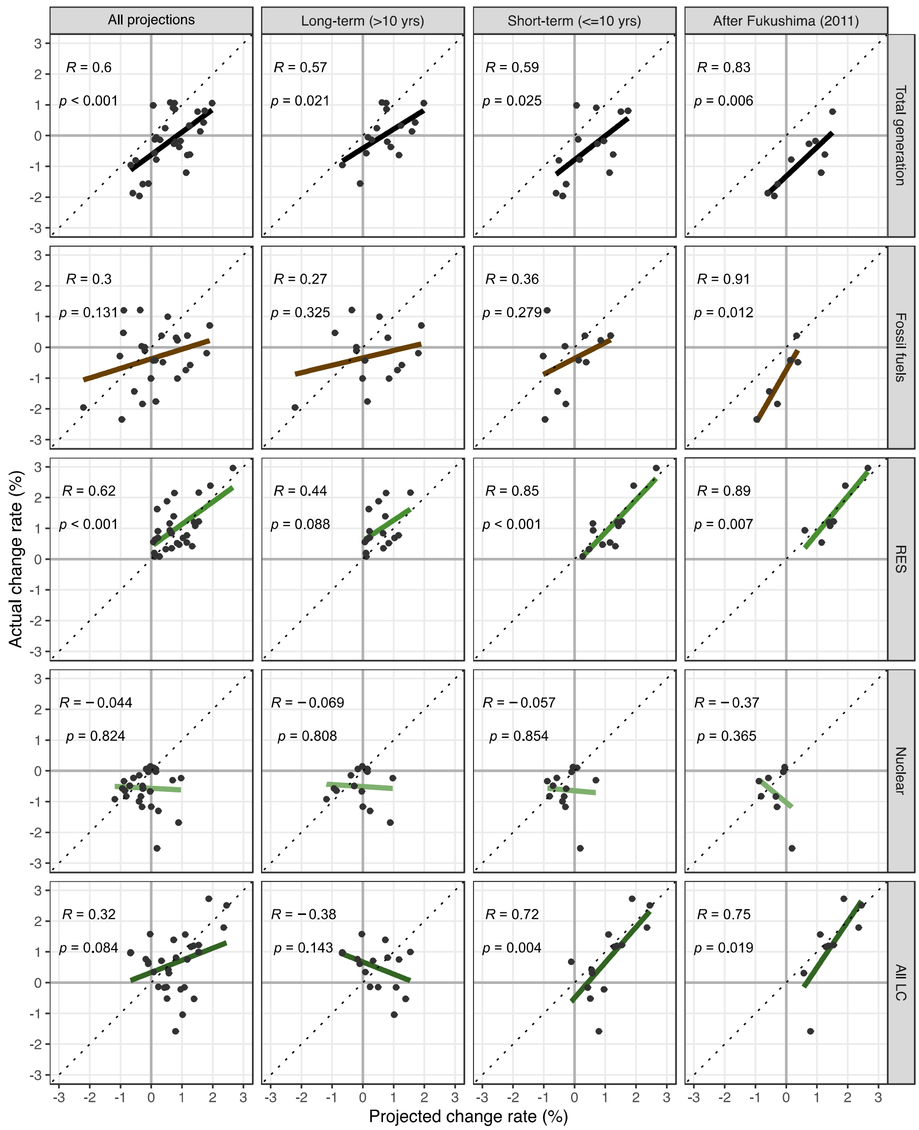


Figure 6.17: Correlation between projected change rates and actual change rates in the G7 in their electricity transitions towards 2020

Notes: The dotted lines indicate the perfect accuracy of projections, where projected change rates (x-axis) and annual change rates (y-axis) perfectly match. Datapoints below the line mean actual change rates are slower than projected change rates (i.e. changes are overestimated in projections). On the other hand, data points above the line mean actual change rates are faster than projected change rates (i.e. changes are underestimated in projections).

In the majority of transition projections developed by the G7 countries, the total generation in the future was overestimated, with predominant data points falling below the dotted line which represents a perfect prediction. A similar trend is observed for fossil fuels, with data points mainly situated below the dotted line, signifying that the projected rates of fossil fuels were often overestimated. As most data points fall beneath the $y=0$ line, it depicts that the actual speed of fossil fuel decline often outpaced the projected rates. This implies that the G7 countries tend to overestimate future electricity demand, leading to a slower decline of fossil fuels in projections. However, in reality, the demand stagnated in the 2000s and 2010s in all the G7 countries except Canada, resulting in a faster decline of fossil fuels (see Section 6.3).

In contrast, the correlation for RES presents a different pattern where the projected and actual growths are closely aligned. This strong correlation is particularly evident in short-term projections (forecasts spanning up to 10 years) where the p-value is < 0.01 (i.e. projections being a statistically significant predictor for actual transitions). In the long-term projections, the actual growth of RES often outpaces the projected rates, suggesting that the long-term potential of RES expansion tends to be underestimated. Nonetheless, all projections for RES show a p-value < 0.01.

Conversely, Figure 6.17 reveals a significantly different picture for nuclear power, illustrating a weak to negligible correlation between projections and actual transitions, accompanied by high p-values and modest R-values. This denotes a substantial challenge in planning and realising the future role of nuclear power. The slight downward trend of correlation lines even suggests that when faster growth (or slower decline) was projected, it actually declined faster. Interestingly, this phenomenon is even more prominent in the projections developed after Fukushima. This indicates that the G7 countries continued *unsuccessfully* aiming to maintain or increase the use of nuclear power towards the future in their policies even after Fukushima, despite the presumably improved consideration of the risks and uncertainties associated with the technology in formulating these policies. This failure to realise projected output from nuclear power resulted in lowering the reliability of projections for low-carbon electricity generation in total (All.LC) despite the near-perfect realisation of projected renewable growth (Figure 6.17).

The varying reliabilities of projections for different energy sources suggest the potential for further strengthening countries' policies in the pursuit of decarbonisation. At the same time, this variation highlights the challenges faced by national policymakers as they navigate the balance between motivations and the associated complexities of transitions.

For example, the frequent underestimation in projecting the future decline of fossil fuels may suggest that countries should anticipate the continuation of this declining trend in the future. This approach could, in turn, incentivise the accelerated growth of low-carbon technologies to substitute fossil fuels. However, pursuing such faster substitution may not align with the interests of fossil fuel industries, which have exerted considerable influence on national energy policymaking. This is exemplified in Germany, where accelerating the phase-out of coal became only possible by compensating for the potential loss of the relevant industries and communities, amounting to 40 billion EUR (see subsection 4.2.1 for details).

Furthermore, the significantly unreliable projections for the future role of nuclear power may suggest that these countries should consider abandoning the technology and, instead, focus on developing more easily achievable options such as RES. On the other hand, this goes against "the many eggs in the basket" approach, which may be the safest strategy to prepare for the uncertainties regarding technological innovation in the future (Grubler, 2012, p. 15; Wilson and

Grubler, 2011). At the same time, nuclear power is expected to make a significant contribution to decarbonising the energy sector in the world by doubling the electricity supply from the source to account for 10% of electricity in 2050 (IEA, 2021b; Rogelj et al., 2018). In this context, the G7 countries, which historically led the development and diffusion of nuclear power, shifting away from the technology to focus on developing renewables may run counter to what is required to accelerate low-carbon substitutions at the global level.

6.6 Summary

While the existing literature identifies both enabling and constraining factors for national governments to accelerate energy transitions, this chapter provides empirical insights into how the overall stringency of national transition policies has evolved in the G7 countries between 2000 and 2023.

This chapter shows that, as of December 2023, none of the G7 countries has yet shown a stringency of policies to achieve the speed of low-carbon substitutions compatible with the IEA net-zero pathway to keep the global temperature increase below 1.5°C (Figure 6.15 and Figure 6.16). However, it is noteworthy that Germany and the UK substantially strengthened their policies to accelerate low-carbon substitutions after the Russo-Ukrainian War in 2022 to improve energy security, reflected in their latest projections compared to their previous ones. While these projected rates are still not 1.5°C compatible, it is remarkable how energy security concerns can accelerate the country's efforts within a few years. While Japan's latest projection in 2021—displaying the highest speed of low-carbon substitutions across the G7 countries so far—exhibits a comparable rate of fossil fuel decline, it still significantly falls short of the acceleration required to develop low-carbon technologies. Whether the Russo-Ukrainian War exhibits the same acceleration effects in Japan as well as other G7 countries remains unclear.

This chapter also demonstrated that the ratchet-up in the state efforts to accelerate low-carbon substitutions can be seen in the G7 countries but not in all countries nor constantly. Among these countries, the constant or near-constant ratchet-up has been observed in the US and Japan, though even their most recent and thus ambitious rates of transitions remain significantly far away from the net-zero pathway. In contrast, though widely considered as leading countries in mitigating climate change, this chapter reveals that Germany and the UK projected rapid low-carbon substitutions only after 2010. Italy started to project accelerating low-carbon substitutions even later than Germany and the UK in the late 2010s, with its low-carbon electricity target slightly declining recently. Despite having largely decarbonised electricity sectors, Canada and France seem to struggle with completing the decarbonisation process, where Canada currently even aims to slightly expand the use of fossil fuels in electricity supply in the coming decade.

Moreover, comparing the projected transitions towards 2020 with the actual transitions reveals that the G7 countries almost always projected a slower decline in fossil fuels than the rate that actually took place. Additionally, these countries often fell short of realising the maintenance and expansion of nuclear power as expected, even in the projections developed after the Fukushima nuclear accident in 2011. This consequently resulted in the frequent underachievement of developing low-carbon electricity by 2020, despite the near-perfect realisation of renewable growth as projected. This indicates that there may be several ways to strengthen transition policies further to accelerate low-carbon substitutions. First, these countries should take into account the fact that their projections on fossil fuel decline have almost always been underestimated.

Projecting rates based on the empirical declining trend and speed of fossil fuels can provide a clearer signal, potentially expediting the development of alternative technologies. Secondly, among the alternative technologies, these countries could focus on more easily attainable options, such as modern renewable technologies, rather than nuclear power, considering the frequent failures to realise the maintenance and revitalisation of the technology as projected in recent decades.

Furthermore, targeting a higher speed of transitions does not guarantee its full realisation. As the pressure to accelerate transitions will arguably persist and intensify, the G7 countries may set increasingly ambitious, albeit potentially ‘hollow’, targets without the actual policy instruments implemented to realise them. This is evident in the substantial disparity that remains between the national pledges of the G7 countries to decarbonise electricity by 2035 and their latest transition projections reflecting actual and planned policies implemented, as examined in this chapter. Exploring the extent and speed at which this gap could be narrowed, along with the feasibility of achieving the increased ambition, is an important area for future research.

7. Discussion

This chapter explores the contributions of my dissertation in the context of the existing literature on political acceleration in energy transitions to mitigate climate change. I begin by briefly revisiting the state of the art while highlighting the gaps in the literature that my dissertation aimed to address in Section 7.1. Against this backdrop, I summarise the methodological, empirical, and theoretical contributions of this dissertation in Sections 7.2, 7.3, and 7.4, respectively. Additionally, I discuss the limitations of my research and outline the need for further research in Section 7.4.

7.1 State of the art and the gap in the literature

There are two major approaches in the literature analysing energy transitions to mitigate climate change.

The one group, comprising energy historians, technology diffusion scholars, and energy economists, examines the long-term trend in the economy-wide use of energy resources and technologies at the global level and compares this historical development with required transitions. By adopting this highly aggregated approach, they demonstrate that the speed of energy transitions has consistently been very slow, spanning multiple decades to even centuries (Fouquet and Pearson, 2012; Grubler et al., 2016; Kramer and Haigh, 2009; Smil, 2010). Furthermore, they argue that the historical development of the energy sector should be categorised as 'energy additions' because new technologies have consistently been added on top of existing ones rather than replacing them (Fouquet and Pearson, 2012; York and Bell, 2019).

Given the consistent speed and nature of these transitions, they do not discern significant political interventions to shift the trend and, thus, often contend that energy transitions have been primarily driven by technology innovation and market forces (Fouquet and Pearson, 2012; Smil, 2010).

From this perspective, these scholars perceive the required transitions to mitigate climate change, which necessitate significant political acceleration, as extremely unlikely because they deviate significantly from the historical trend in the development of the energy sector (Fouquet and Pearson, 2012; Smil, 2024, 2016b, 2010; Stoddard et al., 2021).

The other group, comprising sustainable transition scholars and climate policy researchers, contrastingly pursues highly granular analyses of changes in individual technologies and policies over a short period of time, often at the national level and typically within recent decades. Their primary aim is to identify rapid socio-technical transition cases and examine the role of actors and (often climate) policies in these ‘best practices’ (Chapman and Itaoka, 2018; Kern and Rogge, 2016; Köhler et al., 2019; Sovacool, 2016; Sovacool and Geels, 2016). These contributions primarily focus on the growth of new technologies such as renewables (Chapman and Itaoka, 2018; Jänicke, 2012; Kern and Rogge, 2016; Rogge and Johnstone, 2017), but increasing attention has recently been given to studying the decline of incumbent technologies such as coal (Brauers et al., 2020; Rosenbloom, 2018; Sovacool, 2016).

With the field witnessing rapid growth, scholars are making explosive contributions identifying numerous relevant cases, often involving political interventions. Coupled with the surge in political interest to mitigate climate change and the escalating adoption of climate policies in recent decades, these scholars claim that recent energy transitions have been increasingly governed by policies and taking place faster than in the past (Kern and Rogge, 2016; Sovacool and Geels, 2016). From this perspective, the required rapid transitions are deemed possible, particularly if the identified ‘successful’ examples, such as renewable growth in Germany and the UK, are replicated globally (Kern and Rogge, 2016; Roberts et al., 2018; Sovacool and Geels, 2016).

These contrasting arguments on the historical and expected rates of political acceleration in energy transitions thus arise from the fact that their scopes of analyses and corresponding methodologies are mismatched and are either too broad or too narrow. The main issue with the broad analysis, focusing on long-term changes in global energy use, is that it inevitably overlooks potentially accelerated cases including those driven by policies in specific sectors and countries over a particular period. This is problematic because revolutionary technological transformations often originate from such initially insignificant niches that later expand and disuse exponentially (Sovacool and Geels, 2016).

On the other hand, the primary issue with the highly focused analysis, such as short-term individual technological changes and the impacts of policies within specific socio-technical systems, is the lack of examination regarding the significance of such narrowly scoped cases compared to the systemic long-term transitions in the energy sector required for climate change mitigation. For instance, the rapid growth of renewables, whether accelerated by policies or not, would not automatically accelerate the decarbonisation of the entire energy system if it merely expands on top of existing technologies. These technological interactions are beyond the scope of highly granular studies and are consequently neglected in the literature (Rinscheid et al., 2021).

Moreover, the fact that these transition studies are primarily single case studies without comparative analysis (Grubler et al., 2016; Sorrell, 2018) raises questions about whether this focused case is genuinely an accelerated example compared to other countries and technologies in recent as well as more historical transitions. Perhaps more importantly, this lack of comparative analysis leaves it unclear whether, even if the identified case is accelerated, it is rapid enough to achieve the necessary transitions for climate change mitigation. Advocating for the replication of such cases without verifying the extent of acceleration could potentially hinder, rather than expedite, global decarbonisation processes.

Furthermore, the short-term analysis fails to elucidate the long-term effects of policies, which may diminish over time due to potential weakening, dismantling, or even reversal of policies. These effects could also be overshadowed by other confounding factors. Additionally, the apparent increase in the number of politically ‘accelerated’ cases identified in recent decades may be influenced by a measurement bias, as studying past policies with the same rigour is challenging. Simultaneously, there is a risk of publication or innovation bias, where only successful cases tend to be reported in the literature, overlooking potentially many more cases of failure (Rogers, 2003).

In summary, the existing approaches to analysing energy transitions are either too broad or too narrow, preventing a systematic comparison to understand whether and, if so, how recent energy transitions differ from historical ones. In particular, resolving the contrasting arguments on the rates of political acceleration in energy transitions requires a middle-range methodology and comparative analysis, which allow for a nuanced exploration of the existence and rates of political acceleration in the energy sector across countries and time-periods.

My dissertation aimed to overcome this stalemate in the literature through methodological innovations, enabling me to make new empirical observations and formulate new theoretical insights.

7.2 Methodological contributions

My dissertation makes three overarching methodological contributions to the existing literature in order to resolve the existing debate on the rates of political acceleration in energy transitions: (1)

developing a middle-range approach to analyse energy transitions; (2) advancing this approach while conducting various comparative analyses; and (3) utilising national energy transition projections as proxy to examine the evolution of policies over time.

7.2.1 Developing a middle-range methodology to analyse energy transitions

My dissertation developed a ‘middle-range’ methodology to analyse energy transitions. In contrast to the two major approaches in the literature, this ‘middle-range’ approach stands out as a more balanced way to analyse energy transitions in terms of geography, sectoral coverage, time horizon, and methods (Table 3.4).

First, I focused on analysing national energy transitions since energy transitions are primarily driven by national policies (Falkner, 2016; Helm, 2002; Ikenberry, 1986). Moreover, I focused on large economies, which tend to possess complex energy systems encompassing multiple accelerating and decelerating mechanisms, thereby providing a foundation to examine how policies have affected transitions The speed of energy transitions in these countries, such as the G7 and the EU, also carries significant implications for achieving global climate targets.

Secondly, I examined the changes in the electricity sector, considering all relevant technologies and analysing their interactions. This approach can be applied to other energy sectors, such as transport, buildings, and industry, but I specifically chose the electricity sector for this dissertation because much of the decarbonisation efforts have so far focused on the sector, hence political acceleration is most expected (Nascimento et al., 2022b).

Thirdly, I analysed medium-term transitions in the electricity sector over more than six decades, which is important to distil differences between past and more recent transitions.

Lastly, by focusing on national energy transitions, this middle-range approach employs mixed methods in contrast to the existing approaches, which are either largely based on quantitative or qualitative analysis. As I explain further below, with this approach, I conducted a series of longitudinal comparative case studies combined with statistical analyses to delve into the dynamic relationships among the changes in technological and market trends, energy systems, and policies.

7.2.2 Advancing the approach while conducting comparative analyses

I pursued a step-by-step approach to test and progressively advance this middle-range approach by conducting a series of longitudinal comparative analyses lacking in the existing literature in order to elucidate the rates of political acceleration in energy transitions (Table 7.1).

Table 7.1: Lack of comparative analyses addressed by my dissertation

Lack of comparative analysis in the literature	Comparative analysis conducted in my dissertation	
① Comparison across countries: Individual country cases lack a comparison to others, causing uncertainty about their relative transition speed and extent.	Chapter 4	Electricity transitions in Germany and the UK to test the mid-range approach (addressing ① and ②)
② Comparison within historical periods: Recent changes lack a comparison to historical transitions, causing uncertainty about their relative transition speed and extent.	Chapter 5	Electricity transitions in G7 and EU to advance and verify the approach (addressing ①, ②, and ③)
③ Comparison with future climate targets: Recent changes lack a comparison to necessary climate targets, creating uncertainty about their adequacy in terms of transition speed and ratcheting up of policies.	Chapter 6	Evolution of electricity transition policies in G7 (addressing ①, ② and ③)

In Chapter 4, I tested the middle-range approach to comparatively analyse electricity transitions in Germany and the UK. These countries were selected because they are often considered “climate leaders”, providing a promising opportunity to identify and assess the rates of political acceleration in energy transitions (Kern and Rogge, 2016; Tobin, 2017). I analysed the historical and planned changes in the electricity sector and policies in these countries between 1960 and 2030 by segmenting the period into a sequential set of decadal episodes. This segmentation was introduced to examine the evolving interactions between the changes in policies and the electricity system over time. Such systematic and granular analysis is crucial to understanding the sequence of policy change and its outcomes, but it is rarely conducted in the existing literature, with a few exceptions, such as Cherp et al. (2017).

In Chapter 5, I further advanced and validated the approach by expanding the scope to focus on the G7 and the EU while also comparing their transitions with other comparable economies (see subsection 3.3.3 for more detailed methods). Here, the focus of analysis shifted towards comparing the nature and speed of electricity transitions within historical periods since 1960, as well as with the required transitions outlined by the IEA 1.5°C/net-zero pathway towards 2035 (IEA, 2021a).

In order to trace the changes in the nature of energy transitions, I categorised energy transitions into four types based on the changes and their interplays in fossil fuels and low-carbon technologies (see Figure 3.2. The significance of this conceptualisation is further discussed in subsection 7.4.1): (1) **energy additions** where low-carbon technologies are built on top of, not replacing, fossil fuels; (2) **low-carbon substitutions** where low-carbon technologies replace fossil fuels; (3) **high-carbon substitutions** where low-carbon technologies are replaced by fossil fuels; and (4) **energy reductions** where both low-carbon technologies and fossil fuels decline in the shrinking energy system.

With these categorisations, I specifically aimed to examine whether and how the growing climate policies have altered the changes in the nature and speed of energy transitions beyond historical trends. In this chapter, the segmentation of time periods was reduced to five years instead of ten years. This change was made based on the analysis of Chapter 4, which revealed that technologies, particularly modern renewables, can experience rapid growth within a shorter timeframe than ten years. In this chapter, I also developed empirically grounded speed zones of energy transitions (Figure 5.8, also see Figure 3.3 for more detailed methods), constructed by the density of relevant historical observations to examine the rates of acceleration necessary in the future.

Lastly, in Chapter 6, I employed the middle-range approach to analyse the progression of transition policies in the G7 countries in recent decades, addressing the gap in the literature where the evolution of overall policy stringency to mitigate climate change is rarely studied (more details on the methodological innovation related to this chapter follows in subsection 7.2.3).

These comparisons required a method to normalise changes in the energy system as it varies across countries and over time. To achieve this, my dissertation adapted a metric originally developed by Vinichenko et al. (2021) to comparatively analyse the rate of energy transitions. The results of my empirical chapters confirm the validity of this metric and its usefulness for the variety of comparative analyses conducted in this dissertation.

7.2.3 National transition projections as proxy to examine the stringency of policies

To the best of my knowledge, Chapter 6 of my dissertation is the first attempt to empirically analyse the evolving stringency of national energy transition policies over time. The existing literature on the ratchet-up of policies remains largely theoretical, while some studies analysed the changes in political 'targets' to mitigate climate change in terms of renewable growth (Leipprand et al., 2020; Pahle et al., 2018) or emission reductions (Leipprand et al., 2020; Nascimento and Höhne, 2023).

However, there is often a gap between political targets and the policies actually implemented (Elzen et al., 2019; Kuramochi et al., 2021; Nascimento et al., 2023; Rogelj et al., 2023), indicating that the ratcheting up of policy targets does not necessarily translate to an intensification of actual actions, which are what truly matter, rather than merely raising the targets. For example, while Leipprand et al. (2020) observe the progressive increase in the emission reduction targets of the EU ETS over time, its actual performance has been deemed unsatisfactory due to a lack of harmonisation between the EU-wide cap and national actions in the member states, resulting in the overflow of emission allowances (Bausch et al., 2017).

I thus aimed to analyse the evolving stringency of policies over time by examining the evolution of national energy transition projections. These projections are developed based on the presumed impacts of existing and planned policies at the time of projection development and can therefore be used as a proxy of policy stringency (see subsection 7.5.2 for the limitations of this method and the suggested avenue for future research).

7.3 Empirical contributions

By employing mixed methods to comparatively analyse national energy transitions across the G7, the EU, and other comparable countries over the last six decades, my dissertation demonstrates that climate policies have not accelerated energy transitions in the G7 and the EU beyond historical trends. Moreover, I reveal that none of these countries has ever achieved or planned to achieve a compatible speed of transitions required to meet their political commitment to decarbonising electricity by 2035, resulting in a significant gap between actual and planned transitions and the required transitions for the 1.5°C target. This gap has frequently widened because of the continuous failure of these countries to maintain and re-vitalise nuclear power as planned in recent decades, necessitating increased reliance on fossil fuels in actual transitions.

7.3.1 Changing nature of energy transition but the speed has not been faster in recent decades

While most transition studies and climate policy research focus on energy transitions since 1990 as the starting point for sustainable transitions (Geels et al., 2016b; Hoppe et al., 2023; Kern and Rogge, 2016; Nascimento et al., 2022b), my dissertation analyses show that the majority of the G7 countries and the EU, including Germany and the UK, began decarbonising the electricity sector only after the mid-2000s (Figure 5.6, Figure 5.7, Table 5.2). Until this period, low-carbon technologies were added on top of fossil fuels instead of replacing them to meet the growing demand for electricity, thereby pursuing ‘energy additions’. These countries were about to start decarbonising electricity with rapidly growing nuclear power outpacing their energy demand increase in the 1980s. However, this did not materialise because nuclear power immediately began to stagnate after the Chernobyl disaster in 1986, re-necessitating the G7 and the EU to increase reliance on fossil fuels instead to supply the demand (Figure 5.6).

What changed after the mid-2000s? It may be tempting to assume that it was due to climate policies accelerating the growth of renewables and the decline of fossil fuels. The number of climate policies indeed rapidly grew, particularly after 1990, with ca. 50 policies in force in 1990 to ca. 400 in 2000, ca. 1400 in 2010 and more than ca. 2100 in 2020 (Figure 5.3). Many existing studies claim that these policies have accelerated the growth of renewables and the decline of fossil fuels (IRENA, 2022; Kern and Rogge, 2016; Loftus et al., 2015).

However, my dissertation reveals that the growth of renewables in recent decades has continuously been slower than the historical growth of nuclear power in the 1970s and 1980s, which was also politically driven after the oil crises (Figure 7.1A). After reaching 1% of the market share, which is generally considered the take-off point from which energy technologies start to grow exponentially (Vinichenko, 2018), it took 17 years for nuclear power to supply 15% of electricity in the G7 and the EU. In contrast, it took the same 17 years for modern renewables (all renewable sources except hydropower combined) to supply only 3% of electricity and took an additional 13 years (i.e. 30 years in total) to reach the 15% market share.

The period of political acceleration in energy transitions after the oil crisis also provides a comparative benchmark to assess whether, and if so, to which extent the current decline of fossil fuels has been accelerated compared to the past. This is because the main purpose of the political intervention in the 1970s and 1980s was to remove oil from the energy system to the extent possible to strengthen otherwise looming energy security, including by developing nuclear power. Panel B of Figure 7.1 shows the rapid decline of oil use in electricity supply, achieving a 51% decline in just 10 years between 1973 and 1983 (i.e. 5.1% per year). This decline, however, may not be a suitable benchmark because oil was primarily used in other energy sectors, including transport, industry, and heating.

It is thus more relevant to look at the decline of oil use in the primary energy supply (Figure 7.1B). In addition to efficiency improvement measures, developed countries including the G7 introduced a series of more stringent and 'emergent' measures including restrictions on driving, flying and the use of lights and heating, efficiency programs for industries, as well as directly controlling the oil prices (Johnstone and Schot, 2023). As a result, oil in the primary energy supply in the G7 declined by 25% in 10 years between 1973 and 1983.

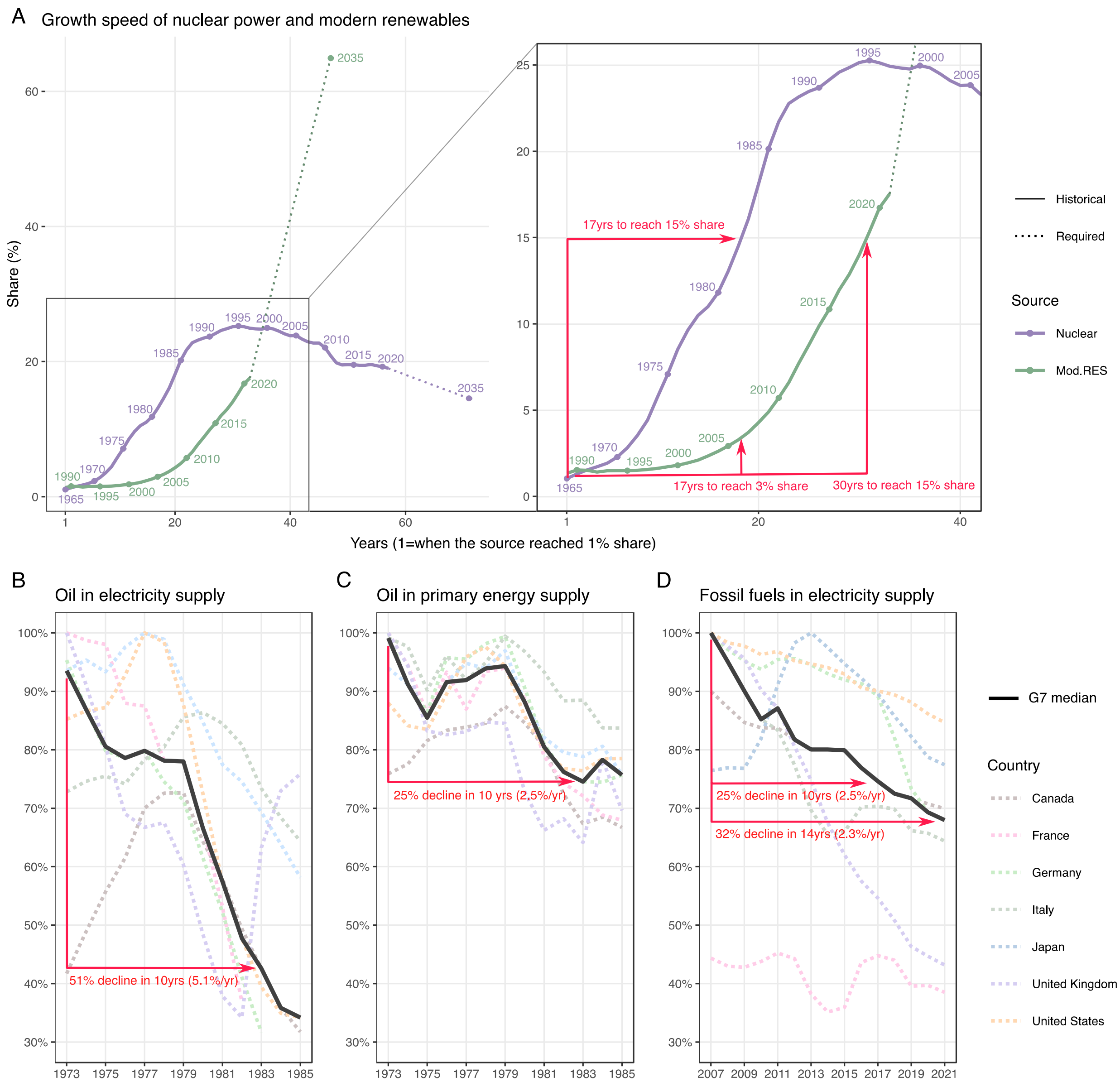


Figure 7.1: Historical growth of nuclear power compared to the recent growth of modern renewables in G7 and EU (A). Historical decline of oil in electricity supply (B), compared to the historical decline of oil in primary energy supply (C), and to the recent decline of fossil fuels in electricity supply (D) in G7.

Notes: Both electricity and primary energy data are from IEA (IEA, 2022), which are smoothed by using three-year moving averages. 100% in the y-axis in Panels B, C, and D means the maximum electricity or primary energy supply from oil in these countries since 1960.

The recent decline of fossil fuels in electricity supply shows exactly the same speed as this historical decline of oil use in primary energy supply: a 25% decline in 10 years between 2007 and 2017 and a slightly slower decline afterwards (Figure 7.1D). While this is remarkable, it is important to note that the recent decline of fossil fuels may have been relatively easier because the electricity demand has been declining since the mid-2000s (Figure 5.2), making fossil fuels simply unnecessary compared to the oil decline in the 1970s where oil was the only energy source to fuel some sectors such as transport and industrial uses.

The pivotal shift from energy additions to substitutions in the mid-2000s was thus enabled neither by the accelerated growth of low-carbon electricity nor the decline of fossil fuels but by the declining demand for electricity, making it possible for slowly growing renewables to replace fossil fuels (Figure 5.6).

7.3.2 No compatible transition has ever occurred or planned for 1.5°C

My dissertation shows that none of the G7 countries have empirically demonstrated in their historical transitions or even planned the rates of acceleration in the future necessary to meet the IEA 1.5°C pathway up to 2023 (Table 7.2).

Focusing on historical transitions since 1960, while existing studies report an increasing number of ‘rapid’ transition cases, mostly within the G7 and the EU countries (see subsection 2.3.3), my dissertation reveals that these countries have never actually achieved the compatible speed of transitions required to meet the IEA 1.5°C pathway (Table 7.2 and see also Figure 5.9 which includes comparable economies to the G7 and the EU). The trend in the existing literature to encourage other countries to replicate their historical cases would, therefore, not result in meeting climate target requirements.

Table 7.2: Compatibility of historical and recent transitions as well as policies implemented after 2000 with the IEA 1.5°C pathway for the G7 countries.

	Historical until 1990		Recent since 1990		Policies after 2000	
	LC growth	FF decline	LC growth	FF decline	LC growth	FF decline
Canada	✗	✗	✗	✗	✗	✗
France	✓ 1972-1987	✗	✗	✗	✗	✗
Germany	✗	✗	✗	− short: 2015-2020	− DE-22 almost comparable	✗
Italy	✗	✗	✗	− short: 2008-2013	✗	✗
Japan	✗	✗	✗	− short: 2015-2020	✗	− JP-21 largely nuclear restart
US	✗	✗	✗	✗	✗	✗
UK	✗	✗	− relatively fast RES	✓ 2005-2020	− GB-23 fastest 5% speed zone	✓ GB-23 2005-2020

Notes: The green sign means compatible (required speed is achieved), and yellow means not compatible but close in some respect (e.g. "short" indicates that a comparable rate was achieved but shorter than the duration required to meet the IEA 1.5°C pathway), and red means not compatible at all.

These starkly different findings from my dissertation research arise from the fact that, unlike existing studies that focus on examining individual technological changes, I analyse the systemic transitions in the electricity sector involving all technologies and their interactions (see subsection 7.2.1 for further discussion on the methodological differences and the merits of my 'middle-range' approach). While Germany is perhaps the most well-studied country in transition literature, often focusing on the recent growth of renewables, the country has actually achieved neither the necessary growth rate of low-carbon electricity nor the decline of fossil fuels (Table 7.2 and Figure 5.9). This is because the growth of renewables has been accompanied by the concurrent decline of nuclear power (Figure 5.7), occasionally necessitating increased reliance on fossil fuels, leading to intermittent rises in the country's GHG emissions over the past decade (Alkousaa and Wacket, 2023).

There are some cases, however, where either the necessary growth speed of low-carbon electricity or the decline speed of fossil fuels was achieved (Table 7.2 and Figure 5.9). My comparative analysis quantitatively confirms the literature that the historical development of nuclear power in France in the 1970s and 1980s exhibits not only rapid (Grubler, 2010; Sovacool, 2016), but actually the fastest growth of low-carbon electricity in history. I also find that a similar speed was also achieved by Sweden during the same decades (Figure 5.9). Looking at the decline of fossil fuels, while the existing literature tends to emphasise the rapid coal decline in the UK (Brauers et al., 2020; Pollitt, 2012; Rentier et al., 2019), my analysis demonstrates that the UK actually achieved among the fastest decline of fossil fuels across the world, which is compatible with the 1.5°C pathway between 2005 and 2020 (Table 7.2 and Figure 5.9).

Not only do historical transitions in the G7 lack any episodes of transitions compatible with the IEA 1.5°C pathway, but these countries have also never implemented nor planned to implement policies as stringent as realising the required transitions in the future up to 2023 (Figure 6.15). Surprisingly, Japan, often labelled a 'climate laggard', projected the fastest rate of low-carbon substitutions in 2021 at 6.6% per year towards 2035. However, even this rate is not compatible with the IEA 1.5°C pathway, particularly due to a lack of acceleration in developing low-carbon electricity other than restarting currently idled nuclear power plants. Consequently, Japan is the only country among the G7 that currently plans to decrease its electricity supply by 2035 (Figure 6.9). While this may help decarbonise the electricity sector, it may not have the same effect on other energy sectors that require additional electricity to reduce emissions.

The UK most recently projected the second-fastest rate of low-carbon substitutions among the G7, reaching 5.9% per year in 2023, following the Russo-Ukrainian War (Figure 6.15). This reflected a political commitment to accelerate the decline of fossil fuels in line with the IEA 1.5°C pathway. However, while the UK also aims to further expedite the growth of low-carbon electricity, this growth is still not compatible with the pathway. Nonetheless, the recent efforts of the UK to accelerate both the decline of fossil fuels and the growth of low-carbon technologies position its latest projection as the most closely aligned with achieving 1.5°C among all the projections of the G7 countries analysed in this dissertation (Figure 6.16).

The third-fastest rate of low-carbon substitutions was targeted by Germany at 5.8% per year in 2022, also following the Russo-Ukrainian War and the subsequent political commitment to accelerate the growth of renewables, aiming for a 4.2% annual increase between 2022 and 2035 (Figure 6.15). While this represents a significant acceleration compared to the 2020 projection, achieving such rapid rates necessitates a fourfold increase in renewable growth compared to the empirical rates observed in 2015-2020. Furthermore, to align with the IEA 1.5°C pathway, Germany needs to hasten the decline of fossil fuels by more than twice the current projection (Figure 6.2). These required accelerations raise feasibility concerns, particularly due to Germany's low-carbon electricity supply undergoing a substantial decline at -3% per year, while the use of fossil fuels increased at 4% per year, resulting in high-carbon substitutions between 2020 and 2022 (Figure 5.10).

Are the UK and Germany leading decarbonisation efforts?

While no comparable episode has occurred since 1960, where the required growth of low-carbon technologies and the decline of fossil fuels for the IEA 1.5°C pathway were achieved simultaneously, the UK stands out for accomplishing the fastest transitions in recent decades among the G7: it is the only country which achieved the necessary rate and duration of fossil fuel decline between 2005 and 2020, and plans to replicate this speed in its latest projection (Table 7.2 and Figure 6.4).

In 2015-2020, the UK also achieved the fastest growth of modern renewables among the G7 at 3% per year (Figure 5.4). This, however, did not lead to the necessary growth of low-carbon electricity because nuclear power, despite increasing state support since the mid-2000s, did not grow but instead declined rapidly (Figure 5.4). If nuclear power would have been re-developed as politically envisaged, the UK may have achieved, for the first time in history, a comparable low-carbon substitution in line with the IEA 1.5°C pathway (Table 7.2).

The same story would not apply to Germany. While it may be tempting to assume that Germany could have experienced a comparable low-carbon substitution episode by not phasing out nuclear power and allowing it to continue running to replace fossil fuels, Germany would still not have achieved the necessary growth of low-carbon electricity in the 2000s or 2010s. This is because the growth rates of modern renewables in Germany were lower than in the UK, with the growth rate even decelerating from 2010-2015 to 2015-2020 (Figure 5.4).

Examining policies post-2000, although still not aligning with the IEA 1.5°C pathway, the UK once again distinguishes itself as the only country showcasing the stringency of policies in 2023 to achieve the fastest 5% speed of low-carbon substitutions with the sufficient decline rate of fossil fuels towards 2035 (Figure 6.16). Realising this projection and further accelerating the necessary growth of low-carbon electricity for the 1.5°C target may require the UK to reverse its long-declining trend of nuclear power, despite the increasing political efforts to revitalise the technology since the mid-2000s—a topic I will further discuss in the next subsection 7.3.3. In contrast, Germany, up to 2023, has not demonstrated the stringency of policies compatible with the decline of fossil fuels required for the 1.5°C target (Table 7.2 and Figure 6.2).

7.3.3 The role of nuclear power in accelerating energy transitions

Nuclear power enabled the first phase of low-carbon substitutions in the G7 in 1980-1985 (Figure 5.6), but it ironically became the reason for a slower transition towards decarbonisation in recent decades.

Figure 7.2 illustrates the continuous decline of nuclear power since the mid-2000s despite the G7's consistent efforts to maintain and re-develop the technology. Particularly, Japan, Canada, and the UK, aimed for a significant upscaling of the technology in the 2000s and 2010s but continuously failed to achieve it (See Panel B in Figure 6.9 for Japan, Figure 6.11 for Canada, and Figure 6.3 for the UK).

My analysis further shows that when these countries aimed for a higher nuclear power supply in their energy transition projections, a more significant decline actually occurred even after Fukushima, despite the presumably improved consideration of the risks and uncertainties associated with the technology (Figure 6.17). The failure to meet the projected growth of nuclear power often led to the underachievement of projected low-carbon electricity growth across the G7 countries, despite the frequent overachievement in the growth of renewables (Figure 6.17).

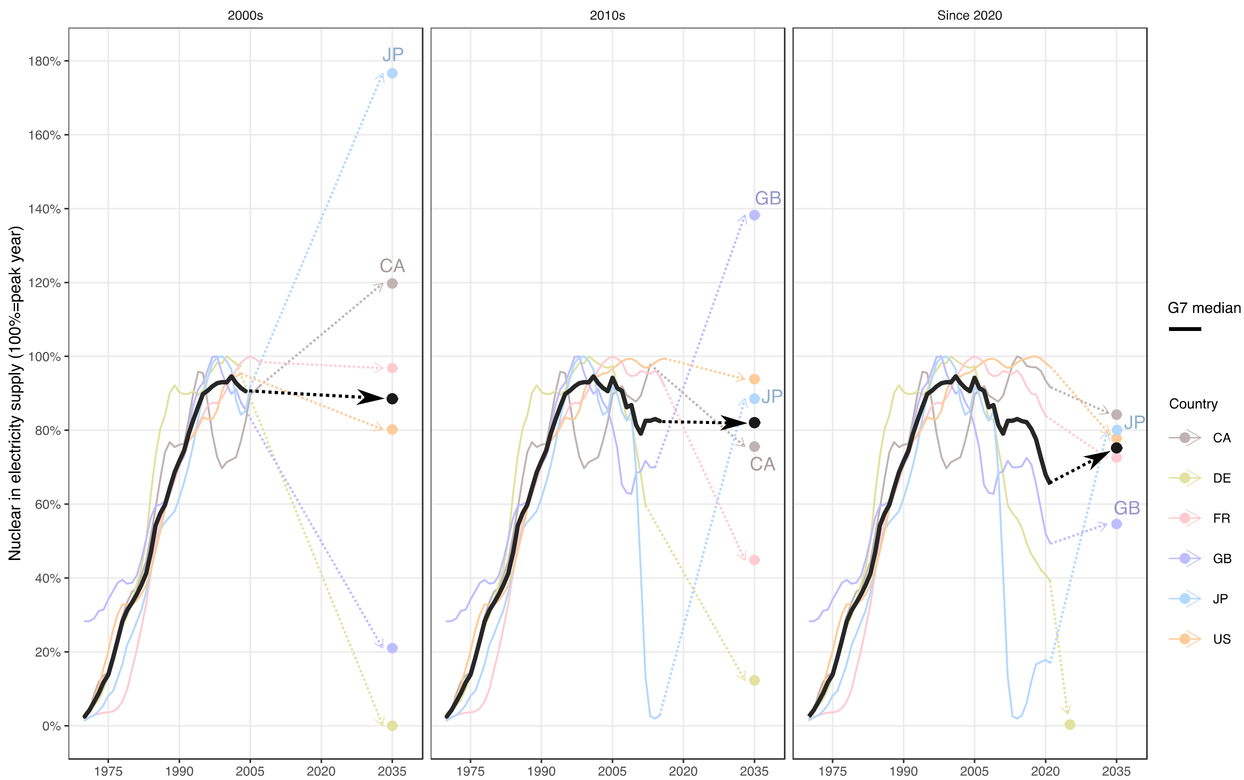


Figure 7.2: Historical and planned supply of nuclear power in 2000s, 2010s, and since 2020.

Notes: Coloured lines show the supply of nuclear power normalised to the maximum value recorded in each G7 country. The black line represents the median of the trajectories of these countries. Italy is excluded since the country phased out nuclear power immediately after the Chernobyl disaster in 1986 and has neither restarted the plants nor planned to redevelop nuclear power.

This continuous policy failure also necessitated the UK to subsequently lower the projected speed of low-carbon substitutions towards 2035 in the 2010s (Figure 6.3). While the G7 countries still aim to increase the output of nuclear power in their current projections (Figure 7.2), the persistent decline trend raises questions about its achievability, suggesting that significantly stronger policies are necessary to reverse the trend.

7.4 Theoretical contributions

My dissertation also makes multiple theoretical contributions. First, this dissertation developed a typology of energy transitions to systematically categorise them into four distinct types that are most relevant for climate change mitigation (Figure 3.2). This approach facilitates the identification of trends in transitions, the examination of the overall impacts of climate policies on altering the trends, and the comparison of transitions across countries and time-periods. Through the application of this typology to conduct multiple comparative analyses, I show that recent transitions are not more policy-driven compared to the past. Additionally, I argue for the importance of the role of context, in addition to technology characteristics, in accelerating energy transitions.

7.4.1 Typology of energy transitions

In the existing literature, various types of technological changes in the energy sector have been uniformly termed as energy transitions. This tendency is particularly noticeable in transition studies, where the expansion of renewables or the decline of coal is frequently labelled as cases of 'low-carbon transitions' without specifying whether the growth of renewables substituted fossil fuels or the decline of coal led to an overall reduction in fossil fuels. This lack of attention to the interactions between technologies is problematic because the expansion or reduction of certain technologies may not always result in the decarbonisation of the entire energy system (see subsection 2.4.1 for more details). A similar tendency can be observed in other energy sectors. For example, while the growth in the new sales of electric vehicles tends to be immediately considered as another case of 'low-carbon transition' (Keith et al., 2019), in reality, we may be adding just more new cars on the road, which would not lead to reducing emissions.

Therefore, my dissertation developed a typology of energy transitions based on the changes and the interplays between fossil fuels and low-carbon technologies to systematically categorise the types of energy transitions most relevant to mitigating climate change (Figure 3.2). This typology is a significant contribution to the literature because it enables systematically tracing the developments of energy transitions including direction and speed over time (Figure 5.6), and allows for comparisons across countries and time-periods (Figure 5.9 and Figure 6.16). Through this comparative analysis, it is also possible to examine how policy introductions impact energy transitions beyond historical trends towards decarbonisation (Figure 5.2, Figure 5.6, and Figure 6.16).

No such typology was introduced in the literature before, as evidenced by the fact that this was one of the key contributions of my paper, which was published in one of the top journals in the field in 2023. However, it is worth noting that the term ‘energy additions’ had already been coined by some scholars (Fouquet and Pearson, 2012; York and Bell, 2019), which inspired the development of this typology by identifying three more types to complete the quadrant classification (Figure 3.2).

7.4.2 Energy transitions have always been policy-driven

Transition scholars and climate policy researchers who focus on analysing recent transitions tend to assume that energy transitions are increasingly governed by (climate) policies compared to historical transitions (see subsection 2.3.3). This is the fundamental assumption on which these scholars base their argument that low-carbon energy transitions are unique and take place faster than historical transitions, particularly in the future following the trend of the growing political attention to mitigate climate change and the increasing number of climate policies introduced in recent decades (Kern and Rogge, 2016; Roberts et al., 2018; Sovacool and Geels, 2016).

However, my dissertation quantitatively validates the arguments of political scientists (see subsection 2.2.1 for my review of their argument), which were predominantly rooted in qualitative analyses, that national governments and policies have consistently played a significant role in energy transitions, spanning historical events, recent developments, and are likely to continue doing so in the future. Focusing on the outcomes of the increasing adoption of climate policies, my dissertation reveals that the inclusion of climate change mitigation in the political agenda has not yet resulted in altering the pace of energy transitions beyond historical trends (Figure 5.2, Figure 5.3, and Figure 5.6). In other words, climate change mitigation and climate policy are not unique; they are another set of policy objectives and instruments akin to energy security and energy policy, which have predominantly shaped historical energy transitions. While climate objectives and instruments may appear more salient because they have surfaced in recent decades, they have not dictated the course of energy transitions as widely assumed in the literature.

This finding has two significant implications. One piece of bad news is that historical energy transition research which argues that "energy transitions are inherently complex and prolonged affairs" and thus "none of today's promises for a greatly accelerated energy transition from fossil fuels to renewable energies will be realized" (Smil, 2010, p. 28) actually factors in historical political efforts, while not explicitly recognised by the scholars (Fouquet and Pearson, 2012). This also explains why recent energy transitions are rather slower than historical transitions in the G7 and the EU (Figure 7.1): recent transitions may be less politically accelerated compared to the past, which may indicate that national governments are now more constrained in accelerating energy transitions than in the past (see my further discussion on this point in the next subsection 7.4.3).

One piece of good news, however, is that history may offer more examples of accelerated energy transition cases from which we can examine how to replicate and further amplify the effects of policies. My dissertation identifies some of these historical examples, including the development of nuclear power in France and Sweden in the 1970s and 1980s (Figure 5.9 and Figure 5.8). These instances stand out as the only historical cases to date where the required growth rate of low-carbon electricity, essential for achieving the 1.5°C target, has ever been attained.

7.4.3 Role of the context and technology characteristics in technological growth

Existing studies often assume that modern renewable technologies, such as solar and wind power, would grow rapidly by highlighting the advantages of their technological characteristics, such as being relatively simple (Malhotra and Schmidt, 2020), granular (Sweerts et al., 2020; Wilson et al., 2023, 2020), decentralised (Wilson et al., 2020), and increasingly cheaper (Cooper, 2016; Lovins et al., 2018).

However, my dissertation shows that it was actually nuclear power, which is relatively more complex, lumpy, centralised, and expensive, that developed faster in the G7 and the EU, even compared to the recent growth of all modern renewables combined (Figure 5.11. Also see Figure 7.1). This supports the view of Roberts et al. (2018) and validates the findings of Vinichenko et al. (2023a), demonstrating the importance of contexts in accelerating energy transitions in addition to technological characteristics. Furthermore, my dissertation goes beyond Vinichenko et al. (2023a) by showing the political contexts behind the different levels of acceleration in nuclear power and renewables and demonstrating how these different speeds relate to the resistance from incumbent actors, particularly fossil fuel industries.

Table 7.3 summarises the main technological characteristics and contexts behind the rapid growth of nuclear power and the slower growth of modern renewables in the G7 and the EU.

Table 7.3: Technology characteristics and historical context of the growth of nuclear power and modern renewables in the G7 and the EU.

		Nuclear power	Modern renewables
Technology characteristics	Complexity	complex	simple
	Size	lumpy	granular
	Installations	relatively few and centralised (slow learning rates)	many and distributed (fast learning rates)
	Costs	more expensive and not declining high investment risks	cheaper and declining lower investment risks
Assumed growth in the literature		**Slow growth**	**Rapid growth**
Historical context when developed in G7 and EU	Time	1970s and 1980s	since 2000s
	Energy demand	rapidly growing	stagnating
	State motivation	energy security (oil crises in the 1970s)	climate mitigation energy security (Russian-Ukrainian War)
	Market	heavily regulated	liberalised
	Mode of policymaking	top-down and technocratic (limited actors)	more democratised, value-laden, contested (many actors and negotiations)
	Incumbent resistance	None to marginal (same political and economic actors)	High (different actors with competing interests)
Historical outcome		**Rapid growth** **(max. 2%, G7 average in 1980-1985)**	**Slow growth** **(max. 1.1%, G7 average in 2015-2020)**

During the 1970s and 1980s, various contextual factors paved the way for significant political motivation and capacity to rapidly develop nuclear power (Table 7.3). First, the demand for electricity rapidly grew at 4% during these decades, necessitating a fast growth of energy technologies to meet the demand (Figure 5.2). Secondly, the oil crises in the 1970s significantly heightened the need for nuclear power to quickly reduce oil dependence. Thirdly, the electricity market was heavily regulated, with national governments directly owning many, if not all, of energy industries or exercising a predominant influence on their developments (see Chapter 4 for the analysis of Germany and the UK, and also see Ikenberry (1986), Kaijser (1992), and Hecht

(2000) for other G7 countries). Fourthly, policymaking in these decades was centralised and often conducted in a technocratic, top-down manner, where only a limited number of actors planned and implemented policies. In such a policy environment, the high costs of nuclear power were less problematised, with such information generally hidden from the public (Bolton, 2022; Grubler, 2010). Lastly, the third and the fourth points mean that both incumbent and new technologies were owned and developed by the same actors, thus the development of nuclear power offered nothing but political and economic benefits.

In contrast, these accelerating factors have been largely absent in recent decades in the development of modern renewable technologies (Table 7.3). Unlike in the 1970s and 1980s, the demand for electricity has been stagnating in the G7 and the EU (Figure 5.2), which does not necessitate the growth of alternative technologies faster than the retirement of existing ones, such as coal power plants. In this context, accelerating low-carbon substitutions would be very costly, as the total costs of building and operating new alternative technologies need to be lower than the marginal costs of existing technologies (Kramer and Haigh, 2009), requiring a substantial amount of subsidies depending on how much acceleration is necessary (Lund, 2015).

Another way to accelerate the substitutions is to expedite the phase-out of existing technologies. Such political acceleration, however, remains rare due to strong resistance from the affected industries and communities (Jewell et al., 2019). When it does occur, it typically requires significant compensation, as showcased in Germany’s coal phase-out (see subsection 4.2.1) and other coal-dependent countries (Nacke et al., 2023). Such public spending would inevitably be visible in today’s liberalised market with more private ownership of energy industries, necessitating transparent accounting compared to the past (Bolton, 2022), which often triggers a significant backlash against such policies (see the relevant theoretical discussion in subsection 2.2.3 and empirical observations in subsection 2.3.4).

The need for decarbonising energy to mitigate climate change has also transformed today's policy-making to be more democratised because "[t]he question of how to transform energy is one of values….[where] [w]hich expenses and risks to bear, and which to avoid, is far from a technocratically determinable choice" (Welton, 2018, p. 598). Accordingly, many more actors, ranging from industries and non-governmental organisations to affected communities of transitions and the general public, who may possess competing interests in energy transitions, now influence policymaking. This inherently requires more negotiations to address different perspectives and balance diverse priorities. As a result, implementing 'ideal' policies is likely to be unattainable (see subsection 2.2.2 for more theoretical discussions in the literature). In other words, today's policymaking is more contested in nature compared to the past (see subsection 2.3.4 for empirically observed cases), which may have shrunk the capacity of national governments to realise their political motivations.

The fact that these changing contexts have resulted in the overall similar evolution of the electricity sector across the G7 and EU since 1960 (Figure 5.7) indicates that it may be better to focus on these evolving contextual factors surrounding the state (Table 7.3), rather than solely focusing on state-specific features such as centralised or federal government or a variety of capitalism to explain national energy transitions (see subsection 2.2.2 for these focused debates). On this point, it is particularly noteworthy that following the Russo-Ukrainian War in 2022, Germany and the UK, one federal and CME and the other centralised and LME, both substantially strengthened their policies to accelerate low-carbon substitutions with an aim to enhance the country's energy security compared to their previous policies (see subsection 6.3.1 for Germany and 6.3.2 for the UK).

While even these policies are still not compatible with the 1.5°C pathway (Figure 6.15 and Figure 6.16), it is remarkable how energy security concerns have led to significant and uniform changes in policies in just a few years, reminiscent of the political efforts observed across all the G7 countries back in the 1970s after the oil crises (Ikenberry, 1986; LaBelle, 2023). We are yet to see whether these policies can be sustained in the coming years to achieve their intended goals and whether such policies will also be introduced in the other G7 countries, though some of these countries may not face the same degree of urgency compared to Germany and the UK.

On the other hand, these countries may need to better acknowledge the potential deterioration in electricity supply security they all may face in the coming decades. This is due to the accelerating speed of electrification in energy demand sectors such as transport, buildings and industry, a trend already underway globally and expected to continue (IEA, 2023c). While addressing the potential shortage of electricity will necessitate stronger efforts in expanding its supply, currently only Germany aims to provide a sufficient amount of electricity compatible with the IEA 1.5°C pathway (Figure 6.1). Notably, Japan even aims to decrease its electricity supply by 2035 (Figure 6.9). Given the time required for the development of energy technologies, countries need to start conducting a more thorough assessment of future electricity needs and integrate this into their climate and energy policymaking.

7.5 Limitations and the need for further research

There are several limitations to my dissertation research that necessitate further studies. These include the relevance of my analyses on the G7 and the EU beyond these countries, the further need to scrutinise the impacts and stringency of climate policies in energy transitions, and the necessity to examine alternative transition pathways beyond those commonly outlined by these countries and international institutions such as the IEA.

7.5.1 Relevance of my dissertation beyond G7 and EU, and the electricity sector

First, it is important to note that the G7 countries and the EU are heavily industrialised economies, which may not necessarily represent electricity transitions in other countries.

Instead of following the conventional development path of developed countries, developing nations are often encouraged to pursue a form of development characterised as ‘leapfrogging’ (Goldemberg, 1998). This entails bypassing the phase of economic development reliant on fossil fuels and transitioning directly to a more sustainable model based on low-carbon technologies such as renewables, often with financial and technological assistance from developed countries. However, the concept of leapfrogging, often explored through scenario exercises, remains largely theoretical: its practicality is questioned in the contexts of developing countries (Murphy, 2001; Zaman, 2020).

Moreover, existing literature debates whether the rest of the countries, particularly those in the global south, can sufficiently develop without industrialisation and the increased use of fossil fuels (Grubler et al., 2018; Lindvall and Karlsson, 2023; Semieniuk et al., 2021). Therefore, further research is necessary to investigate the similarities and differences in development trajectories and potential future paths of developing countries, as well as the role of domestic and international policies in them.

Secondly, my dissertation specifically focused on analysing transitions within the electricity sector. The decision to concentrate on this sector stems from the assumption that transitions in other sectors have, on average, been slower than those in electricity. This assumption is grounded in the prevailing emphasis of policies, which have predominantly targeted accelerating transitions in the electricity sector in recent decades (Nascimento et al., 2022b). However, it is important to note that this assumption may introduce a potential bias. It assumes a uniform pace of transitions across various sectors, potentially overlooking the diverse speeds at which each sector might be undergoing changes.

Therefore, further work is necessary to examine whether and how energy transitions in other countries and other sectors have taken place compared to climate target requirements. The middle-arrange comparative approach I developed and applied in this dissertation can be useful for such diverse analyses, for example, to analyse energy transitions in developing countries or to examine the progress of transitions in other sectors such as transport (e.g. e-mobility), buildings (e.g. net-zero buildings), and industry (e.g. low-carbon steel and cement production).

This approach also enables the identification of historically relevant cases for future transitions, as I demonstrated particularly in subsection 5.2.4. Only through systematic identification and thorough examination of these cases, while exploring ways to replicate and potentially expedite their rate of acceleration, can we address the questions that remain underexplored in the literature: "What does it take?" (Grubler et al., 2016, p. 24), and "How much will it cost?"(Sovacool and Geels, 2016, p. 236) to mitigate climate change, including the feasibility and desirability of these actions.

7.5.2 Scrutinising the true impacts and stringency of climate policies

Another limitation of my dissertation is the fact that my research only shows the overall trend of electricity transitions as eventual outcomes of numerous co-evolving factors, including policies.

While I did not find evidence in Chapter 5 that the increased number of climate policies has correlated with faster or radically different transitions in the G7 and the EU, this does not mean climate policies did not have effects. It is possible that the effects of climate policies were overshadowed by confounding factors, including other policies and non-policy elements. To precisely isolate the impact of climate policies, one would need to perform a counterfactual analysis by identifying situations identical in all aspects except the presence of climate policies or by conducting quasi-experimental or other similar methods.

In fact, this field is evolving with respective studies reporting a wide range of impacts varying from 'no' discernible effects to 'significant' impacts even looking at the same policies (see, for example, Hoppe et al. (2023) synthesising these studies), highlighting the substantial need for further advancements in the literature. The lack of consensus in these studies perhaps fuels the ongoing debate on the impacts of climate policies, presenting a dichotomy between 'every policy/effort counts' (Kern and Rogge, 2016; Sovacool and Geels, 2016) or 'all policies/efforts fail' (Smil, 2024, 2010), which is hardly productive.

Therefore, a more nuanced understanding is necessary by scrutinising which policies, in what sequence and combination, and under what conditions (where and when certain policies are effective or not) may maximise the impacts. Additionally, a greater understanding of how these impacts compare to climate target requirements is crucial, as such analysis is significantly lacking in the existing literature.

Similarly, using energy projections to analyse the overall stringency of policies in Chapter 6 faces the same limitation. On the one hand, this chapter further reinforces the findings of Chapter 5 by demonstrating that even policy targets do not go beyond historically observed rates of change and thus policies have not yet been able to override the inertia of energy systems and become the primary driving force of transitions, in contrast to some arguments in the literature (Kern and Rogge, 2016; Sovacool and Geels, 2016). I also show that no G7 country has yet shown the level of overall stringency of policies required for achieving 1.5°C. On the other hand, this does not necessarily mean that the stringency of policies has not increased over time. This is because the stringency of policies can be cancelled out by negative macro-economic trends for decarbonisation in transition projections (e.g. lower fossil fuel prices than anticipated in previous projections). At the same time, it can also be the case that the stringency is enhanced by positive trends (e.g. increased speed of technology diffusion not attributable to policies).

A potential approach to delve deeper into the changing stringency of policies involves identifying and scrutinising a multitude of alterations in modelling assumptions related to non-political factors. By reversing these changes, a clearer understanding of the impacts solely attributable to policy changes can be obtained. Although this method would likely require collaboration with the modellers responsible for national projections, it holds significant value for countries. This is because conducting such analyses allows for the identification of assumed policy impacts, which can then be compared with the empirically observed impacts of the same or similar policies. This, in turn, facilitates the improvement of countries' projection exercises and informs what additional changes would be necessary to achieve their state objectives.

7.5.3 Societal transformations rather than technological accelerations

Lastly, my dissertation analysis heavily relied on the IEA 1.5°C pathway to comparatively analyse historical transitions and the required transitions in the G7 and the EU. While this selection can be justified by the fact that the G7 requested the IEA to develop this pathway in 2021, which was later adopted as the G7's target in 2022 (G7, 2022), there could be many other potential development pathways. These pathways might involve more radical socio-economic transformations rather than simply accelerating the growth of low-carbon technologies and the decline of carbon-intensive technologies. While this is beyond the scope of my dissertation research, the findings that there remains a significant gap to follow the IEA 1.5°C pathway may necessitate more discussion about giving up on such pathway and instead pursuing radically different efforts such as significantly constraining energy demand, re-structuring political economies, or fundamentally reshaping societal norms and practices.

8. Summary and conclusion

This dissertation commenced with Chapter 1 and Chapter 2, collectively arguing for the necessity of scrutinising political acceleration in energy transitions. Despite the clear imperative for politically accelerating energy transitions to mitigate climate change, the existing literature lacks clarity on how policies accelerate energy transitions, whether recent transitions under climate policies are faster, or how the overall stringency of policies has evolved to mitigate climate change. The primary reason for this gap in the literature lies in existing analyses being either too broad, emphasising the slowness of the global transition, or too narrow, focusing on the recent piecemeal changes in specific countries without assessing their significance in comparison to other countries, historical transitions, or climate target requirements.

Against this backdrop, this dissertation aimed to achieve the following three objectives:

(1) Developing an approach with an appropriate granularity to examine political acceleration in energy transitions.
(2) Applying this approach to analyse historical and planned political interventions in the energy sector and their outcomes in terms of the nature and speed of energy transitions.
(3) Comparing this historical analysis with climate target requirements to elucidate the challenges in accelerating energy transitions to mitigate climate change.

To fulfil these objectives, I developed the ‘middle-range’ methodology based on critical realism in Chapter 3. It is termed ‘middle-range’ because of its more focused scope than the existing global and cross-sectoral analyses, yet broader than the alternative approach, looking solely at individual technological changes (Table 3.4). To facilitate the comparative analyses of this dissertation among actual, planned, and required energy transitions and across countries, I also developed a typology of energy transitions most relevant to mitigating climate change (Figure 3.2). This typology is a theoretical contribution to the existing literature where various forms of technological changes have been uniformly labelled as energy transitions (see subsection 7.4.1 for more details). By systematically categorising them into four distinct types ('energy additions', 'low-carbon substitutions', 'high-carbon substitutions', and 'energy reductions') based on the changes and their interplays between fossil fuels and low-carbon technologies, this typology enables tracing the changes in the nature of energy transitions and their direction and speed towards decarbonisation and facilitates comparisons across countries and time-periods. Furthermore, to clarify the extent of acceleration necessary in the future to mitigate climate change, I expanded on the existing methods to build 'empirically grounded speed zones' of energy transitions constructed from relevant historical cases and their density of observations (Figure 3.3).

I applied this middle-range methodology to analyse electricity transitions in the G7 and the EU, where political acceleration is most expected, given their significant economic, financial and technological capabilities, their political commitment to accelerating decarbonisation efforts, and their leadership in introducing climate policies in the sector in recent decades. To test and advance the methodology, I pursued a step-by-step approach (see subsection 7.2.2 for more details) to gradually broaden the scope of analysis to conduct the following three longitudinal comparative case studies, respectively guided by the research questions of this dissertation:

	Research questions	Comparative cases
Chapter 4	How have the state interventions in the energy sector differed across countries, and how have the differences affected their transition outcomes?	Historical transitions in Germany and the UK
Chapter 5	Have climate policies altered energy transitions beyond historical trends, and if so, how in light of climate target requirements?	Historical and required transitions in the G7 and the EU
Chapter 6	How has the stringency of national energy transition policies changed over the last decades, and how does this evolution compare to historical and required transitions?	Historical, planned, and required transitions in the G7

I now briefly present the summary of these three empirical chapters. Chapter 4 identified a series of rapid transition cases involving diverse state interventions in Germany and the UK (see Table 4.3 for the summary). In the 1960s and 1970s, both states were generally supportive of developing various technologies with a clear preference for domestic sources such as coal and nuclear power to supply their rapidly growing demand for electricity. Since the 1990s, however, their policies started to diverge, where Germany started to phase out nuclear power to protect the otherwise declining coal industry while the UK liberalised and privatised the electricity market to trigger a 'dash to gas' and a 'rush from coal'. Particularly after the 2010s, this divergence intensified as Germany recommitted to phasing out nuclear power and began reducing coal power while endorsing gas as a 'bridge source'. In contrast, the UK accelerated the decline of both coal and gas power, opting instead to increase state support for nuclear power. Both countries have strongly supported the development of renewables since the 2010s.

A particularly important finding from Chapter 4 is the fact that despite these increasing differences in policies between Germany and the UK, the speed of technological growth and decline in these countries have remained remarkably similar. This is particularly the case when technologies targeted by the states to develop (various renewables in these countries) or destabilise (coal and nuclear in Germany and coal and gas in the UK) are considered together (Figure 4.6 and Figure 4.7). This indicates that while countries can choose which technology to develop or destabilise depending on national circumstances, the overall technological speeds of growth and decline may not vary significantly. The question arose, therefore: Are these speeds accelerated in recent decades with climate policies compared to the past?

Chapter 5 was thus designed to examine whether the speed of technological change has been accelerated in recent decades with climate policies by expanding the scope of analysis to the G7 and the EU. This analysis revealed that electricity transitions in these countries have largely correlated with changes in electricity demand throughout the last six decades (Table 5.2). Under the growing demand, which lasted until 2005, various technologies were developed on top of one another, and thereby, these countries pursued energy additions. Since 2005, the decreasing demand for electricity necessitated the decline of fossil fuels as low-carbon electricity started to grow with modern renewable technologies, albeit at a slower rate compared to the historical growth of low-carbon electricity with nuclear power in the 1970s and 1980s.

This analysis demonstrates that while the number of climate policies increased dramatically since 1990, from less than 50 to more than 2000 in 2020 in the G7 and the EU (Figure 5.3), they have not accelerated energy transitions either by expediting the growth of low-carbon electricity or hastening the decline of fossil fuels beyond historical trends. In contrast, achieving the political commitment of these countries to decarbonise electricity by 2035 to be in line with the global 1.5°C target necessitates unprecedentedly radical acceleration in energy transitions: low-carbon technologies need to develop five times faster, and fossil fuels must decline two times faster compared to the rates observed in 2015-2020 (Figure 5.6). Unfortunately, no country has ever achieved such rapid energy transitions in history (Figure 5.9).

This analysis of the number of climate policies and the historically demand-driven energy transitions spurred another question: Has the overall stringency of energy transition policies increased in recent decades?

Chapter 6 accordingly delved into examining the evolving stringency of energy transition policies in the G7 countries in recent decades. By utilising national energy projections as a proxy, I revealed that none of these countries has yet implemented or planned policies compatible with achieving their decarbonised electricity target by 2035 as of 2023. Contrary to the existing claim in the literature, energy transitions have not been increasingly governed by policies. Instead, the planned speed of transitions has predominantly remained within historically observed rates (Figure 6.16).

Furthermore, it is noteworthy that most of these countries began implementing policies to accelerate the decarbonisation of the electricity sector only after 2010, including Germany (Figure 6.1) and the UK (Figure 6.3). While this acceleration was driven by the progressive growth of modern renewable technologies, the continuous failure of policies to maintain and revitalise nuclear power in recent decades resulted in the frequent underachievement of developing low-carbon electricity (Figure 6.17).

After conducting these three empirical chapters, I discussed the methodological, empirical, and theoretical contributions of this dissertation to the literature in Chapter 7 while outlining its limitations and proposing multiple avenues for future research.

Most importantly, the middle-range methodology developed in this dissertation proved to be useful in comparing energy transitions across countries and time-periods. By conducting multiple longitudinal comparative analyses, this dissertation refutes the existing claim in the literature and demonstrates that energy transitions have always been political, but they have been primarily driven by changes in energy demand throughout the last six decades in the G7 and the EU. Recent transitions have not occurred more rapidly, nor have they been more politically governed in these countries beyond historical trends (Figure 7.1). Consequently, none of these countries have yet empirically demonstrated or even planned the rates of acceleration necessary to achieve 1.5°C (Table 7.2). In other words, in contrast to the claim in the literature, there has been no 'successful' case of transitions comparable with the magnitude of acceleration required to mitigate climate change (Figure 5.9 and Figure 6.16).

However, there is an emerging sign of potentially significant acceleration in the future, notably following the Russo-Ukrainian War in 2022, at least in Germany and the UK, to expedite the development of low-carbon electricity in Germany, accompanied by the hastened decline of fossil fuels in the UK. While this emphasises the importance of contexts in accelerating energy transitions (Table 7.3), realising this recently envisaged acceleration may be challenging due to several feasibility concerns. These concerns arise from the fact that such acceleration requires an immediate increase in the growth rates of low-carbon electricity by two to five times compared to the most recent empirical rates in these countries (see Figure 6.2 for Germany and Figure 6.4 for the UK). Increasing the reliance on nuclear power can be another option, but the G7 countries have continuously failed to maintain and revitalise the technology as planned in recent decades (Figure 7.2), resulting in frequently increased reliance on fossil fuels to fill the gap (Figure 5.6 and Figure 5.10). It is thus important to monitor the progress of these countries in the future, particularly concerning whether the transitions are empirically accelerated to achieve their decarbonised electricity target by 2035, a key milestone not only for the G7 and the EU but globally to keep the temperature increase below 1.5°C.

There are several limitations in this dissertation, calling for further research. First, the scope of this dissertation analysis is limited to the G7 countries in the electricity sector since 1960. It is possible, though not empirically verified (see subsection 7.5.1 for more details), that transitions may differ in other countries and other sectors, potentially showing more political acceleration. The middle-range comparative approach developed in this dissertation can be readily applied to conduct such analysis. For example, it can be used to analyse energy transitions in developing countries or to assess progress in other sectors such as transport (e.g., e-mobility), buildings (e.g., net-zero buildings), and industry (e.g., low-carbon steel and cement production).

Secondly, while this dissertation has demonstrated that the impacts and stringency of climate policies have been more limited than widely assumed in the literature, a thorough examination of the true impacts and stringency requires a more robust causal analysis than the overall trend analysis conducted in this dissertation (see subsection 7.5.2 for more details). This is important because the effects and the stringency of climate policies may have been cancelled out by other confounding factors, including other policies and non-political variables. Despite the growing body of literature on this topic in recent years, further advancements are needed to elucidate which policies, in what sequence and combination, and under what conditions (where and when certain policies are effective or not) may maximise the impacts of climate policies to accelerate energy transitions.

Thirdly, what is essential for mitigating climate change in the future may not merely be the acceleration of developing low-carbon technologies to replace fossil fuels. Instead, pursuing more societal transformations, departing from historical development norms, may prove to be a more fruitful avenue than aiming for a radical acceleration in energy transitions, which has not materialised even after more than 30 years of climate policies. Rather than relying solely on policymakers and policies to induce such changes, it may be up to all of us as citizens, businesspersons, and scholars to initiate such transformations. The cause of climate change is the use of fossil fuels, but addressing climate change may not solely rely on low-carbon technologies to replace it; perhaps more importantly, it should involve accelerating low-carbon behaviours and practices that may not require decades to develop and diffuse.

I would like to conclude this chapter by providing policy recommendations that can be drawn from my dissertation research for the G7, the EU, and beyond.

The first recommendation is to carefully select model cases to learn from to accelerate energy transitions. While my dissertation research shows that there has been no ‘perfect’ case in history that achieved a comparable nature and speed of transitions to meet the 1.5°C target in the G7, the EU, and other comparable countries (see Figure 5.9 for historically the fastest 10 transition cases towards decarbonisation), I identified some close precedents which achieved either the necessary growth of low-carbon electricity or the decline of fossil fuels. These cases, some of which took place in the 1970s-1980s driven by the exceptionally rapid growth of nuclear power in Spain (Figure 5.8), France and Sweden (Figure 5.9), may thus offer more fruitful lessons for accelerating transitions rather than some individual technological changes such as renewable growth in

Germany that have taken place more recently thus more salient (i.e. recency bias) but has not yet resulted in accelerated systemic transitions towards decarbonisation.

Identifying such relevant cases requires carefully designed comparative analyses that consider national contexts and the nature and speed of targeted transitions, as demonstrated in this dissertation with a framework and methods applicable to other sectors and countries. Since more acceleration may take place in the future, it is important to continuously assess ongoing transitions against historical benchmarks and required transitions to update the list of model cases to inform policymaking based on evolving evidence.

The second recommendation is to better reflect the emerging ex-post analyses on the empirical impacts of climate policies on the development and updates of energy transition policies and projections. Given the significant variance in reported policy impacts between studies even for the same policy instruments (Hoppe et al., 2023), replicating a policy that is successful in one place and time does not guarantee similar results in different contexts. It is also important to be aware that the same policy may have had no effect or perhaps even negative effect elsewhere, but such cases tend to be neglected in the literature due to innovation and publication biases (Grubler et al., 2016; Rogers, 2003). Moreover, the lack of consensus on impacts suggests that assumed impacts of existing and planned policies in national energy projections are likely incorrect, highlighting the necessity of removing the margin of error based on evolving insights from policy impact literature.

One important example of such necessity is the substantial disparity between the significant role that carbon pricing plays in energy and climate modelling exercises and its so far negligible empirical impact in accelerating energy transitions towards decarbonisation (Lilliestam et al., 2022, 2021; Patt and Lilliestam, 2018). One cause of no acceleration in energy transitions with climate policies so far may stem from this lack of such reflection in energy and climate policymaking, which needs to be addressed as meeting the climate target requirements for 1.5°C needs radically different and stronger actions rather than incremental changes.

The last recommendation, which is particularly relevant for the G7 countries, is to address the significant gap between the substantial expansion of electricity supply necessary for climate change mitigation and its markedly stagnating growth in the last decades. Currently, only Germany in its latest policy aims to supply the amount of electricity necessary for the accelerated electrification of other energy sectors for decarbonisation (Figure 6.1). In contrast, Japan currently even targets a decrease in electricity supply (Figure 6.9), which may help decarbonise electricity but is likely to slow down the decarbonisation of its entire energy system. With the electrification of various energy demand sectors already underway and expected to accelerate in the future (IEA, 2023c), the security of electricity supply may increasingly deteriorate unless stronger actions are taken to expand its supply.

Historically, such energy security concerns facilitated the acceleration of energy transitions, including more recently in some G7 countries after the Russo-Ukrainian War in 2022. This suggests that recognising the importance of and accordingly strengthening efforts to expand electricity supply could drive the faster development of low-carbon electricity. It is, however, crucial to note that under such rapid increase in energy demand, various technologies, including those based on fossil fuels, tended to grow in historical transitions (Figure 5.2 and Figure 5.6). In contrast, future transitions require achieving the accelerated growth of low-carbon technologies, resulting in the expedited decline of fossil fuels.

Appendix A

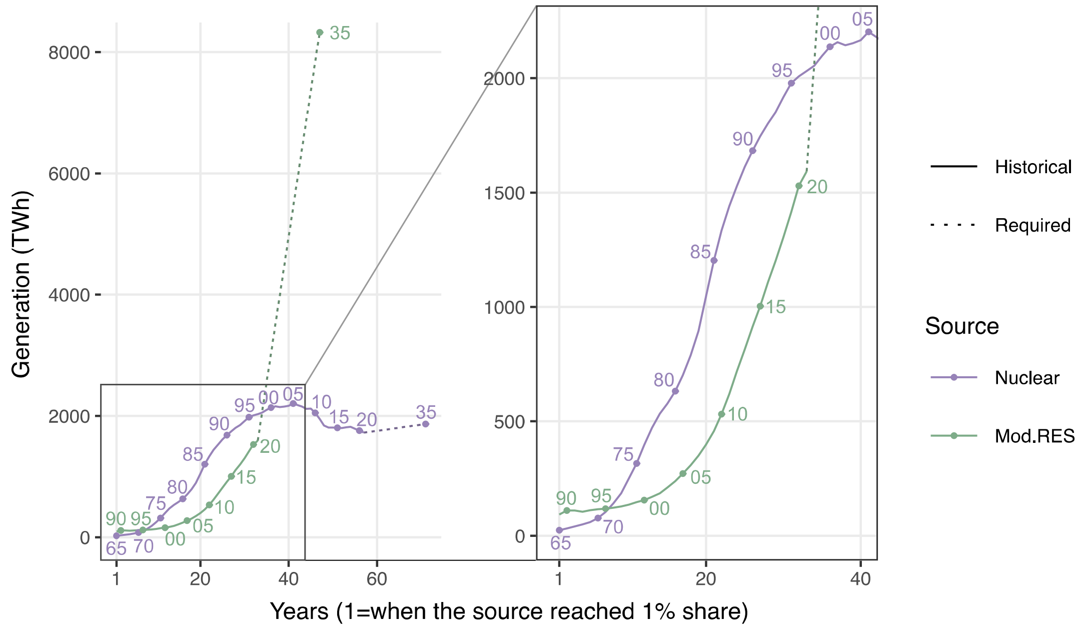


Fig. A1: Growth speed of nuclear power and modern renewables in generating electricity after reaching a 1% market share in the G7 and the EU.

Table A1: Country codes used in this dissertation.

Code	Country
AR	Argentina
AU	Australia
BR	Brazil
CA	Canada
DE	Germany
ES	Spain
EU24	EU member states excluding France, Germany, and Italy
FR	France
GB / UK	United Kingdom
IT	Italy
JP	Japan
NL	Netherlands
NO	Norway
PL	Poland
RU	Russia
SE	Sweden
TH	Thailand
UA	Ukraine
US	United States
VE	Venezuela
ZA	South Africa

Table A2: First year of available data in the IEA energy statistics (IEA, 2022)for the EU member states.

Country	Year
Austria	1960
Belgium	1960
Denmark	1960
Finland	1960
France	1960
Germany	1960
Greece	1960
Ireland	1960
Italy	1960
Luxembourg	1960
Netherlands	1960
Poland	1960
Portugal	1960
Spain	1960
Sweden	1960
Hungary	1965
Bulgaria	1971
Cyprus	1971
Czechia	1971
Malta	1971
Romania	1971
Slovakia	1971
Croatia	1990
Estonia	1990
Latvia	1990
Lithuania	1990
Slovenia	1990

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