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Have climate policies accelerated energy transitions? Historical evolution of electricity mix in the G7 and the EU compared to net-zero targets

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ABSTRACT

Climate policies are often assumed to have significant impacts on the nature and speed of energy transitions. To investigate this hypothesis, we develop an approach to categorise, trace, and compare energy transitions across countries and time periods. We apply this approach to analyse electricity transitions in the G7 and the EU between 1960 and 2022, specifically examining whether and how climate policies altered the transitions beyond historical trends. Additionally, we conduct a feasibility analysis of the required transition in these countries by 2035 to keep the global temperature increase below 1.5°C. We find that climate policies have so far had limited impacts: while they may have influenced the choice of deployed technologies and the type of transitions, they have not accelerated the growth of low-carbon technologies or hastened the decline of fossil fuels. Instead, electricity transitions in the G7 and the EU have strongly correlated with the changes in electricity demand throughout the last six decades. In contrast, meeting the 1.5°C target requires unprecedented supply-centred transitions by 2035 where all G7 countries and the EU must expand low-carbon electricity five times faster and reduce fossil fuels two times faster on average compared to the rates in 2015–2020. This highlights the insufficiency of incremental changes and the need for a radically stronger effort to meet the climate target.

1. Introduction

Avoiding dangerous climate change requires rapid energy transitions to replace fossil fuels with low-carbon sources within the next decades. According to the International Energy Agency (IEA), in order 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 [1]. To demonstrate the leadership in spearheading this transition, the Group of Seven (G7) countries and the European Union (EU) committed to achieving this target in 2022 [2].

However, the feasibility of such rapid transitions is debated. On the one hand, it is considered highly infeasible, if not impossible, as required transitions significantly deviate from the past development of the energy sector, where new energy technologies diffused over many decades [3–5], and were often added to—rather than substituted—older technologies [3,6]. On the other hand, many scholars argue that present and future energy transitions should be more radical and faster because they are increasingly driven by climate policies [7–9]. Though such ability of climate policies to alter the nature and speed of energy transitions is critical for climate mitigation [10], it has not been empirically quantified. To bridge this gap, we aim to answer the following 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 impacts of climate policies for the feasibility of achieving climate targets?

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To answer these questions, we develop a new approach to systematically categorise, trace, and compare energy transitions across countries and time-periods. Depending on the changes in high and low-carbon technologies, energy transitions can be divided into four types: *energy additions*, *low-carbon substitutions*, *high-carbon substitutions*, and *energy reductions*. We apply this approach to analyse historical electricity transitions between 1960 and 2022 in the G7 and the EU—which have showcased leadership in introducing climate policies over the past decades [11–13]—and examine the feasibility of their required transition by 2035 to keep the global temperature increase below 1.5 °C.

We find that 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, they have not accelerated the speed in the G7 and the EU between 1960 and 2022. Instead, electricity transitions have strongly correlated with the changes in electricity demand throughout the last six decades. Achieving their commitment to "fully or predominantly decarbonise" electricity by 2035 [2] thus requires unprecedented transitions with drastically different measures rather than incremental changes.

2. Literature review

The feasibility of rapid energy transitions is heavily debated in two bodies of literature: historical analyses of large-scale changes in energy systems, and socio-technical transition studies focusing on specific countries or sectors. The former literature defines energy transitions as long-term structural changes of energy systems [4], and generally converge on two arguments. First, the development and diffusion of new energy technologies typically require many decades. This observation, initially put forth by Marchetti and Nakicenovic in the 1970s [14], has since been substantiated as a prevailing trend in the use of primary energy sources [15] and technologies across various energy sectors including electricity supply [16,17], transportation [18], heating and lighting [3], as well as end-use technologies such as cars and washing machines [19]. Second, new energy technologies are typically added on top of instead of replacing older technologies, which have resulted in the dramatic increase in global energy consumption since the industrial revolution [5,20]. In other words, while older technologies may experience a decrease in market share, they rarely decline in absolute terms [6,21]. Thus, past energy transitions are more accurately characterised as 'energy additions' [3,6]. In light of these characteristics of historical energy transitions, some scholars assert that "none of today's promises for a greatly accelerated energy transition from fossil fuels to renewable energies will be realised" [15].

However, this view typically focusing on globally aggregated changes may overlook potentially rapid and profound transformations occurring at more granular levels. Indeed, by focusing on technological change often at the national level, socio-technical transition studies identify a number of accelerated cases such as the rapid growth of nuclear power in France [22], the expansion of renewables in Denmark, Germany, and the United Kingdom (UK) [8,23], as well as decline in coal use in the Netherlands and Canada [22,24]. The rapidity in these cases is attributed to a combination of factors, including energy security crises; shifts in political, business, and social actors and institutions; enhanced international cooperation; and technological innovation [8,9,22]. Among these factors, the role of the state is generally understood as the dominant one to 'steer' the overall transition processes [25,26] by initiating, governing, and accelerating them through national policies [8,9,22]. Indeed, more than 1600 national policies specifically targeting the energy sector existed in G20 countries in 2019 [11]. It is argued that these policies have contributed to the cost reductions in solar and wind power [27,28], and facilitated a faster diffusion of these technologies compared to the past [8,29]. In light of these views, scholars argue that present and future energy transitions are expected to be more radical and faster than previous transitions [7–9,22].

While such granular analyses are well-suited for identifying various changes over time, the current approach taken by the existing studies has two significant shortcomings in analysing energy transitions. The first shortcoming is the ambiguity surrounding terms such as 'accelerated' or 'fast' due to the insufficient use of comparative analyses [30,31]. For example, although the recent growth of renewables in Germany is often described as 'fast' [8,32–34], the absence of a comparative benchmark based on the historical growth rates of other technologies in Germany or similar countries makes it unclear if this case is truly accelerated. More importantly, it remains uncertain whether the growth of renewables in the 'frontrunner countries' or 'climate leaders' such as Germany and the UK [8,35] is sufficiently fast to achieve climate targets.

The second shortcoming is that the existing studies do not clarify whether the recent changes in policies and specific technologies have resulted in any significant systemic developments towards decarbonisation. Globally, greenhouse gas (GHG) emissions have continued to rise at an unprecedented rate since 1990 [36], suggesting that factors driving acceleration including climate policies may be counterbalanced by opposing forces and developments. Notably, vested interests of fossil fuel industries are frequently identified as a primary obstacle, actively impeding the introduction and effectiveness of climate policies [36–39]. Even looking at the counties identified with accelerated transition cases, for example, the rapid decline in coal use in the Netherlands and Canada was accompanied by an increased use of natural gas, potentially perpetuating a reliance on fossil fuels rather than accelerating the shift to low-carbon alternatives [40,41].

Furthermore, the rapid development of low-carbon technologies does not necessarily lead to decarbonising the overall energy system. For instance, although Germany achieved a record growth of renewables in 2022, the concurrent decline of nuclear power and resurgence of fossil fuels have led to an increase in the country's GHG emissions in recent years [42]. Such systemic developments are often overlooked by socio-technical studies with their tendency to focus on individual changes in specific socio-technical systems. While studies on the growth of new technologies which once dominated the field [10,43,44] have recently been supplemented by studies of technological decline [24,32,45–48], these 'innovation' and 'exnovation' studies still analyse growth and decline of technologies separately [49]. As a result, the existing literature runs the risk of erroneously portraying cases of *energy additions* or, even, *high-carbon substitutions* as sustainable transitions by merely looking at a fraction of the overall system.

In summary, the feasibility of achieving rapid energy transitions is subject of an ongoing debate. Existing analyses from different bodies of literature are often either overly broad such as global changes and overlook granular changes at the national level, or excessively narrow and unable to trace the impacts of policies or specific technological changes on the overall energy system. This gap results in uncertainties regarding whether and how recent transitions, claimed increasingly driven by climate policies, are actually different from previous transitions. In particular, the feasibility of required transitions in the future to mitigate climate change, involving both substantial technological growth and decline simultaneously, remains significantly understudied.

3. Research approach

In this section, we develop a new approach to systematically categorise, trace, and compare the types and speed of energy transitions. This approach also enables us to examine the impacts of climate policies and assess the feasibility of required transitions to mitigate climate change. The summary of the framework and methods is presented in Fig. 1. The following subsections provide further details and introduce electricity transitions in the G7 countries and the EU from 1960 to 2035 as the cases examined in the rest of the paper.

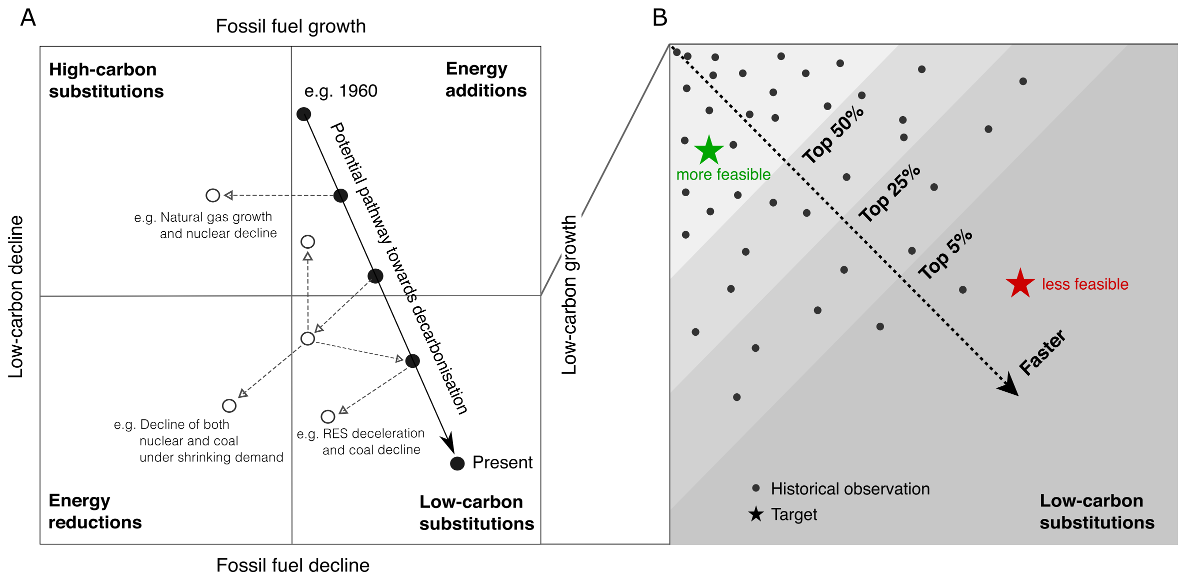

Fig. 1. Analytical framework to systematically categorise, trace, and compare the types and speed of energy transitions over time (A), and to analyse the probabilistic feasibility of low-carbon substitutions to achieve climate targets (B).
Notes: A: Typology of energy transitions based on the changes in high and low-carbon technologies (See Sections 3.1 and 3.5). The arrows indicate a potential pathway and other possible developments towards (or away from) decarbonisation. B: Probabilistic feasibility zones based on the proportion of relevant historical observations (See Sections 3.3 and 3.5). Zones represent the fastest speeds (lower right with the darkest area which includes the top 5% of historical observations), the second fastest (top 25% to 5%), third fastest (top 50% to 25%), and last/slowest (below 50%). Examples of historical observations ($n = 40$) are depicted with dots while decarbonisation targets are shown with stars.

3.1. Categorising, tracing, and comparing the types and speed of energy transitions

To analyse energy transitions, it is crucial to consider the changes in all technologies involved in the system. In contrast to previous approaches which focus on either the growth of low-carbon technologies [8,22,50–52] or the decline of fossil fuels [21,22,24,46,47,53], we analyse both changes simultaneously in order to identify four main types of energy transitions (Fig. 1A): (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.

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 [3,6]. 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 [54,55]. 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 [39,51], or a sudden loss of low-carbon sources due to, for instance, adverse weather for renewables or nuclear accidents [56]. 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 [57–59], which is more closely related to *low-carbon substitutions*.

This systematic categorisation of energy transitions makes it possible to trace and compare the types and speed 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 Fig. 1A.

3.2. Examining the impacts of climate policies beyond historical trends

Systematically categorising, tracing, and comparing energy transitions enables us to examine the impacts of climate policies (see Section 3.5 for more detailed methods). We follow the conventional definition of climate policies as "(national) sectoral or overarching policies that result in lasting emission reductions" [11]. Our primary interest is to examine whether and how these policies resulted in significant changes in the type and speed of energy transitions beyond historical trends.

3.3. Assessing the feasibility of low-carbon substitutions

Using historical transitions as reference cases, we analyse the feasibility of required rapid energy transitions in the future. Such comparative analysis, linking historical observations to assessing the feasibility of future scenarios or targets, has been so far utilised in evaluating global climate scenarios [28,60,61], as well as analysing the speed of national and regional technological growth [62,63], and technological decline [21,53,64,65]. This study extends this analysis to examine both technological growth and decline simultaneously in order to analyse energy transitions more comprehensively. To do so, we use a systematic method of mapping future transitions onto a 'feasibility space' [66,67], constructed from historical reference cases and divided into probabilistic feasibility zones [21,62] (Fig. 1B).

3.4. Scope and case selection

We apply the systematic comparative approach—described in the preceding subsections, and summarised in Fig. 1—to analyse the historical electricity transitions (1960–2020) in the G7 and the EU in comparison to their required transitions (2020–2035) to keep the global temperature increase below 1.5°C. The most recent changes from 2020 to 2022 are additionally analysed to examine the latest developments in these countries.

We focus on the electricity sector because the majority of climate policies has been implemented in this sector so far [11,68]. The choice of the G7 countries and the EU is based on their pioneering role in introducing climate policies and their active engagement in the international climate regime [12,13]. Particularly after 1990, these countries have consistently made commitments to mitigating climate change, and have faced increasing pressure to lead these efforts as among the largest economies with significant economic, financial, and technological capabilities [12]. We hypothesise that, therefore, if energy transitions under climate policies are increasingly policy-driven and faster, we should observe the impacts in the G7 and the EU over time, particularly in the recent decades in the electricity sector. Specifically, we expect to see an accelerated development of low-carbon electricity and a greater substitution of fossil fuels over time.

3.5. Methods

To trace and compare the types and speed of electricity transitions over time in the G7 and the EU, we calculate annual rates of change in energy technologies for electricity generation over five years from 1960 to 2020 and 15 years for the required transition from 2020 to 2035. The choice of a five-year interval for historical analyses strikes a balance between capturing trends and accounting for potential rapid changes within short timeframes. For the latest developments, we calculate the rates between 2020 and 2022. These multi-year changes are referred to as 'episodes' throughout the rest of the paper. To account for the varying sizes of the electricity sector across countries and time-periods, we normalise the rates of change by the average total electricity generation during the respective episodes as follows:

$$ACR_i = \frac{\left(S_{i_t} - S_{i_0}\right) * 2}{(T_0 + T_t)} * \frac{1}{(Y_t - Y_0)}$$

where ACR_i represents the *annual change rate of electricity supplied by a given source* (i) calculated as the difference between the *supply in the start year* (S_{i_0}) *and end year* (S_{i_t}), normalised to the *total electricity generation averaged between the start year* (T_0) *and end year* (T_t), divided by the number of *years between the start year* (Y_0) *and end year* (Y_t). The original form of this metric to quantify the pace of energy transitions was developed by Vinichenko et al. [21]. Subsequently, we aggregate the change rates based on the classification of energy technologies into high-carbon and low-carbon categories (as outlined in Table A1) for the analysis of this study.

The feasibility analysis of the required transitions in the G7 and the EU is conducted in the following manner. First, we calculate the required rates of low-carbon substitutions in the G7 and the EU between 2020 and 2035 to achieve its currently committed "fully or predominantly decarbonised electricity" target by 2035, thereby keeping the global temperature increase below 1.5°C [2] (i.e. this would be the star target rate as depicted in Fig. 1B).

Secondly, these required rates are compared to the density of the relevant historical observations. To construct a dataset of such historical cases, we first identify all national five-year episodes of low-carbon substitutions worldwide in 1960–2020. We then calculate 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, we select the episodes with the highest $ACR_{Transition\_speed}$ values while ensuring that there is no overlap or double-counting of years. Table A2 shows the example of this approach choosing four episodes with the highest $ACR_{Transition\_speed}$ values in France, namely 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 (see Table A3 for country codes used in this article).

Subsequently, we further refine our selection from the compiled dataset of national low-carbon substitution episodes by focusing on those with an average total electricity generation exceeding 100 TWh. We set this threshold because systems smaller than this threshold tend to exhibit more rapid growth of renewables [69] and decline of fossil fuels [21], which we consider 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, United Kingdom, and United States (US)) was ca. 1100 TWh. Thus, we adopt an optimistic rather than conservative approach, considering that all episodes above this 100 TWh threshold have direct relevance to all G7 countries and the EU. This results in a final selection of 19 countries and their 56 episodes (Table A4).

Finally, we perform kernel density estimation with the final selection of the dataset, using R's package ggdensity [70] to delineate feasibility zones. Each zone is defined to encompass 50%, 75%, and 95% of these historical episodes, with the remaining 5% representing historically the fastest national low-carbon substitution episodes.

3.6. Data sources

We use IEA's Extended Energy Balances [71] for electricity data in 1960–2020, Ember's Yearly Electricity Data for the most recent data between 2020 and 2022 [72], and IEA's Achieving Net Zero Electricity Sectors in G7 Members [1] for the climate target requirements in 2020–2035 to achieve 1.5°C in the G7 and the EU. The G7 and the EU requested this IEA report in 2021, and subsequently adopted the advised target in 2022, making this report highly relevant for their future transitions [2]. As we aim to analyse the trends of technological changes in electricity generation, we smoothen IEA's historical data by using three-year moving averages. We do not apply the same operation for Ember's historical data or IEA 1.5°C pathway data[1] because the purpose of using the former is to illuminate the actual latest development, and the latter is scenario data with a specific target. Climate Policy Database [73], maintained by NewClimate Institute in Germany, is used for tracking climate policies over time in the G7 countries and the EU.

4. Results

This section first provides an overview of the historical and required electricity generation in the G7 countries and the EU in 1960–2035 in Section 4.1. Subsequently, we show the rates of technological growth and decline in comparison to the number of climate policies introduced during these periods in Section 4.2. We combine these results to trace the type and speed of electricity transitions in Section 4.3. We further

[1] Since the data for the year 2020 was provisional during the report's publication, it was replaced by the fixed data from IEA's Extended Energy Balances [71]. To ensure consistency, the required transition rates in 2020–2035 are calculated with this actual 2020 data and the 2035 target data. Additionally, the 2035 data has a very small gap (<0.2%) between the total value and the sum of individual values. To address this small discrepancy, we scaled each value by the gap to equate their sum with the total value.

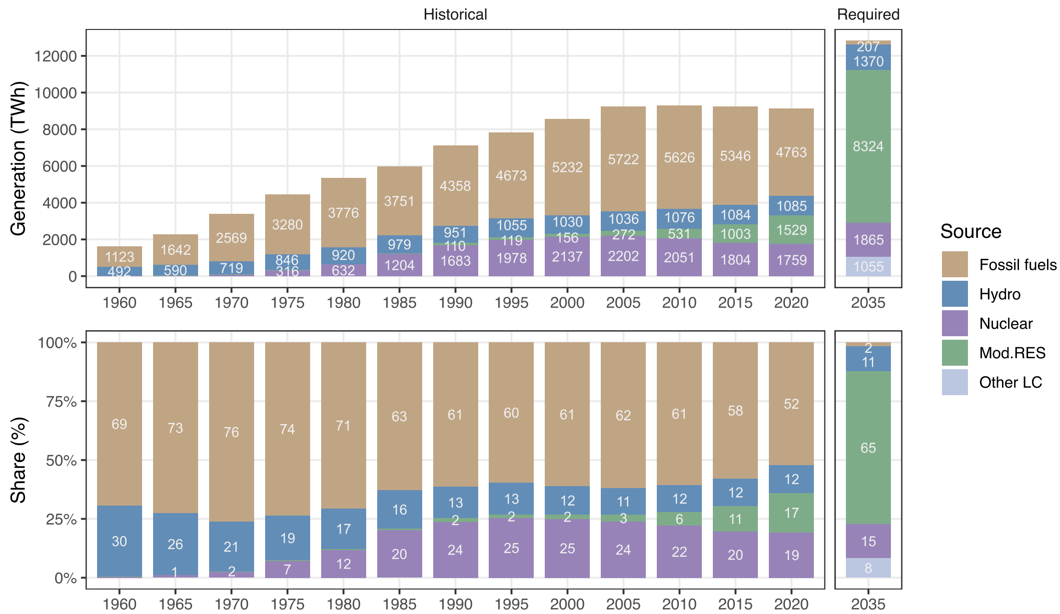

Fig. 2. Historical and required electricity generation to keep the temperature increase below 1.5°C in the G7 and the EU in 1960–2035.
Note: Mod.RES refers to modern renewables which include all renewable sources excluding hydro (see Table A1 for source categories). Other LC includes ammonia, hydrogen, 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 A5 for the first year of available data for the EU member states).

show how the required transition compares to historical observations in the G7 and the EU as well as other comparable countries in Section 4.4. Lastly, we show the latest developments of the G7 and the EU in 2020–2022 in Section 4.5.

4.1. Historical and required electricity generation in the G7 and the EU

Electricity generation in the G7 countries and the EU steadily increased over five times from 1960 to 2005, after which the growth stagnated (Fig. 2). Fossil fuels had been the main source of electricity, however their share decreased from its peak 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 [1]. 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.

4.2. Speed of technological growth and decline in the G7 and the EU

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 (Fig. 3A). In contrast, the number of climate policies introduced increased particularly after 1990, reaching its peak in 2005–2010 and starting to decrease thereafter (Fig. 3B).[2] Most of these policies have been targeted at the electricity sector, except in 2015–2020. 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%.[3]

It is important to point out that while modern renewables started to develop particularly after 1990 (Fig. 2), 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 (Fig. 3A). This occurred despite the continuous decrease in costs for solar, onshore and offshore wind technologies, as shown in Fig. 4.

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 (Fig. 3A).

[2] It is important to note that while the number of introduced climate policies can indicate political activity towards mitigating climate change, it might not reflect the strength of climate governance, especially considering that earlier policies could still be in effect. Furthermore, a higher number of policies does not necessarily indicate stronger climate governance, as policy stringency is not extensively analysed in Climate Policy Database [73]. 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 [93]. We also see this phenomenon in the G7 and the EU as a whole as well as individually (Fig. A1).

[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 (Fig. A2).

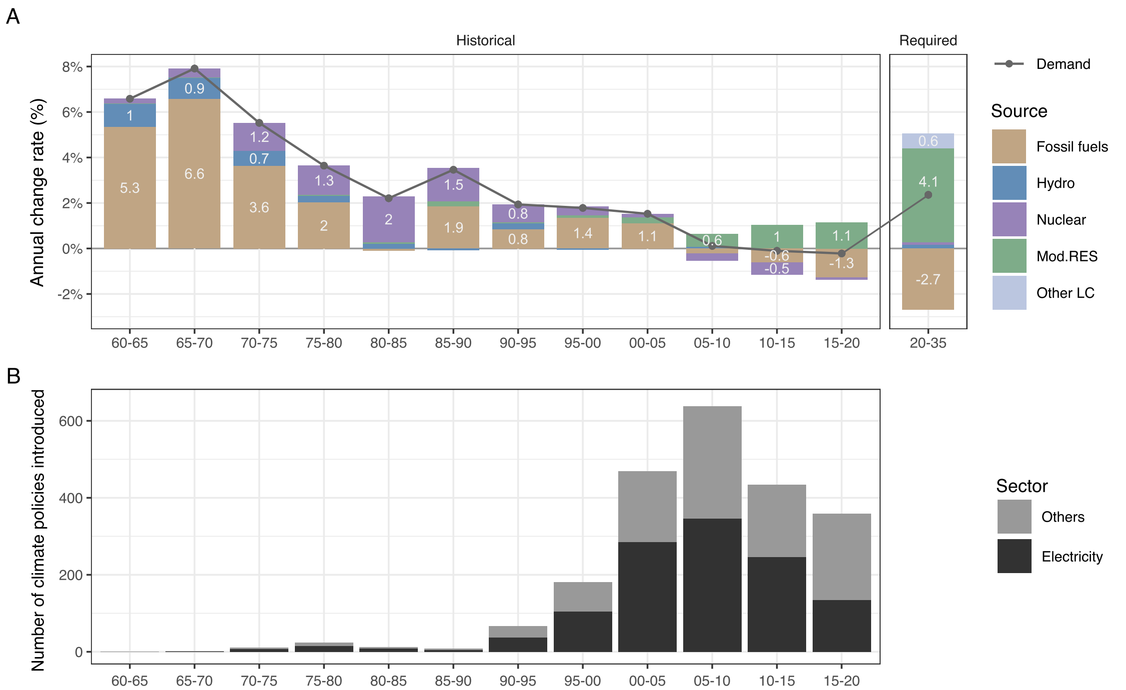

Fig. 3. Speed of historical and required electricity transitions (A), and the number of climate policies introduced in the G7 and the EU (B).
Notes: Years are expressed in two digits (60–65 refers to 1960–1965). Mod.RES refers to modern renewables which include all renewable sources excluding hydro. Other LC includes low-carbon electricity produced from ammonia, hydrogen, and fossil fuels with CCUS.

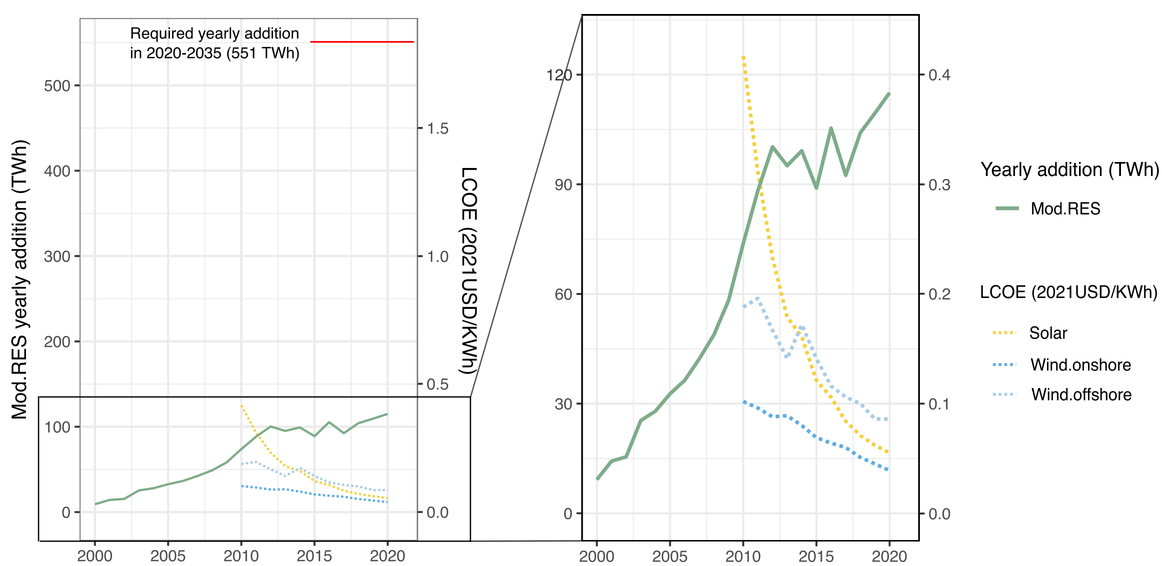

Fig. 4. Costs of solar, onshore, and offshore wind in comparison to yearly addition of modern renewables in the G7 and the EU in 2000–2020 and the required addition in 2020–2035.
Note: The costs represent the global weighted average costs of these technologies obtained from IRENA [74].

4.3. Evolution of the type and speed of electricity transitions in the G7 and the EU

Fig. 5 synthesises the findings from Sections 4.1 and 4.2, illustrating the evolution of the type and speed of electricity transitions in the G7 and the EU in 1960–2035 based on our typology of energy transitions (see Fig. 1A).

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 Fig. 3). 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 (Fig. 3B), the G7 and the EU continued to undergo

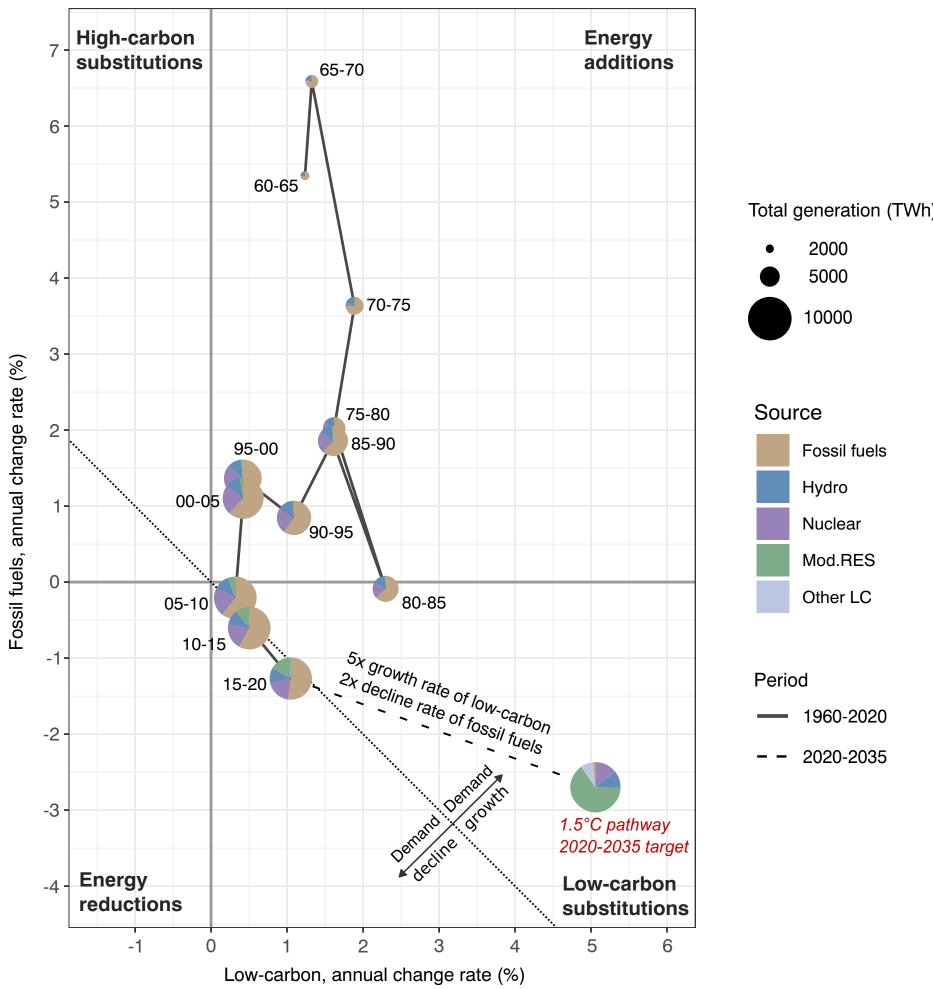

Fig. 5. Historical and required electricity transitions in the G7 and the EU in 1960–2035.
Notes: The pies show the electricity mix at the end of the five-year episodes in the G7 and the EU in 1960–2020 and the required mix in 2035 to keep the global temperature increase below 1.5°C. The size of pies indicates the total generation, while colours represent sources. Texts next to pies refer to years (e.g. 15–20 is the episode in 2015–2020). Relevant data is available in Table A6. The individual historical trajectories of the G7 main member states are available in Fig. A3, which generally show a similar trend observed in the G7 and the EU as a whole.

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 from 2005, the G7 and the EU entered a new period of low-carbon substitutions, characterised by the increasing adoption of modern renewables (Fig. 2). 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 Fig. 3).

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.

4.4. Frontier speed of national low-carbon substitutions in 2020

Fig. 6 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 feasibility zones delineated by their density, as outlined in Fig. 1B (see also Sections 3.3 and 3.5 for detailed methods). The required low-carbon substitutions under the IEA 1.5°C pathway for the G7 and the EU falls within the fastest 5% feasibility 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,[4] and sustain such speed for 15 years in 2020–2035.

Three out of 56 low-carbon substitution episodes achieved this top 5% speed in 1960–2020: FR79-84, ES82-87 and UA91-96. Table 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 (Fig. 5).

[4] 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.

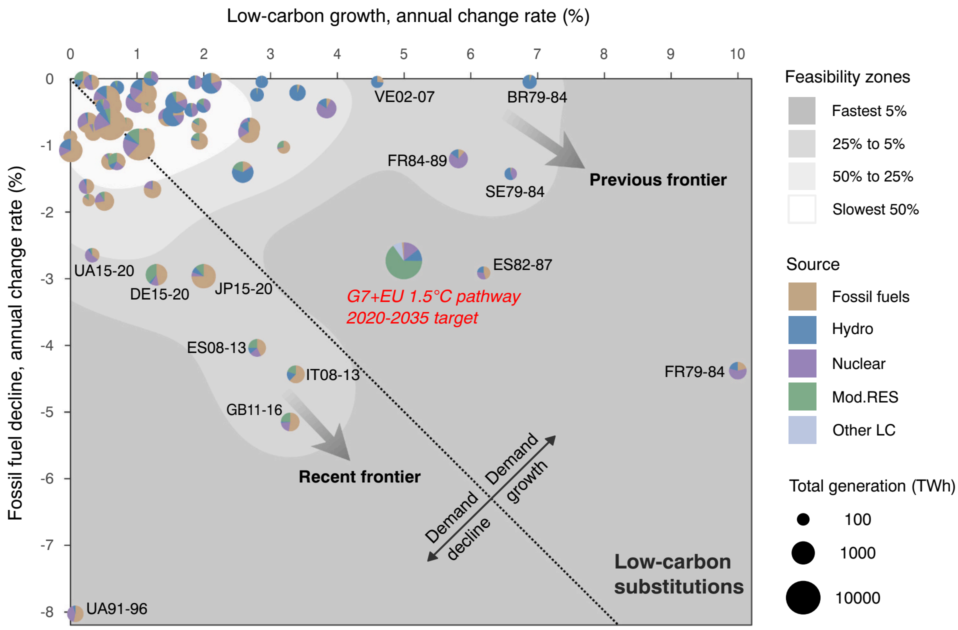

Fig. 6. Feasibility space, zones, and frontiers of low-carbon substitutions.
Notes: Feasibility zones are defined by the density of historical episodes, which are divided into the bands based on the frequency of observation (Sections 3.3 and 3.5). Pies are fastest five-year episodes of low-carbon substitutions in countries more than 100TWh 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 feasibility zone does not necessarily perfectly match the indicated proportion due to the smoothing effect of the density estimation function. See Table A3 for country codes and Table A4 for the details of the episodes.

Table 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	(within, 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.

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.

These distinct characteristics observed in the previous and more recent low-carbon substitution episodes produce two distinct feasibility frontiers (Fig. 6). As a result, there is 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 sustained the required transition speeds for a continuous period of 15 years, although there have been some notable episodes that came close (Fig. 7). 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.

4.5. Latest developments in the G7 and the EU

In 2020–2022, none of the G7 countries and the EU achieved or made significant progress towards the required rates of low-carbon substitutions, as shown in Fig. 8. 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 generating 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 far from the required fastest 5% speed to follow the IEA 1.5°C pathway.

5. Discussion

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 the feasibility of achieving climate targets?

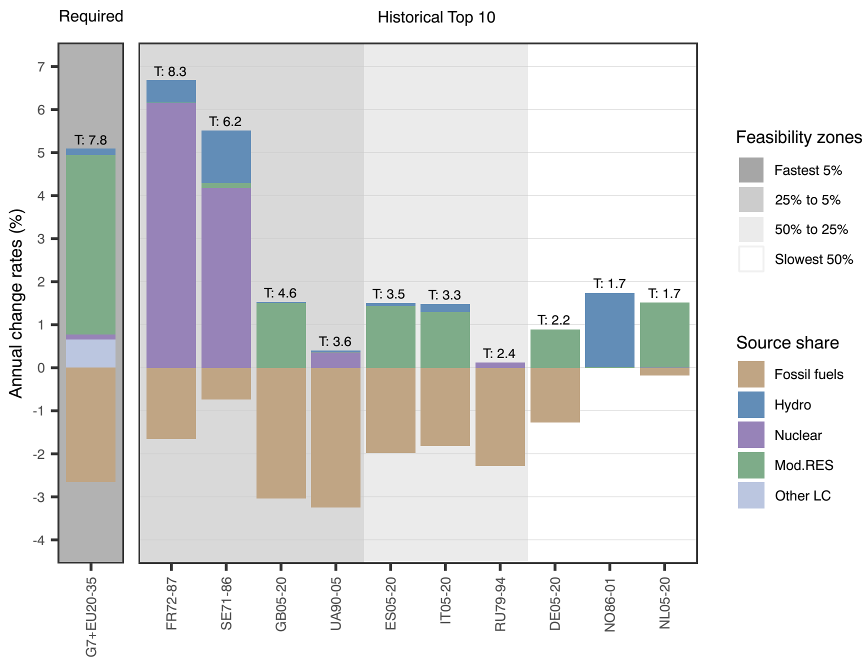

Fig. 7. Required speed of low-carbon substitutions in 2020–2035, compared to the historically top 10 fastest episodes of low-carbon substitutions for 15 years in all case countries.
Notes: Bars depict the growth of low-carbon electricity (above 0) and the decline of fossil fuels (below 0), while colours 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 by the same approach described in Section 3.5, but for 15 years instead of five years). The feasibility zones and their corresponding shading are the same as those used for five-year changes. In other words, there has been no historical case where the fastest 5% low-carbon substitution speed observed over a five-year period was sustained for a duration of 15 years, which is required in the future. See Table A3 for country codes.

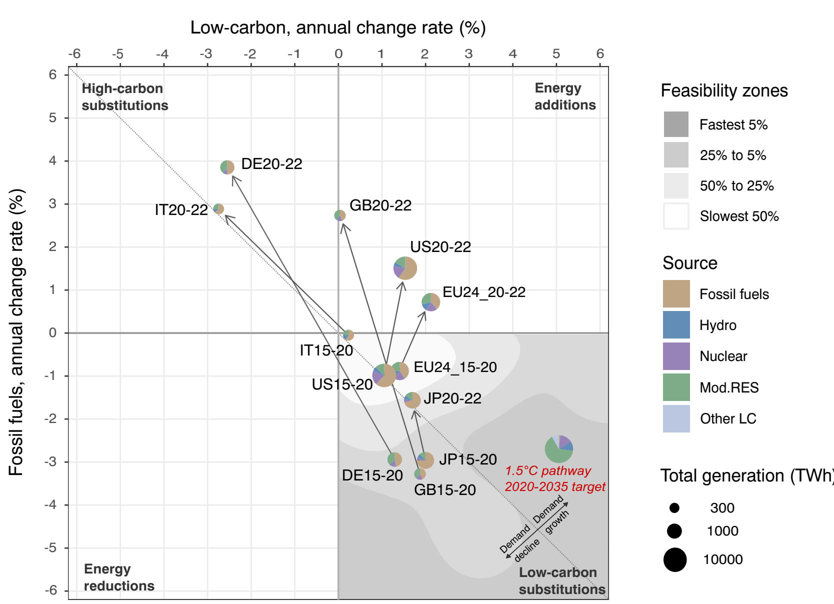

Fig. 8. Latest developments in the G7 countries and the EU.
Notes: EU24 countries are EU member states excluding France, Germany, and Italy. Canada and France are excluded as their electricity generation is almost fully decarbonised, though they would still need to accelerate developing low-carbon sources to be compatible with the IEA 1.5°C pathway. The required change rates for these individual countries/group are shown in Fig. A2 and available in Table A7.

Table 2
Historical and required electricity transitions in the G7 and the EU in 1960–2035.

Period		# of climate policies introduced	Demand	Supply: technologicalchanges and speed Fossil fuels	Low-carbon (main growing source)	Types of energy transitions and speed
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% (Modernrenewables)	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%	Rapidlow-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.

5.1. Evolution of the electricity sector in the G7 and the EU

Table 2 summarises the key features on electricity transitions in the G7 and the EU in 1960–2035. The overarching historical trend we observe 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 2 and Fig. 3A). 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. [51] on the impacts of different demand conditions for the development of modern renewables and nuclear power in Germany and Japan).

5.2. Impacts of climate policies in the G7 and the EU

In parallel to 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 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 2 and Fig. 3A) 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, but 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 (Fig. 3A). Here, nuclear power serves as a particularly relevant benchmark, as it was also accelerated by policies following the oil crises in the 1970s [51,69,75,76], leading to the first but limited period of low-carbon substitutions in 1980–1985 in the G7 and the EU (Fig. 5). Interestingly, the growth of nuclear power in the 1970s–80s outpaced the recent growth of all modern renewables combined (Fig. 9) (also see Fig. A4 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 [8,29].

Nuclear power has so far also grown faster in individual G7 countries and the EU except Germany (where it grew at the same speed) and the UK and Italy (where it grew slower) (Fig. A5). 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 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 (Fig. 4), indicating that re-accelerating the growth would need much stronger policies than historically observed.

The progress towards decabonisation 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 (Fig. 5). 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 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 of climate policies did take place when the electricity demand stagnated and declined, particularly after 1990 (Fig. 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 (Fig. 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 (Fig. A2). Climate policies in

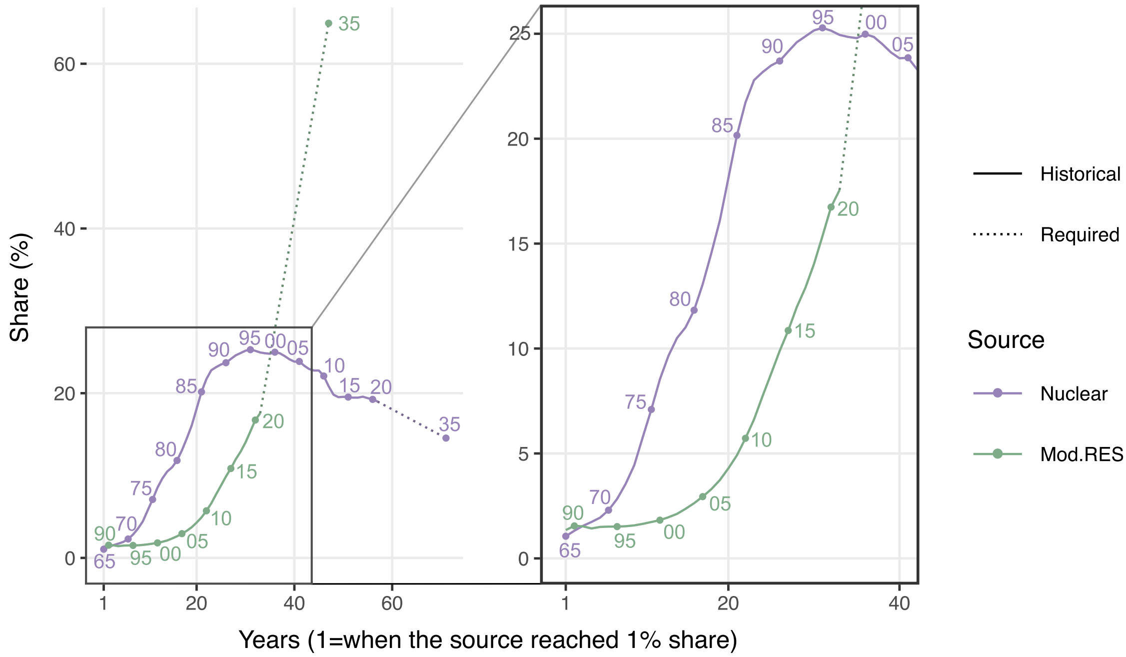

Fig. 9. Growth speed of nuclear power and modern renewables in electricity generation after reaching a 1% market share in the G7 and the EU.

these countries may have played a role in restricting the use of fossil fuels under declining demand, although not necessarily 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 (Fig. 7).

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. Feasibility of achieving the IEA 1.5°C pathway in the G7 and the EU, and beyond

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 (Fig. 5). Such high speeds of low-carbon substitutions were historically achieved only for five years in France and Spain in the 1980s (Fig. 6). Furthermore, there is no historical precedent of sustaining such speeds for a continuous period of 15 years (Fig. 7). 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 [15,21,50–53,62,65], our study 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, our study shows that there are some precedents that achieved either the necessary level of low-carbon technology growth or fossil fuel decline for five years (Fig. 6) and 15 years (Fig. 7), producing two distinct feasibility frontiers in low-carbon substitutions.[5] 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 [77–80]. 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" [77], 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 but this would also face numerous challenges including increasing cost and construction time overruns, rising oppositions against the technology for perceived risks, as well as eroding industry base which have taken place already for decades [81]. Additionally, deploying such a capital-intensive and controversial technology may be more difficult in today's increasingly liberalised market [76].

In terms of the precedents for the necessary decline of fossil fuels, the UK in 2005–2020 and Ukraine[6] in 1990–2005 achieved a rapid decline (faster than -3%) which was primarily driven by the declining demand for electricity [21]. 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 [82,83].

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

[5] 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 (Fig. 7).

[6] 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 [21].

added and low-carbon electricity generation stagnated and even declined in most countries (Fig. 8), necessitating even faster transitions by 2035. On the one hand, there are multiple intertwined causes contributing to this deviation including the post-COVID 19 economic recovery, recent energy crisis induced by the Russo-Ukrainian War, and unfavourable weather for renewables in Europe [84]. On the other hand, achieving the decarbonised electricity target by 2035 requires an unprecedented effort to withstand and overcome disruptions including unexpected challenges, which may also arise in the future.

Our findings concerning the G7 countries and the EU have implications for achieving climate targets globally. Since the G7 and the EU account for a substantial share of the world economy, their transitions inevitably have a profound impact on the pace of global decarbonisation. Moreover, technologies and policies typically diffuse from wealthy industrialised and technologically advanced countries to the rest of the world [85–87]. The Paris Agreement encourages such diffusion through its technology and capacity transfer mechanisms. This means that energy transitions worldwide are likely to be similar in their speed and character to the ones observed in low-carbon technology leaders such as the G7 and the EU.

6. Conclusion

This paper contributes to the on-going debate on the feasibility of rapid energy transitions to mitigate climate change. Our focus is to examine whether and how climate policies have so far altered the nature and speed of energy transitions beyond historical trends, and analyse the implications for future transitions. To achieve this, we developed a new approach to systematically categorise, trace, and compare energy transitions across countries and time-periods. We applied this approach to analyse the historical electricity transitions in the G7 countries and the EU where the majority of climate policies has been introduced. We also compared this historical observation to the required transition to keep the global temperature increase below 1.5°C.

We find that 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, they have not accelerated the speed beyond historical trends in the G7 and the EU. Instead, electricity transitions have strongly correlated with the changes in electricity demand throughout the last six decades. The recent growth of low-carbon electricity with modern renewables remains 50% slower as compared to the historically fastest speed achieved in 1980–1985 with nuclear power 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, enabling the substitution by relatively slowly growing renewables.

Meeting the decarbonised electricity target by 2035 in the G7 and the EU is extremely challenging. It requires to achieve immediate and unprecedented supply-centred transitions, with rates and duration of technological growth and decline that have never been observed simultaneously 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 low-carbon electricity generation stagnated and declined, making the achievement of the target even more difficult. Counteracting this trend and meeting the target, therefore, requires unprecedented and drastically different measures 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.

There are several limitations to our study, which call for further research. First, it is important to note that the G7 countries and the EU are heavily industrialised economies, which may not necessarily represent energy transitions in other countries. Existing literature, however, debates on whether the rest of the countries, particularly those in the global south, can sufficiently develop without industrialisation and the increased use of fossil fuels [58,61]. Therefore, more research is necessary to investigate the similarities and differences in their development trajectories and potential future paths, and the role of policies in them.

Second, while we do not find evidence that the increased number of climate policies has correlated with faster or radically different energy transitions, this does not mean climate policies did not have effects. It is possible that the effects of climate policies were cancelled out by confounding factors including other policies and non-policy factors. To precisely isolate the effects of climate policies, one would need to either compare situations identical in all aspects except the presence of climate policies (but finding such ideal natural experiments is very difficult) or trace causal mechanisms connecting climate policies to energy transition outcomes. This is an important area for future studies.

As a concrete example for such investigation, while we show that low-carbon electricity grew slower in the recent decades in the G7 and the EU, a more comprehensive analysis is necessary to examine its underlying causes. In particular, it is crucial to investigate why, despite the significant increase in climate policies and substantial cost reductions, modern renewables have not developed faster than nuclear power in the past. Given that only France and Sweden achieved the necessary growth rate of low-carbon electricity through the deployment of nuclear power in the 1970–1980s, it is important to investigate whether and how a similar level of acceleration can be replicated in today's more liberalised and democratised energy markets. More broadly, the role of democracy in energy transitions requires further scrutiny as its effects are contested in the literature, ranging from slowing down to accelerating sustainable transitions [88–90].

To conclude, climate policies have so far had limited impacts on energy transitions in the G7 and the EU, significantly falling short of the required transition to meet climate targets. Further work is necessary to examine whether this is the case in other countries as well as other sectors. The systematic comparative approach we developed in this paper can be useful for future studies 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 identifying historically relevant cases for future transitions, as we demonstrated particularly in Section 4.4. 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?' [31], and 'How much does it cost?' [9] to mitigate climate change, including the feasibility and desirability of these actions.

Declaration of generative AI and AI-assisted technologies in the writing process

During the revision of this work the authors used ChatGPT in order to get suggestions for improving the readability of the texts. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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

Data availability

All data that support the findings of this study are included within the article.

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Appendix A

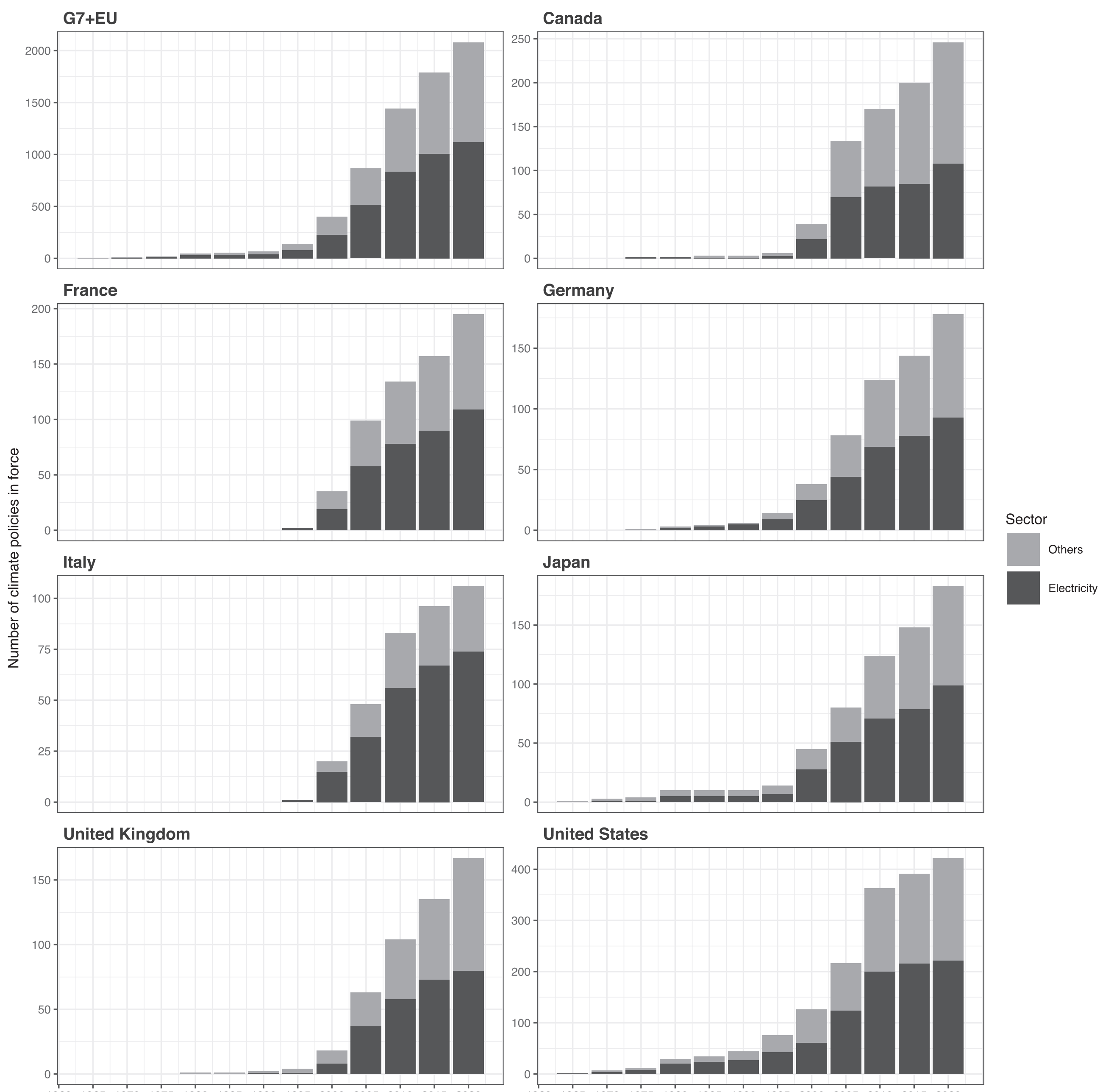


Fig. A1. Number of climate policies in force in the G7 and the EU as a whole and individually in 1960–2020.
Note: To calculate the number of climate policies in force each year, we aggregate the count of policies introduced in that year or earlier, excluding those that were terminated by that year. However, it should be noted that the end year of policies is rarely recorded in the Climate Policy Database, presumably due to the difficulty of tracking policy terminations compared to their introductions. Consequently, the total number of policies in force may be overestimated.

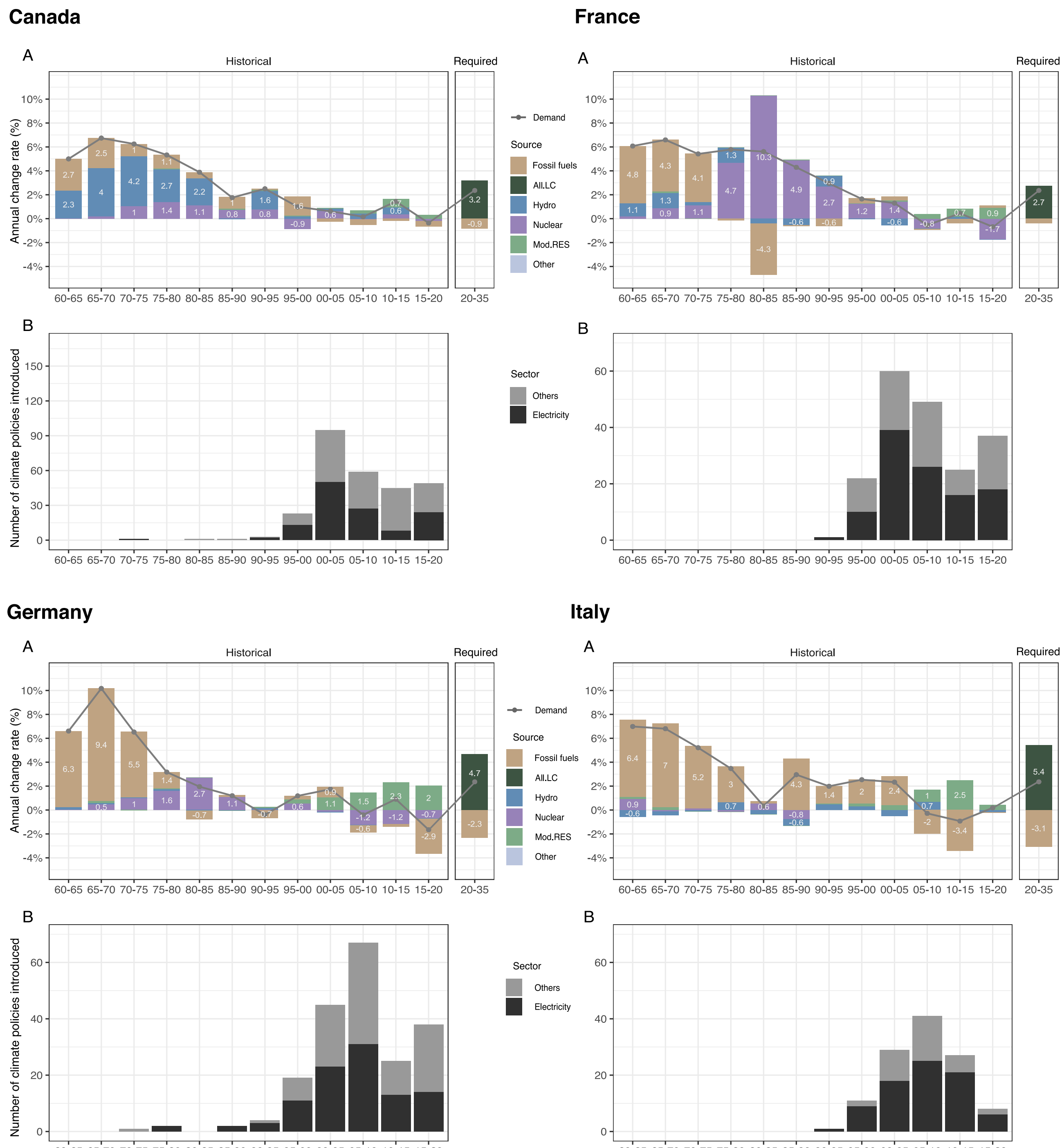
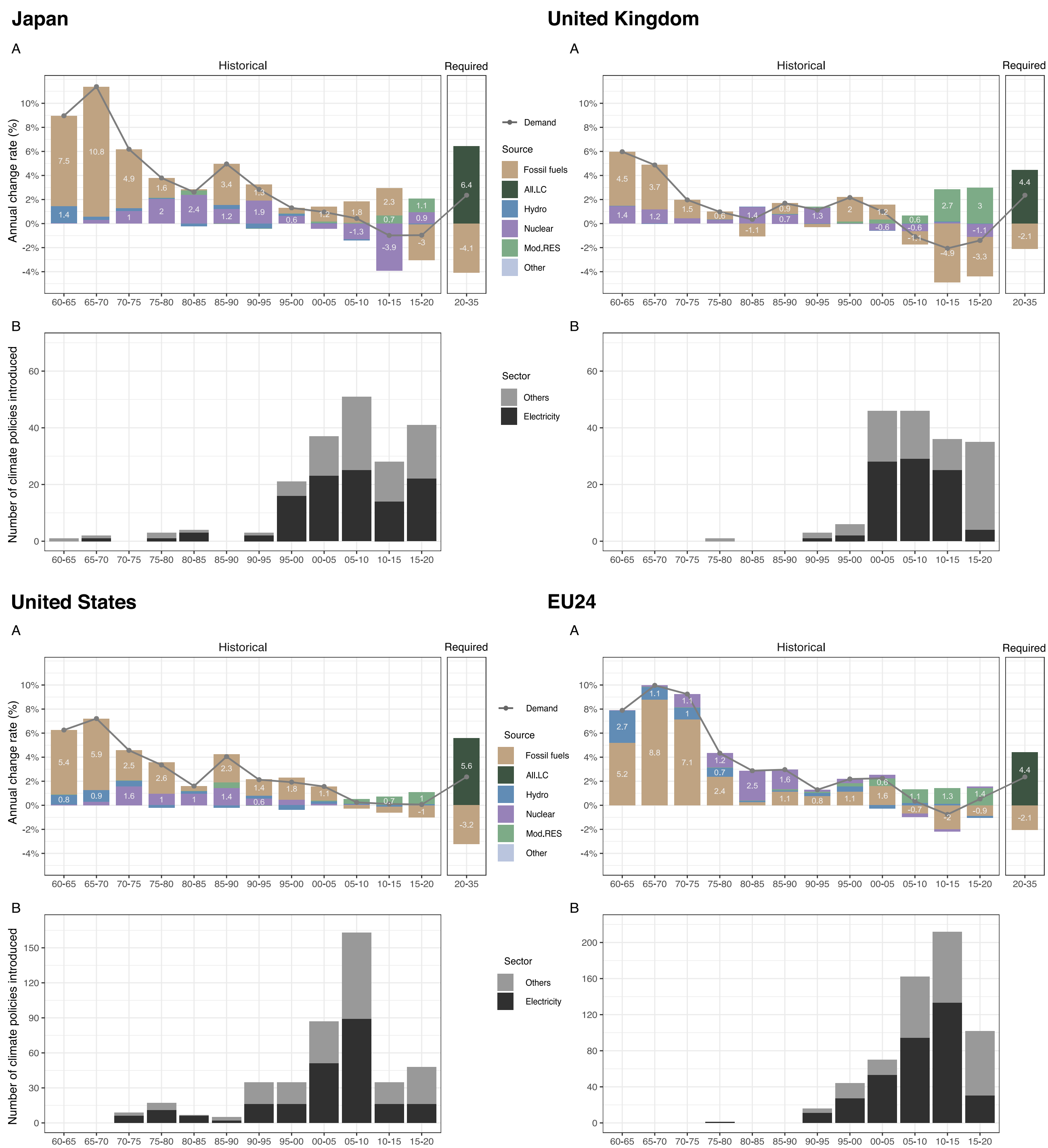


Fig. A2. Speed of historical and required electricity transitions in 1960–2035 in the G7 main member states.
Note: To account for the limited availability of data regarding the targeted share of each low-carbon source in individual countries in 2035, a new category called "All.LC" is introduced in the 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 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, as expected in the IEA report for G7 + EU as a whole. 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 3.5.



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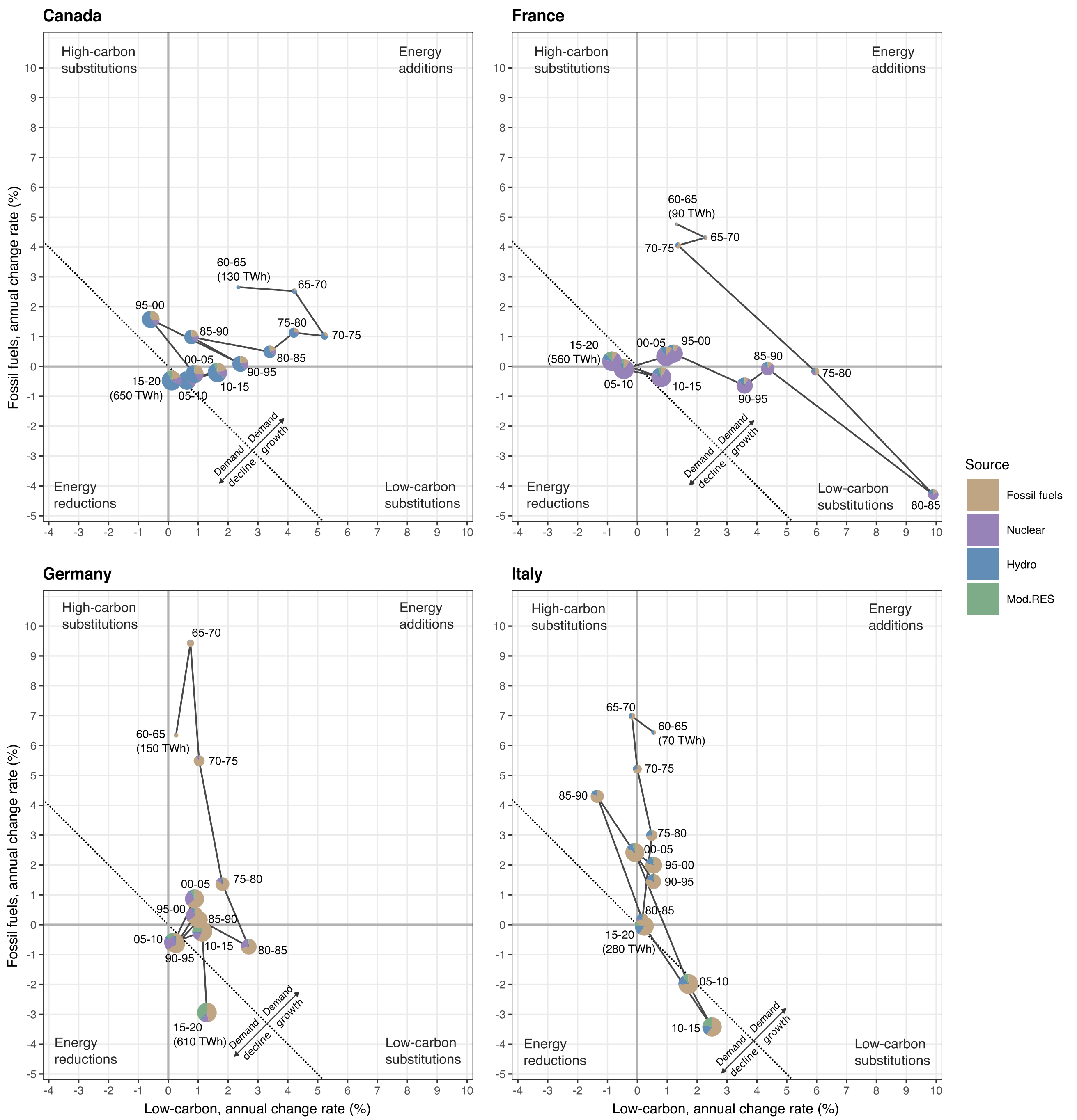

Fig. A3. Historical developments of the electricity sector in the G7 main member states in 1960–2020.
Note: The pies show the electricity mix at the end of the five-year episodes. The size of pies indicates the total generation, while colours represent sources. Texts next to pies refer to years (e.g. 15–20 is the episode in 2015–2020). The total generation amounts in parentheses are approximate.

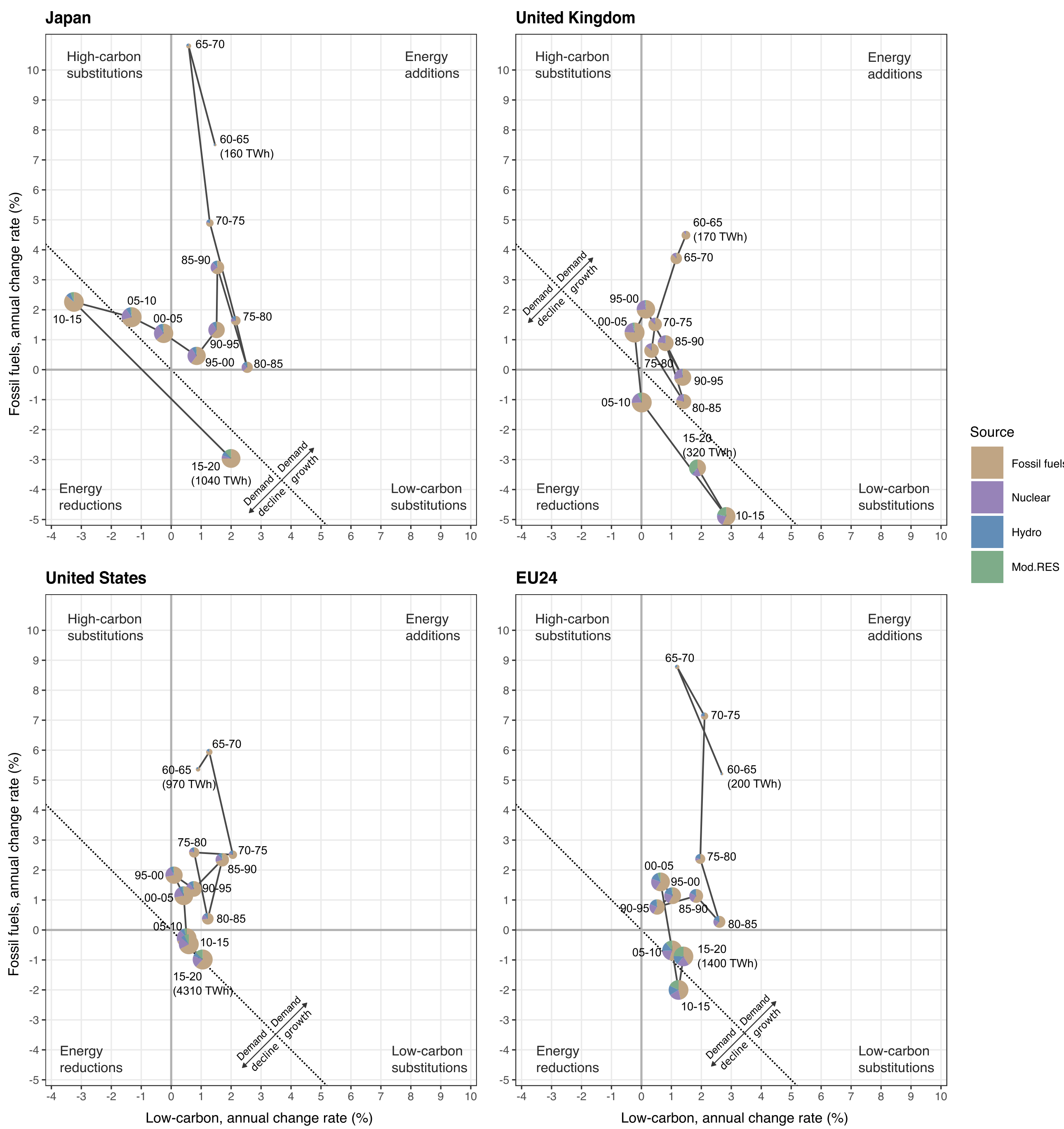

Fig. A3. (*continued*).

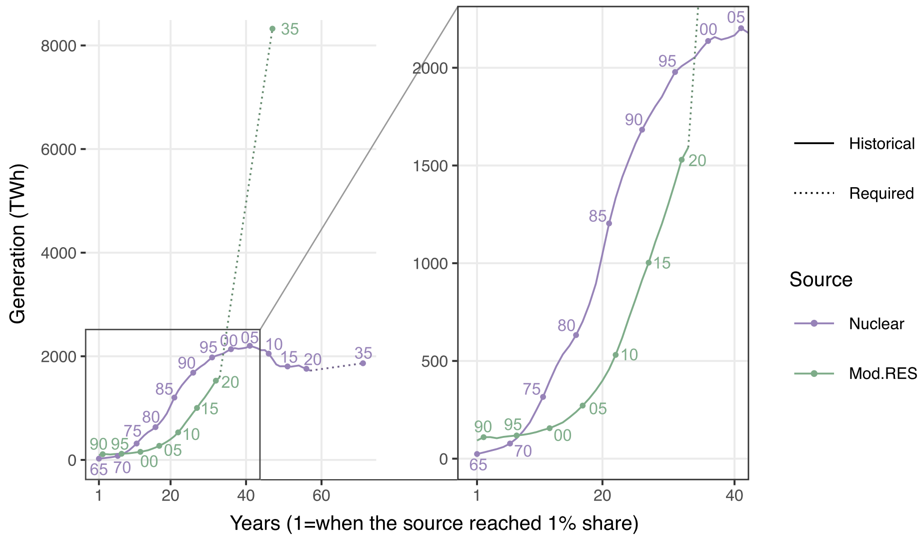

Fig. A4. Growth speed of nuclear power and modern renewables in generating electricity after reaching a 1% market share in the G7 and the EU.

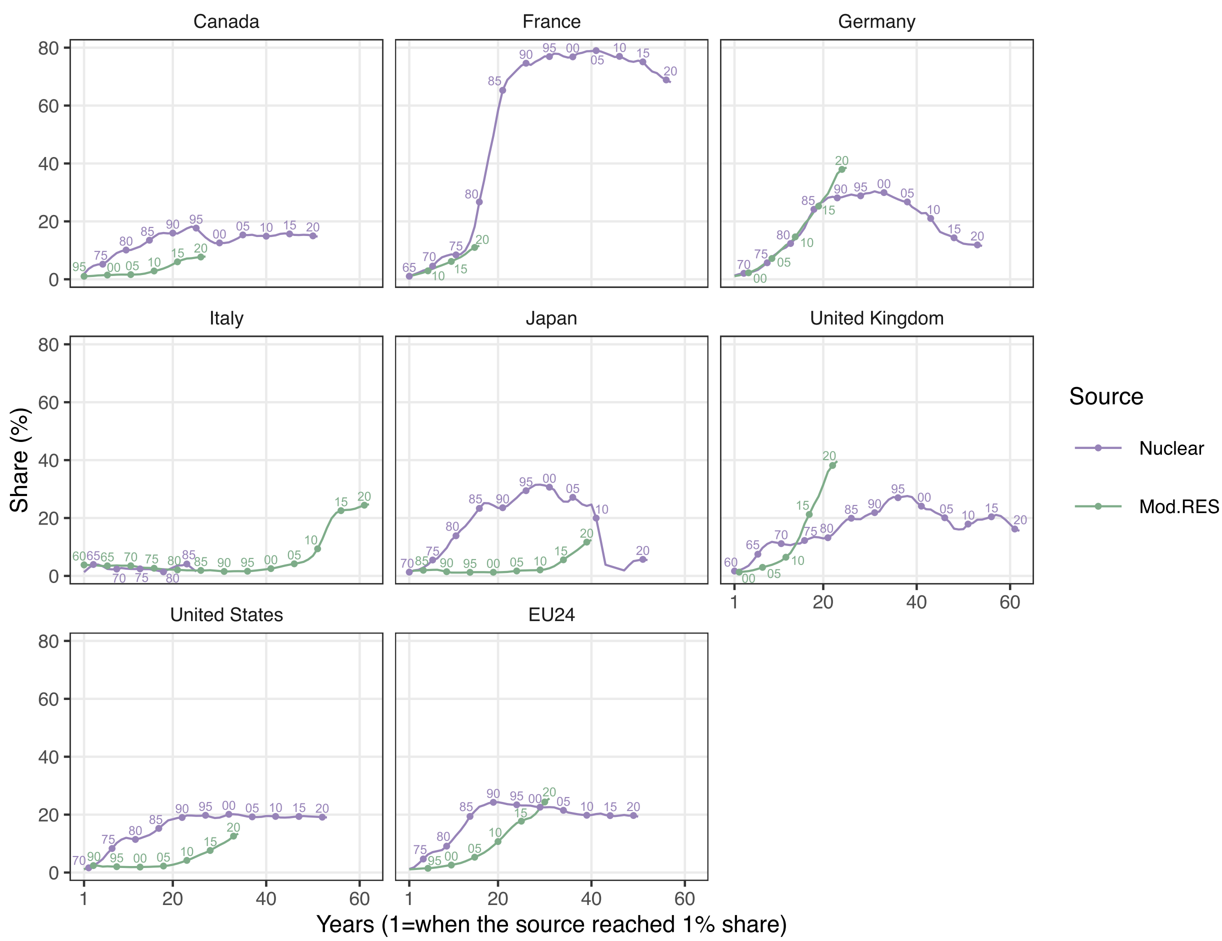

Fig. A5. Growth speed of nuclear power and modern renewables in the share of electricity generation after reaching a 1% market share in the G7 main member states.

Table A1
Source categories used in this article.

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

Note: While existing studies generally find biofuel-based electricity as low-carbon [91], 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 [92].

Table A2
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 %	
	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 %	overlap
	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 %	
	1988	1993	FR88-93	429.1	81.2	−3.2	3.8 %	−0.1 %	3.9 %	overlap
	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 %	
	2008	2013	FR08-13	562.7	22.0	−6.1	0.8 %	−0.2 %	1.0 %	overlap
	2007	2012	FR07-12	569.3	3.6	−0.1	0.1 %	−0.004 %	0.1 %	

Note: Selected episodes are bolded in the table.

Table A3
Country codes used in this article.

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	United Kingdom
IT	Italy
JP	Japan
NL	Netherlands

(*continued on next page*)

Table A3 (*continued*)

Code	Country
NO	Norway
PL	Poland
RU	Russia
SE	Sweden
TH	Thailand
UA	Ukraine
US	United States
VE	Venezuela
ZA	South Africa

Table A4
Low-carbon episodes used to delineate feasibility zones.

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	10,893.6	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 %
	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 %

Note: The top G7 + EU required transition was not used to delineate the zones but is shown here as a reference.

Table A5
First year of available data 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

Table A6
Five-year G7 + EU episodes in 1960–2020 and the required transition to achieve 1.5 °C in 2020–2035.

Period	Country	Year		Episode	Total average generation (TWh)	Generation change (TWh)		Annual change rate	
		Start	End			Low-carbon	Fossil fuels	Low-carbon	Fossil fuels
Historical	G7 + EU	1960	1965	G7_60-65	1940	120	519	1.2 %	5.3 %
	G7 + EU	1965	1970	G7_65-70	2816	187	928	1.3 %	6.6 %
	G7 + EU	1970	1975	G7_70-75	3914	369	711	1.9 %	3.6 %
	G7 + EU	1975	1980	G7_75-80	4900	397	495	1.6 %	2.0 %
	G7 + EU	1980	1985	G7_80-85	5659	650	−25	2.3 %	−0.1 %
	G7 + EU	1985	1990	G7_85-90	6537	524	607	1.6 %	1.9 %
	G7 + EU	1990	1995	G7_90-95	7463	407	315	1.1 %	0.8 %
	G7 + EU	1995	2000	G7_95-00	8190	171	559	0.4 %	1.4 %
	G7 + EU	2000	2005	G7_00-05	8893	188	490	0.4 %	1.1 %
	G7 + EU	2005	2010	G7_05-10	9258	148	−96	0.3 %	−0.2 %
	G7 + EU	2010	2015	G7_10-15	9260	233	−280	0.5 %	−0.6 %
	G7 + EU	2015	2020	G7_15-20	9186	482	−583	1.0 %	−1.3 %
Required	G7 + EU	2020	2035	G7_20-35	10,894	8265	−4410	5.1 %	−2.7 %

Table A7
Required annual change rates for G7 countries and the EU to achieve 1.5 °C in 2020–2035.

Country	Source	2020 (TWh)		2035 (TWh)		Generation change (TWh)	Annual change rate
		Value	Total	Value	Total		
G7 + EU	Fossil fuels	4617	8966	207	12,821	−4410	−2.7 %
	Low-carbon	4349	8966	12,614	12,821	8265	5.1 %
Canada	Fossil fuels	117	652	15	932	−101	−0.9 %
	Low-carbon	535	652	917	932	382	3.2 %
France	Fossil fuels	49	527	12	754	−37	−0.4 %
	Low-carbon	479	527	742	754	263	2.7 %
Germany	Fossil fuels	252	566	13	809	−238	−2.3 %
	Low-carbon	315	566	796	809	482	4.7 %
Italy	Fossil fuels	162	279	6	398	−155	−3.1 %
	Low-carbon	117	279	392	398	275	5.4 %
Japan	Fossil fuels	772	1009	23	1443	−749	−4.1 %
	Low-carbon	237	1009	1419	1443	1183	6.4 %

(continued on next page)

Table A7 (*continued*)

Country	Source	2020 (TWh)		2035 (TWh)		Generation change (TWh)	Annual change rate
		Value	Total	Value	Total		
United Kingdom	Fossil fuels	125	310	7	443	−118	−2.1 %
	Low-carbon	185	310	436	443	251	4.4 %
United States	Fossil fuels	2588	4239	98	6061	−2490	−3.2 %
	Low-carbon	1651	4239	5963	6061	4313	5.6 %
EU24	Fossil fuels	553	1385	32	1980	−521	−2.1 %
	Low-carbon	831	1385	1948	1980	1117	4.4 %

Note: 2020 data is calculated based on IEA Extended Energy Balances [71] for all the countries, and 2035 data for G7 + EU is taken from IEA's Achieving Net Zero Electricity Sectors in G7 Members [1]. The latter data has a very small gap (<0.002 %) between the total value and the sum of individual values. We thus scaled each value by the gap to equate their sum with the total value. We then calculated the 2035 data for the G7 member states, assuming 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, as expected in the IEA report for G7 + EU as a whole. Annual change rates are calculated based on the same method described in Section 3.5.

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