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To cite this article: Judy Jingwei Xie *et al* 2025 *Environ. Res. Lett.* **20** 064009

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ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
28 October 2024

REVISED
14 March 2025

ACCEPTED FOR PUBLICATION
25 April 2025

PUBLISHED
13 May 2025

LETTER

Past socio-political transitions away from coal and gas show challenges and opportunities ahead

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Keywords: fossil fuel phase-out, energy transition, integrated assessment models, feasibility, k-means clustering

Supplementary material for this article is available online

Abstract

Transitioning away from fossil fuels presents substantial challenges, given the growing mismatch between pledges submitted to international climate negotiations and the mitigation strategies that limit warming to below 1.5 °C or 2 °C presented in the Intergovernmental Panel on Climate Change Sixth Assessment Report. The scientific case for phasing out coal-fired electricity is clear, and many countries are progressing towards this. However, despite widespread concerns about risks and trade-offs, natural gas is often considered a bridge fuel, and there is currently no progress towards phasing down its capacity. Previous work on the political feasibility of coal phase-out only considered limited socio-political factors, missing the importance of governance quality and policies supporting the energy transition. There is even more limited understanding of factors associated with gas phase-down, while Europe and North America fall behind trajectories required to limit warming below 1.5 °C. We use multivariate regression and clustering analyses on over four decades of data to investigate the drivers and synergies of coal and gas transitions. This reveals opportunities to overcome fossil fuel lock-in through renewable energy expansion, energy policy reforms, and power market restructuring. Countries with greater reliance on fossil fuel infrastructure and workforce face additional difficulties in phase out. Social factors such as higher belief in climate change are positively linked with more ambitious coal phase-out efforts. However, disentangling these links for gas remains difficult given the limited historical evidence of phase-down progress. We identify four archetypes (Coal Reliance, Gas Reliance, Limited Policy, and Transition Underway) that illustrate different ways countries have transitioned from coal and gas over time. These provide blueprints for potential future transitions in other countries. Recognizing the diverse social, political, and institutional factors that shape transitions can inform the design of politically relevant future scenarios.

1. Introduction

The committed CO_2 emissions from existing energy infrastructure exceed the remaining carbon budget (the amount humans can emit) associated with a 1.5 °C warming limit [1], and this budget is rapidly shrinking [2]. Despite global consensus on the threats posed by fossil fuels—climate change, mortality [3], and biodiversity loss [4]—the phase-out of fossil fuels is a controversial subject among the public [5] and policymakers. At the international climate negotiations in Dubai (COP28), details around fossil fuels in the Paris Agreement's first Global Stocktake were contentious. However, by signaling a need for 'transitioning away from fossil fuels' [6], the adopted outcome text acknowledges the required course of action.

There is a notable difference between how coal and gas are treated in political and academic discussion. Progress towards phasing out coal is evident, with many countries establishing zero-coal pledges

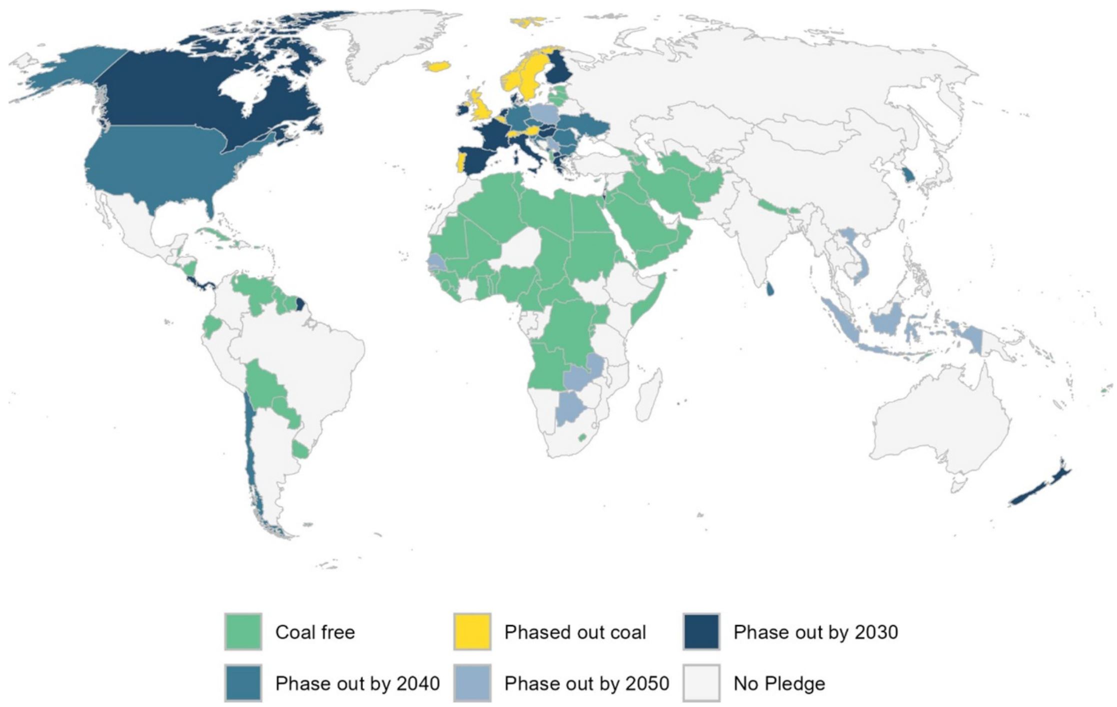

Figure 1. Country-level coal phase-out status and pledges as of 2024. 'Coal free' indicates countries that have not historically used coal in power generation and have no coal power plants under announcement, permitting, or construction. 'Phased out coal' indicates countries that used coal in power generation but have phased it out completely. Countries with zero-coal pledges are separated by timeline into 'Phase out by 2030' (such as Canada and other OECD or countries in the Powering Past Coal Alliance (PPCA)), 'Phase out by 2040' (such as Germany with a 2038 phase out pledge), and 'Phase out by 2050' (such as Poland with a 2049 phase out pledge). 'No Pledge' indicates countries that have or plan to have coal power plants without any phase out pledges. The future coal phase-out pledges are based on analysis reproduced from Our World in Data [22], licensed under CC BY 4.0. Additional coal phase-out pledge data are adapted with permission from © 2006–2025 Third Generation Environmentalism Ltd. (E3G) licensed under CC BY-NC 4.0 [23], adapted with permission from Beyond Fossil Fuels [24], and adapted with permission from Bloomberg Global Coal Countdown [25].

(figure 1). The UK, home to the world's first coal power station in 1882 [7], became the first G7 nation to end coal-fired electricity [8, 9], providing an important example of coal phase-out by a major industrialized nation. Comparable progress in phasing out natural gas remains lacking. While global integrated assessment models (IAMs) consistently show that Paris-aligned scenarios require a rapid global phase-out of unabated coal [10], there is considerable variability across models and scenarios regarding the phase-down of natural gas [11].

More detailed national studies suggest that the modeled rapid phase-out of coal in regions such as China and India may be infeasible [12], and that scenarios should rely on faster phase-out of oil and gas in Organisation for Economic Co-operation and Development (OECD) countries [13]. Historically, some countries switched to natural gas to accelerate their coal-phase out [14] and some scenarios propose similar strategies in China and India. This is particularly attractive for the US [15] where natural gas prices are kept low through increasing domestic production and constrained exports [16]. However, with rapidly declining cost of renewable energy [17], the viability of natural gas as a bridge fuel is questionable, given its under-estimated lifecycle and climate impacts [18], lock-in effects, economic risks from infrastructure costs [19], and geopolitical concerns [20]. The record number of new gas pipelines built in China and India for imports risk becoming stranded assets [21]. We therefore argue that existing trajectories for coal and natural gas transition pathways must be considered together to better understand their connections and the shared or unique drivers that could inform technology assumptions in IAMs.

What should be considered in the next generation of policy-informing scenarios? A growing literature shows that social, political, and institutional factors are important in the energy transition [26], particularly in the shift away from fossil fuels. Current energy system models often fail to capture socio-political aspects in as much detail as techno-economic factors [27, 28]. This limits our ability to develop and explore transition pathways that align with different interpretations of socio-political feasibility [29]. Studies have begun to investigate the political and institutional factors that influence coal phase-out [30, 31] and implement these insights into IAMs [13, 32]. Recent studies have also used clustering to explore regional trends, including national models of climate governance (institutions shaping climate policy and performance) [33], the strength of climate policy [34], and the interactions of political and economic factors in national climate policies [35].

We build on this growing research area in several ways. First, we provide a more detailed analysis of coal and gas transitions by examining a wide range of sensitivities and measurements of phase-out at the country and plant level. Second, we test various social, political, and institutional factors associated with coal or gas declines. In particular, we incorporate recent insights from social sciences and political developments through a wider range of covariates and model specifications than previous studies [30, 36] while expanding the focus on gas transitions. Finally, we explore temporal dynamics by showing how certain policies are linked to more progressive action in specific regions. Our approach demonstrates how insights from diverse disciplines can be applied to scenario evaluation, highlighting opportunities to create transition scenarios that are more useful and acceptable to decision-makers worldwide.

2. Data and methods

To understand the coal and gas transition landscape, this study employs four research approaches to identify: (1) regional gaps in the transition, (2) examples of ambitious country- and plant-level phase-out, (3) historical enablers and barriers at the country level, and (4) time- and country-dependent trends. In line with the technological feasibility literature [12, 36], we first benchmark future coal and gas transition pathways against historical examples. These pathways include Intergovernmental Panel on Climate Change (IPCC) and IEA scenarios, focusing on four important fossil fuel regions: China+, India+ (two regions named after their most dominant country), Europe, and North America. Second, we conduct case studies to examine country- and plant-level phase-outs that are obscured in aggregated regional comparisons, with a focus on natural gas phase-outs. Third, using historical coal and gas transition data from 1980 to 2022, we conduct univariate and multivariate linear regressions, incorporating a detailed set of social, political, institutional, and technological variables to identify the barriers and enablers of coal and gas phase-out. Unlike previous studies that focus on the most recent data [30, 31], this analysis provides insights into long-term drivers of the transition. Finally, we apply k-means clustering to identify time- and country-dependent archetypes, revealing transitional characteristics and context dependency beyond the current understanding [35].

2.1. Coal and gas transition variables

The degree to which countries have transitioned away from coal and gas power plants can be assessed in various ways, including the reduction in peak capacity [31], in generation [12], or the share of coal in the electricity supply [30, 36]. These three measures reflect different aspects of the transition: long-term phase down, short-term phase down, and the reduced reliance, respectively. Historical data on coal and gas capacity and retirements at the plant-level were derived from the Global Coal Plant Tracker and Global Gas Plant Tracker [37, 38]. Data on electricity generation from coal, gas, wind, and solar and their shares of total electricity generation were compiled from multiple sources [39–41].

The resulting response variable dataset includes the share of coal reduction from peak capacity, coal generation decline, and gas generation decline. Gas reduction from peak capacity was excluded as no country has experienced this. The peak capacity of coal is defined as the largest capacity observed in a country (capacity in the most recent year if no decline was observed). Capacity reduction is defined as the percentage reduction in capacity from the peak capacity, distinguishing it from cases where plant retirements are offset by new construction without reducing total capacity. Generation decline is similarly defined as the percentage reduction in electricity produced from its peak. Descriptions and summary statistics for the variables are provided in tables S1–S2.

2.2. Social, political, and institutional variables

The selection of social, political, and institutional factors (table 1) is based on both empirical relationships and open data, while building on existing understanding from the literature (table S4). We include new variables describing climate change belief and support for reducing fossil fuels use from a global climate change opinion survey [5], to explore the connection between public opinion and phase-out progress. Country-level employment in mining is considered, as the negative employment impact of phase-out [42] may generate resistance. Although governance indicators such as state capacity [31] and government functionality [30] have been correlated with coal phase-outs, we focus on political and institutional factors that are more actionable. These factors reflect the influence of fossil fuel incumbents, power market reforms [43, 44], and economic development. We disaggregate the categories of national climate policies, focusing on energy supply [45] and different types of power market reform [43, 44]. Explanations of the variables, summary statistics, and comparison to previous studies are provided in supplementary section 2. We used data imputation to retain more data and present the detailed procedures and justifications in supplementary section 3.2.

2.3. Regression analysis

We developed linear univariate and multivariate regression models to understand the barriers and enablers for historical coal and gas retirements. All non-binary variables were standardized before analysis. Using empirical relationships, we first identified the most significant variables within each category. For example, we found that among energy supply policies, economic and regulatory policies had

Table 1. Description of the social, political, and institutional variables.

Category	Independent variable	Description
Social	Climate change belief	The share of population that believes climate change is caused mostly by humans (%)
	Support for less fossil fuels	The share of population that supports less fossil fuel use (%)
	Employment in mining	The share of workforce in mining including both coal and natural gas
Policy	Power market choice of supplier	Whether a country allows consumers to choose their own retail power suppliers (binary)
	Number of economic policies	The number of energy supply policies involving tax incentives, subsidies, carbon pricing, and emissions trading
	Number of regulation policies	The number of energy supply policies involving zoning & spatial planning, disclosure obligations, standards, and norms
Institutions	Annex I member	Whether a country is part of the UNFCCC Annex I classification (binary)
	Log GDP per capita	Natural logarithm of gross domestic product per capita (Log constant 2015 US$ per capita)
Technologies	Coal supply independence	The share of coal supply fulfilled by domestic production (%)
	Gas supply independence	The share of gas supply fulfilled by domestic production (%)
	Coal share in electricity	The share of electricity generated by coal (%)
	Gas share in electricity	The share of electricity generated by gas (%)
	VRE share in electricity	The share of electricity generated by wind and solar (%)

greater explanatory power. We iteratively built onto multivariate models using sets of variables within the same category to improve model fit while reducing multicollinearity (avoiding variable inflation factors above 2.5). Social variables were excluded due to limited time-series data coverage. Univariate models were presented to both illustrate simple relationships and validate multivariate results, especially when the explanatory power of one variable is influenced by the co-existence of another related variable in the model. We also conducted logistic regressions to examine whether retired coal power plants are converted to gas. The iterations, variable coefficients, and model fits are reported in supplementary section 4.

2.4. K-means clustering of defined archetypes

To produce more accessible insights, and drawing on literature that clusters countries with non-categorical variables [34, 35, 46], we applied k-means clustering to countries with both coal and gas power plants to identify distinct transition archetypes. We first conducted principal component analysis on 13 features encompassing all dependent and independent variables from the previous model. Each data point represents a country-year pair with existing coal or gas power plant information. We selected the first seven principal components which describe 83.6% of the variance. We evaluated the potential of clustering into two to five clusters, with four clusters chosen to achieve a high degree of separation while retaining high variance. To mitigate the random effect of political elections and other short-term events, we identified clusters based on the most frequent cluster (mode) across each half-decade. Archetypes were qualitatively characterized by the range of variables the clusters represent. Further details on the analysis and cluster characterization are provided in supplementary section 5.

3. Results and discussions

3.1. Mismatches between fossil fuel scenario narratives and pledges

Ample coal phase-out literature highlights that Paris-aligned scenarios assume China and India will reduce coal reliance faster than historically observed in developed countries [12, 36]. However, slow progress in developed regions reducing natural gas dependence has been overlooked. The four important fossil fuel regions possess different gaps in energy transitions aligned with limiting warming to 1.5 °C with no or limited overshoot, as reported in the IPCC AR6 (figure 2).

China+ and India+ are both set to generating more coal-fired electricity than 1.5 °C scenarios suggest (figures 2(a) and (b)). Although Europe and North America have reduced coal use, their stated policies and pledges are insufficient (figures 2(c) and (d)). This misalignment does not imply infeasibility, but suggests a faster decline in oil and gas is needed [13, 32]. The 1.5 °C scenarios present ambiguous future gas pathways [47], especially in China+ where a rapid increase until the 2030s is followed by a rapid decrease by mid-century (figure 2(e)). This would result in substantial stranded assets, and might be unrealistic given the lack of existing widespread gas

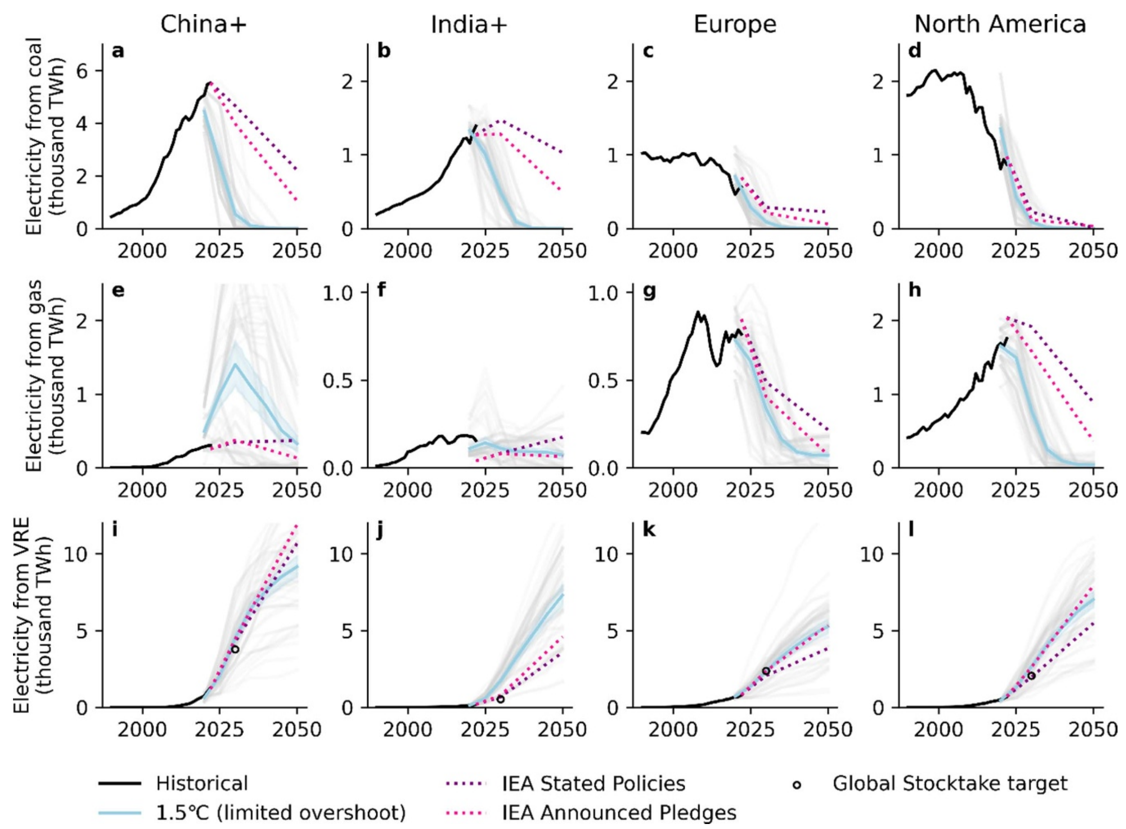

Figure 2. Electricity generation from coal, gas, and variable renewables (solar and wind) from 1990 to 2050. Historical data in black lines are from Ember and the Energy Institute synthesized by Our World in Data [39]. Future data in solid light grey lines are from the C1 scenario category (1.5 °C with no or limited overshoot) in the IPCC AR6 Database [49]. Light blue thick lines represent their mean, and the shaded areas the 95% confidence interval. The AR6 variables shown are 'Secondary Energy|Electricity|Coal|w/o CCS', 'Secondary Energy|Electricity|Gas|w/o CCS', 'Secondary Energy|Electricity|Solar', and 'Secondary Energy|Electricity|Wind'. Future data in dotted lines are from the IEA 2023 World Energy Outlook [50]. All rights reserved. Black empty circles denote the 'tripling renewable capacity by 2030' target from the First Global Stocktake, assuming the same utilization as today. The selected regions are based on the R10 grouping. China+ includes China (incl. Hong Kong), Cambodia, Korea (DPR), Laos (PDR), Mongolia, and Vietnam. India+ includes India, Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, and Sri Lanka. Note that the IEA data plotted for India+ only includes India.

infrastructure, the low cost of renewables [17], geopolitical tensions [20], and climate goals [48]. Such scenarios also conflict with the urgent need to reduce coal use in the region.

In Europe, the gas trajectory is slightly behind 1.5 °C scenarios, while North American stated policies project gas generation to halve by mid-century instead of approaching complete phase-out (figures 2(g) and (h)). The misalignment persists in less stringent scenarios (figures S5–S6) and would be more pronounced if coal declines in developing regions follow more realistic pathways [13]. China's leadership in renewable energy deployment means the regions discussed here broadly align with the tripling renewable capacity target set during the first Global Stocktake (figures 2(i)–(l)).

Existing policies and pledges reveal gaps in existing scenarios regarding regional diversity with fossil fuels. Nevertheless, several countries have made ambitious progress in transitioning from fossil fuels (figure 3). Historical precedence shows that reducing coal generation by 50% typically requires 15–30 years (figure 3(b)), while for gas, it takes 10–15 years (figure 3(e)). Austria, Belgium, the UK, and Portugal are highlighted for having eliminated coal power generation and phased out their coal fleets. Austria and Portugal transitioned away from coal within just 20 years but had relatively small coal fleets. Denmark and Romania show promising evidence of replacing coal with renewable energy growth (figure S4). Finland rapidly reduced gas generation alongside coal, though its initial reliance was already low due in part to regional geopolitics [20]. Other countries that have reduced gas reliance experienced sudden trade shocks leading to rapid declines in the first decade followed by partial recovery. For example, the loss of Argentinian gas imports to Chile [51], and the rapid rise of cheap US coal imported into Europe [52] have led to sudden declines in gas in electricity (figure S7).

The decline of coal capacity is lower than for generation, while gas decline is only evident in reduced generation (figure 3). Retaining small capacities of rarely used fossil fuel generators can support system reliability without jeopardizing climate goals, but capacity reduction indicates permanent

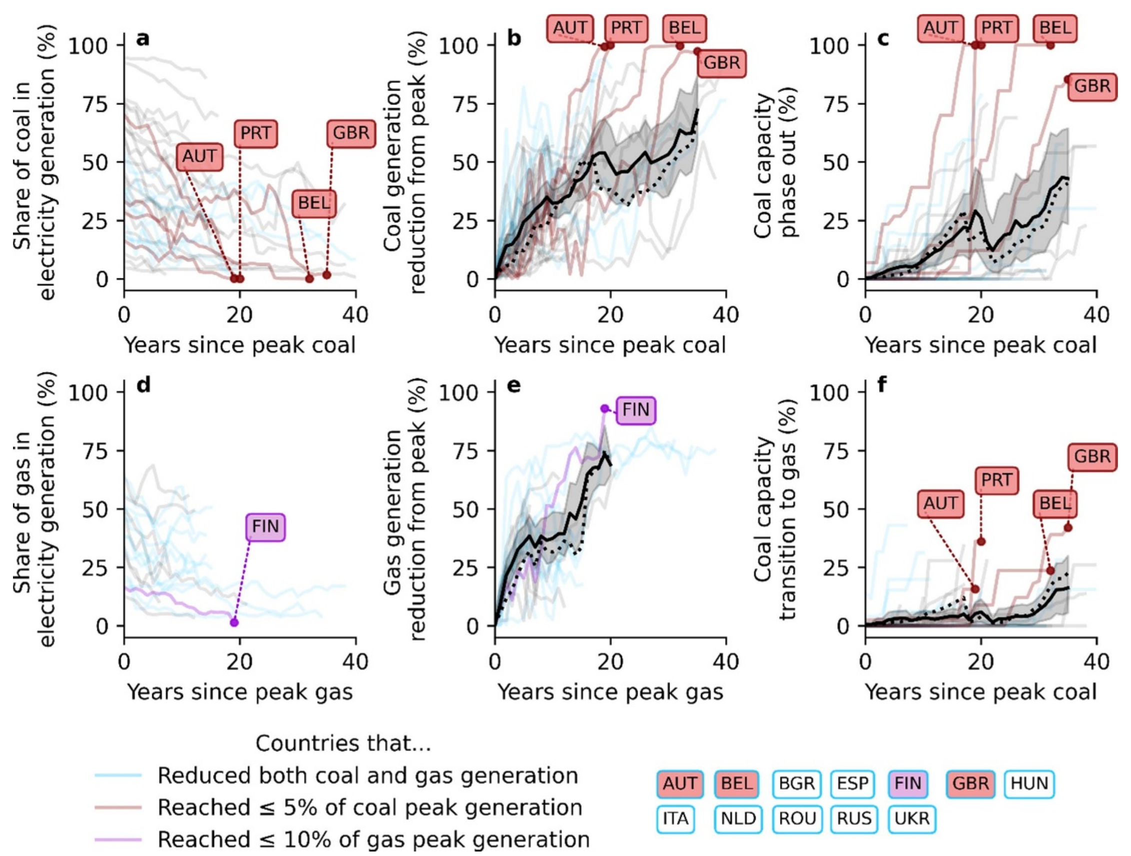

Figure 3. Country-level progress in reducing reliance on coal and gas power generation between 1990 and 2022. The individual plots represent (a) the share of coal in electricity generation, (b) reduction in coal generation from its peak, (c) reduction in coal capacity from its peak, (d) the share of gas in electricity generation, (e) reduction in gas generation from its peak, and (f) coal capacity transitioned to operate on gas. Countries with more than 5 years of consistent decline are shown, including 34 countries for coal, 19 countries for gas, and 12 countries with both. Countries labeled in red have reached less than 5% of peak coal generation; those labeled purple have reached less than 10% of peak gas generation; those labeled blue have reduced coal and gas generation simultaneously; those labeled gray are other countries. Solid black lines give the simple mean, and gray shaded areas represent the 95% confidence interval; dotted black lines are the mean values weighted by either capacity or generation.

commitments to the transition. From plant-level analysis, we find that 28.1% of global coal power units had retired as of 2023, compared to only 1.3% of natural gas units. While many gas plants are younger than coal, fleet age alone does not explain this disparity (figure S3). Coal retirement is more advanced in the US, Western Europe, and Eastern China, but only Western US and Western Europe are phasing out coal capacity with less new coal is built than is being retired (figure S1). Although older gas plants begin retiring in 2020, no country is on track to phase out natural gas power plants. A total of 34 units in the 107 retired gas units as of 2023 were prematurely retired (<30 years of operating lifetime), most of which were based in the US (figure S8).

Plant-level geospatial analysis shows that around one-third of retired coal power plants globally have transitioned to natural gas, especially in the Eastern US. This strategy is also evident in Portugal and the UK (countries with complete coal phase-out) (figure 3(f)). Larger coal plants are more likely to switch fuels (table S17). Belgium, France, the UK, and the US have nearly replaced all the reduced coal generation with natural gas (figure S4), which may delay the gas phase-out necessary for the 1.5 °C target. This bridge-fuel strategy can only replace 1.5–2.4 times the operating lifetime of the displaced coal before the climate benefits are negated [48] (i.e. a gas plant emits as much in 6–10 years as a coal plant would in 4 years). This buys some time for regions with existing natural gas infrastructure. For those without, building up natural gas infrastructure would be more costly and risk energy security when cheaper, low-carbon alternatives exist.

3.2. Social, political, and institutional context of the transition

Political and institutional proxy variables, such as high GDP and state capacity [30, 31], are associated with faster coal phase-out but are too broad to provide actionable policy insights. Figure 4 shows how social, political, and institutional characteristics are correlate differently with coal and gas transitions. We used univariate regression models to explore simple relationships. To understand the complex interactions while reducing multicollinearity and confounding effects, we selected a subset (excluding

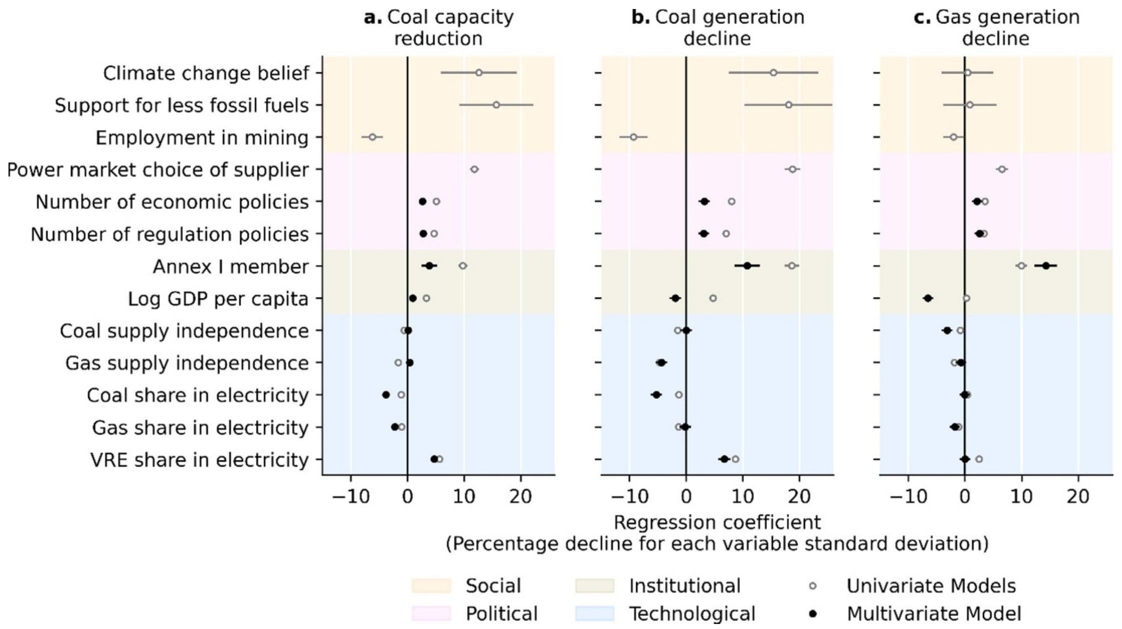

Figure 4. Multivariate and univariate linear regression models for fossil fuels transitions during 1980–2022. Dependent variables include (a) coal capacity reduction, (b) coal generation decline, and (c) gas generation decline. The univariate models focus on countries with either coal ((a) and (b)) or gas (c) infrastructure, while the multivariate models focus on countries with both coal and gas infrastructure. VRE (variable renewable energy) refers to wind and solar. Scatter points represent regression coefficients, with error bars showing 95% confidence intervals. The variables containing the zero value in the black vertical line are insignificant. Power market choice of supplier and Annex I member variables are binary, while the others are standardized. Background colors indicate the broad type of variables. Detailed statistics of the models can be found in tables S7–S16.

limited social variables) for multivariate regression analysis.

The social factors considered here are more connected with coal decline than gas. Public belief in anthropogenic climate change and support for reducing fossil fuels are well connected with more coal phase-out but show no correlation with gas generation decline. There is evidence of consumers considering values beyond low electricity prices, for example, surveys on supplier switching found other positive factors such as the availability of green electricity in Sweden [53] and political preferences in the UK [54]. Such tendencies may support reducing coal dependency. Similarly, countries with higher proportions of shares of mining workers are less likely to phase out coal and gas, which may be linked to undesirable socioeconomic impacts on the workforce [42].

Political and institutional factors exhibit stronger correlations with both coal and gas, with choice of supplier (reformed market), more economic and regulatory policies, and being part of the UNFCCC Annex I (*i.e.* OECD countries and economies in transition [55]) connected with declines in both fossil fuels. Higher GDP per capita is weakly linked to coal capacity reduction but shows inconsistent relationships with generation decline for both technologies.

Path dependency variables also play a role in coal and gas declines. Countries with higher shares of coal are less likely to reduce coal generation, and the same applies to gas. This highlights the difficulty of moving away from technologies that are highly relied upon. Countries with less independent coal supply (or higher coal import dependence) are more likely to reduce gas generation, and vice versa, indicating the volatility brought by competing imports. For example, efficient European gas plants closed prematurely in the early 2010s due to the sharp drop in imported US coal prices [52] (figure S7).

3.3. Time-varying regional characteristics and clusters

The regression analyses identify trends among variables that are common to the transition, but do not capture time-varying and region-specific patterns. Importantly, our historical analysis draws insights from the transitions already occurring in North America and Europe. Political, policy, market and other factors might present strongly differing contexts in other geographies or jurisdictions and transferability of our insights to other regions should therefore be carefully considered.

Using k-means clustering, we highlight dynamic patterns and drivers in countries over time, which resulted in four archetypes (figure 5). The Coal Reliance and Gas Reliance archetypes show limited phase-out progress with heavy reliance on each respective fossil fuel. The Limited Policies archetype includes countries less reliant on fossil-fueled electricity while but with fewer energy supply policies. The Transition Underway archetype shows the most progress (supplementary section 5). Before the 2000s,

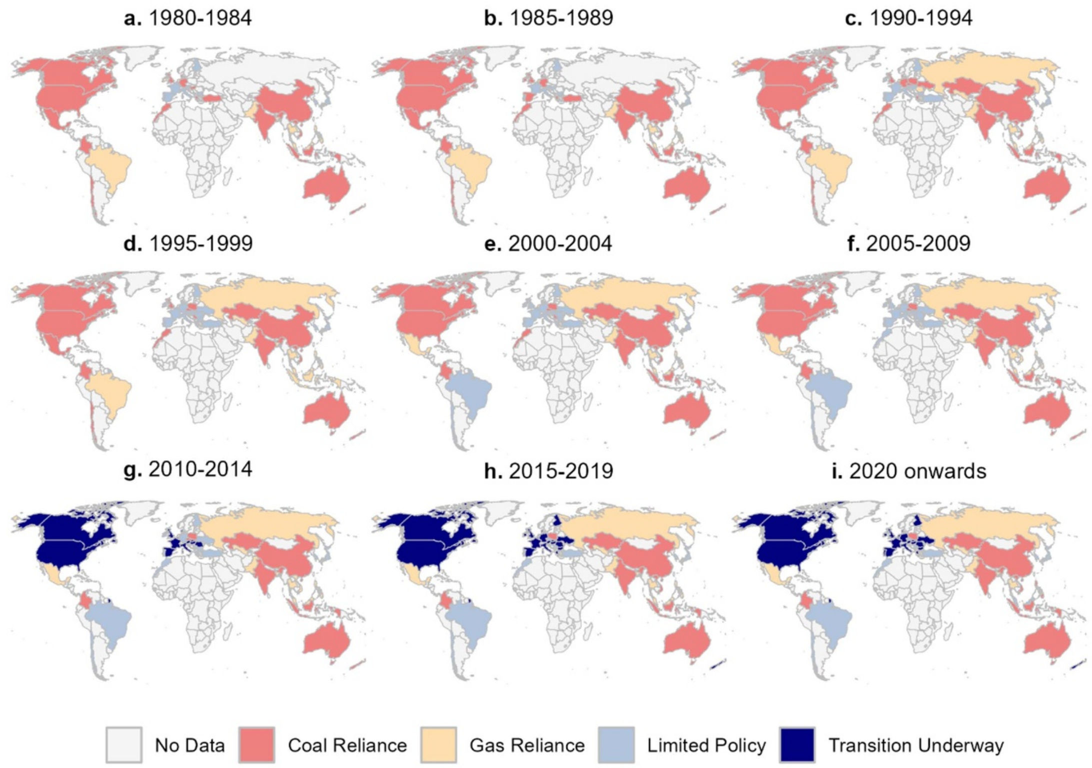

Figure 5. Regional k-means clustering of coal and gas transition characteristics over time. Clusters represent the most frequent values (modes) during each period. Clustering includes countries with both coal and gas power generation facilities. Countries labeled 'no data' lacked power plant data at the time.

countries were mostly characterized by Coal Reliance, Gas Reliance, and some Limited Policy archetypes. Countries that are currently Transition Underway went through several transition stages and align with observed progress and pledges to phase out coal (figure 1).

Transition Underway countries are concentrated in the advanced economies of Europe and North America, in addition to New Zealand. They are characterized by high GDP per capita and relatively low GDP growth, except for eastern Europe nations like Romania and Ukraine. Transition Underway countries have now decoupled electricity from economic growth; however, their conditions prior to joining that cluster were more reflective of other countries in the sample (supplementary section 5.4).

Gas Reliance countries have relatively independent gas supply and limited coal supply. They have generally remained in the same clusters over time, suggesting limited willingness or substantial challenges in transitioning. Brazil started transitioning away from Gas Reliance since the 2000s but has not progressed to Transition Underway and has no coal phase-out pledge (figure 1). Achieving an equitable fossil fuel phase-out, especially for Gas Reliance regions requires cooperative frameworks, delayed phase-out timelines, and financial assistance [56]. Removing fossil fuel subsidies showed greater impact in oil- and gas-exporting regions (MENA, Reforming Economies, Latin America) [57]. Context-specific support is much needed for fossil fuel producing low and lower–middle income countries [58]. Regardless of gas's role in future energy systems, it is evident that current production levels far exceed Paris-aligned goals [59].

Some countries in the Coal Reliance group, particularly in Europe, have gradually reduced their fossil fuel reliance and moved into the Limited Policy and Transition Underway archetypes. These shifts are linked with developments in renewable energy and more climate legislation. Poland, historically a major coal producer, remains in the Coal Reliance group. However, the uneconomic nature of coal mines, unavoidable energy investments, air pollution, and political pressure from the EU may drive its transition in the near future [60]. Despite fears of coal phase-down reversal amidst the Russian war, Europe further reduced its fossil fuel demand in 2023 through renewable energy growth and a recovery in French nuclear power [61]. This marks an improvement from the 2010s European coal rebound driven by cheap imports [52].

Historically Coal Reliance countries like the US and Canada are characterized as Transition Underway from the 2010s. This progress spanning several decades is linked to both conditional factors (e.g. high GDP and diverse economic systems [56]) and implementable lessons (e.g. having more energy supply policies). The 2024 Clean Air Act's proposed emission limits for new gas-fired combustion turbines reaffirms the role of regulatory policy [62]. In contrast, China has not relied heavily on natural gas due to the top–down power market structure which regulates electricity prices from imported fuels [63]. Recent steps towards a unified national power market system [64] may offer more flexibility to use gas and enable the phase-down of coal. China's coal-to-gas policy in the heating sector aims to reduce air pollution, but risks being undermined by potential gas supply shortages [65]. Meanwhile, India has developed new liquified natural gas import terminals to help meet the rising demand for electricity from gas [66]. Although China and India have not reduced their coal reliance, switching reliance towards gas risks future lock-in if it cannot be transitioned away from fast enough.

4. Conclusion

This work builds on the argument that transitioning away from coal is not a 'one-size-fits-all' process [67] through evaluating the synergies between coal and gas phase-outs across national electricity systems. While the climate and health [68] costs of coal-powered electricity are clear, historical evidence around reduced gas use is mixed. Repowering phased-out coal infrastructure to operate on natural gas can reduce stranded assets, and some countries leading on coal phase-out have followed this approach. However, developed regions such as North America are notably behind with gas reductions required for Paris-aligned scenarios.

Through clustering analysis, we highlight the dynamic nature of these transitions rather than focusing on the static characteristics in recent years. We find that many regions go through the transition in staggered phases, which creates opportunities to explore transferrable lessons from those that started the process earlier. Multivariate regression and cluster analyses reveal that these lessons include expanding renewable energy, providing choice over power market suppliers, and enacting more national climate policies. We also find conditional factors, such as the partial decoupling of electricity generation from GDP in countries before reaching Transition Underway, which could limit the applicability of findings to all contexts. However, diverse countries including Mexico, Republic of Korea, Thailand, Australia and Poland currently have comparable GDP and electricity supply growth to countries at the time they moved into Transition Underway.

Renewable electricity plays a positive role in the transition away from coal and gas, which is also positively linked with energy market reform and energy supply policies. These findings align with previous studies. For example, UK investment in renewables was a strong driver for short-term emissions reduction [69]. Volatile gas markets lead to coal rebounds [51, 52, 65], while high US reliance on gas could hinder renewable energy development [70]. However, economic competition can accelerate renewable energy adoption [71] and we find it is a driver for early gas retirement. In the OECD, energy market liberalization has reduced barriers to entry and promoted uptake of renewable energy [72]. Similarly, under reformed power markets, EU state-owned utilities were more likely to expand renewables with the presence of pro-adoption policies [73]. Our extension of the coal phase-out literature invites future exploration of other unique factors that influence gas transitions.

National policies and power market reforms are important in moving countries from early to mature stages of coal and gas transitions, although the relationship is weaker for gas. The dynamics of gas phase out are more complex, given the dichotomy of countries with strong public acceptance of anthropogenic climate change but limited evidence of gas decline. Detailed policy attribution can help identify specific mechanisms and causal relationships that drive phase-out [74]. Although top–down markets such as China have not historically contributed to coal phase-out, our results do not imply infeasibility. With political will, these countries would be capable of implementing more ambitious and disruptive policies, which would benefit from compensatory packages [75] and social dialogue [76]. Power market liberalization should also be accompanied by an understanding of the technological system. Transformative change in gas-dependent countries will be especially difficult, potentially requiring recognition of their specific circumstances and global compensatory policies [56].

Our analysis is constrained to historical evidence and so draws primarily on progress in Europe and North America. They hence provide a useful starting point that can be enhanced with region-specific differences and accents to understand transitions in other geographies. However, we examined the past challenges these countries overcame, offering more insight than focusing only on current-day circumstances. Additionally, the scarcity of global, granular and longitudinal public perception data limits the analysis depth. Nonetheless, existing data show interesting results such as no clear link between gas decline and belief in climate change. This evidence does not imply the ineffectiveness of broader public acceptance of climate change in future. Further research into public discourse in the energy transition and the regional differences can provide a more nuanced understanding. Our work does not account for within-country differences in climate progress, public perception, or power market reforms, which future work could investigate, especially for large and complex countries like the US and China. Future work could investigate a wider array of factors and consider causality to further elucidate the drivers of coal and gas transitions, and the relative strength of conditional factors (such as GDP) and the transferrable lessons considered here.

Recognizing the social, political, and institutional diversity of countries, this work can inform more targeted policies and interventions. These insights can also improve the structural models and scenario assumptions in IAMs, addressing some of the feasibility and justice concerns raised about IAM pathways [77]. A socio-political feasibility perspective is important for scenario evaluation, and our findings highlight opportunities to systematically and purposefully incorporate this, leading to broader relevance and acceptance of IAM-based transition scenario research.

Data availability statement

The data used here are all from publicly available sources and are referenced when they are introduced throughout the manuscript.

The data that support the findings of this study are openly available at the following URL: https://github.com/judyjwxie/coal-gas-phaseout-analysis.

Acknowledgments

J.X. would like to thank the Imperial College London President's PhD Scholarship for the financial support. Some of the work was conducted as part of the Young Summer Scientist Program (YSSP) at the International Institute for Applied Systems Analysis (IIASA). J.X. and E.B. would like to acknowledge funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement No. 101056873 (Project ELEVATE). The authors would also like to thank Gaurav Ganti (Climate Analytics), Jenna Greene (University of Wisconsin—Madison), the staff at the Energy, Climate, and Environment Program at IIASA, and discussants at the 16th Integrated Assessment Modeling Consortium (IAMC) Annual Meeting for their helpful inputs on earlier versions of this work.

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Conceptualization, J.X. and E.B.; Methodology, J.X., E.B., J.R., and I.S.; Formal Analysis, J.X.; Investigation, J.X. and E.B.; Writing—Original Draft, J.X., E.B., J.R., and I.S.; Visualization, J.X., Supervision, E.B., J.R., and I.S.; Project Administration, J.X.

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