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Research Article

Coal phase-out pledges follow peak coal: evidence from 60 years of growth and decline in coal power capacity worldwide

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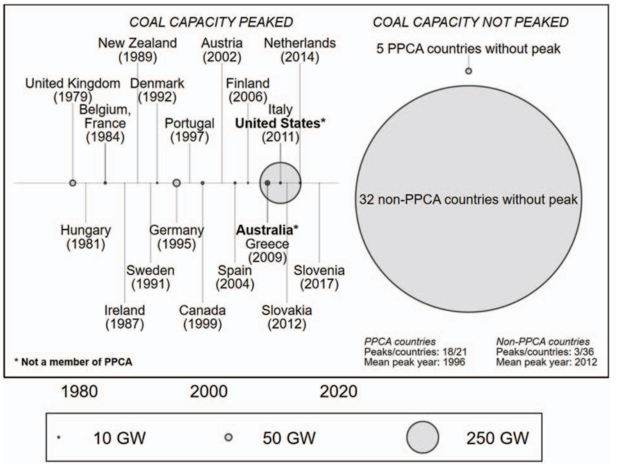
Abstract

Transitioning to net-zero carbon emissions requires phasing-out unabated coal power; however, recently it has only been declining in some countries, while it stagnated or even increased in others. Where and under what circumstances, has coal capacity reached its peak and begun to decline? We address this question with an empirical analysis of coal capacity in 56 countries, accounting for 99% of coal generation in the world. The peaks in national coal power have been equally spread per decade since 1970. The peaks are more likely to occur in country-years with high levels of electoral democracy, higher GDP per capita, slower electricity demand growth, and with low levels of political corruption. Normally, peaking coal power preceded rather than followed political coal phase-out pledges, often with long time lags. We conclude that though the cost of coal alternatives are declining and concerns over climate change increasing, coal power does not automatically peak even in situations with low demand growth, aging power plants and high import dependence. A quick and decisive destabilization of coal regimes requires, in addition, having sufficient economic capacities and strong democratic governance.

Graphical Abstract



Lay Summary: Recently, the use of coal has declined in some countries, but remained stable or even grown in others. We investigate under what conditions coal power peaks, i.e. stops growing and then declines. Peaking coal power has mainly occurred in wealthy democracies with low corruption and slow electricity demand growth and has occurred with steady frequency since the 1970s despite cheaper renewables and climate concerns. We also find that political commitments to phase-out coal such as the Powering Past Coal Alliance generally follow rather than precede peaking coal.

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Introduction

Achieving climate targets requires rapid and universal phase-out of coal power [1, 2]. This means that the use of coal power should peak almost immediately [3, 4], which would also imply significant premature retirement [5, 6]. So far, this process has been uneven around the world. On the one hand, the use of coal has declined in OECD and most of its member economies. Moreover, in 2016, a group of countries formed the Powering Past Coal Alliance (PPCA) pledging to phase out unabated coal power. However, most of the initial PPCA members used little coal and therefore their pledges do not significantly contribute to climate change mitigation [7]. An additional two dozen countries pledged to phase-out coal during COP26 in Glasgow, although some of these pledges either do not indicate the actual phase-out date or place it far in the future [8]. At the same time, the use of coal continues to increase in Asia [9], and the G20 countries have failed to make an agreement on a coal phase-out date. Is coal power really on the way out? If so, in which countries and when did this process start? What does it tell us about the likelihood of sufficiently rapid phase out of coal power in the future?

As any other technology, coal power evolves through a technology lifecycle, which involve periods of expansion, stagnation and decline [10, 11]. At the **expansion** stage, increased use of coal power is supported by increasing energy demand, and in some cases energy security concerns. Decades of coal power growth result in strong socio-technical regimes capable of persistent expansion and self-replication and locked-in in stable configurations, that involve massive infrastructure, business models, supporting public discourses and favorable policies, including subsidies [12, 13]. Nevertheless, at one point coal power expansion slows down and **stagnates** due to slowdown in electricity demand growth, resource depletion and advances in competing power technologies as well as public concerns over air pollution and climate impacts [14]. Despite the coal regime resistance [15], it may eventually be destabilized, through mutually reinforcing processes of declining legitimacy, withdrawn political support and economic bankruptcy [11, 16, 17]. This evolutionary pattern includes a distinct 'peak' of coal power that is preceded by a period of growth and stability and followed by a decline.

The peaking of coal power is thus a milestone in the technology cycle. By analysing in which countries and under what conditions coal power has peaked historically it should be possible to better understand the timing of its future peak in major coal users. It is particularly interesting to see whether political pledges to phase out coal precede and thus possibly trigger 'peak coal power' or follow the peaks and thus merely articulate ongoing decline processes. This paper aims to investigate the extent, timing and prevalent conditions of peaking coal power in countries around the world as well as its relationship with political pledges to phase out coal. We use survival (event history) analysis to examine the dynamics of coal power capacity in 55 countries that account for 99% of coal generation in the world. We show that coal power has peaked in the majority of countries with high income, strong democracy and low corruption. We further show that pledges to phase out coal followed rather than preceded peaking coal capacity, often with considerable delay. Peak capacity was also followed by pronounced decline of coal power generation, which indicates the importance of this milestone for emission reduction.

Analytical framework

The factors and mechanisms potentially affecting lock-in and destabilization of coal power regimes and thus explaining peaking coal power are schematically illustrated in Fig. 1. These can be broadly viewed from techno-economic, socio-technical and political perspectives [18]. In the techno-economic sphere, coal power production competes for the electricity market with other technologies. Though cost of producing electricity is a central factor in this competition, other attributes of competing technologies such as their environmental friendliness and convenience also play a role [19]. For example, as incomes rise, societal preferences shift from burning fossil fuels to more advanced forms of electricity production [20]. The competition can be particularly strong if **electricity demand** does not expand sufficiently fast to allow room for both simultaneous growth of coal and other technologies. In the socio-technical perspective, it is important that coal's competitors are usually emerging technologies (such as renewables, nuclear or natural gas requiring offshore explorations, fracking, long-distance pipelines or LNG infrastructure), which require state support, advanced technological capacities and innovation to grow. Literature on technology diffusion has shown that **high income** is an important factor predicting earlier and faster expansion of new complex technologies such as nuclear [21, 22], wind and solar power [23–25]. Furthermore, stronger democracy has been shown as favoring earlier uptake of modern renewables [25].

The final group of mechanisms that affect coal lock-in and destabilization involves the political action of the state [26, 27]. The state may be motivated to either keep or phase out coal based on such imperatives as ensuring secure supply–demand balance [28]. This motivation may be affected by the overall **import dependence** of the country and particularly its **dependence on imported coal.** States tend to be more concerned about energy security under increasing **electricity demand.** The state may also have other imperatives such as **climate protection**, increasing employment, ensuring fair energy prices, etc., but commitments to these imperatives are usually difficult to directly measure and compare across countries. The state can implement its energy goals by providing support (e.g. subsidies) or alternatively suppressing (e.g. through bans and taxes) certain energy technologies. An important factor of whether the state is capable of implementing its energy goals is the quality of its institutions [29] and its general economic capacity. State capacity has also been noted as a factor in coal decline in Brutschin, Schenuit [5] and Meckling and Nahm [30].

Thus, the evolution of a national coal power sector is shaped by market forces, technological developments, and policy actions. Market and political forces strongly interact. The coal sector is in particular likely to politically lobby for support and against any constraints on its activities [15, 31, 32]. The effectiveness of such lobbying efforts is affected by the **strength of the coal sector**. For example, a sector that includes both domestic coal mining and power generation might be stronger than the sector that consists only of power production based on imported coal. A coal sector with **younger** fleet of power plants will exhibit more resistance (due to the larger risk of stranded assets) than a sector with **aging power plants.** Another critical factor in the balance of state and market factors is the quality of the state institutions, particularly **democracy** and **transparency** (the ability to contain corruption) [5, 7, 8, 33]. The influence of interest groups should decrease as democracy increases and corruption decreases, and overcoming the resistance and lock-in of the coal sector should therefore become more likely as these factors change [11, 26].

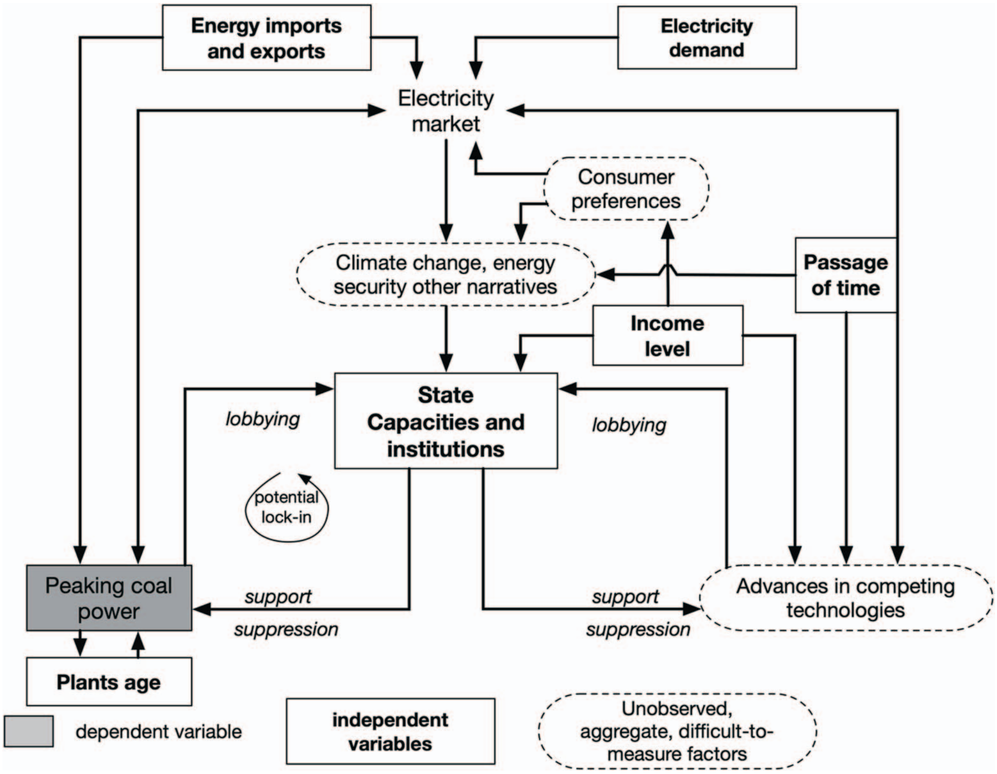

Figure 1. Mechanisms and factors of coal power lock-in and destabilization

This analysis allows us to identify hypotheses with respect to variables that may speed up or slow down destabilization of coal sector as summarized in Table 1.

Method

Calculating national coal power capacity

We record coal capacity based on the 'World Electric Power Plants Data Base' (WEPP) from S&P Global [35], which describes 14 035 units of coal-fired power plants, in 91 countries. We chose to use WEPP because this database has better coverage than other alternatives, such as Global Plant Tracker [36]. We consider only operative (8660) and retired (5375) units and exclude units that are planned or under construction. Since very few coal power plants are planned or constructed after coal capacity peaks, inclusion of such units does not affect our findings.[1]

The WEPP dataset lack start or retirement year for 19.6% of the units, which account for 5.1% of total global capacity. We brought the share of missing values down to 17.4% by (1) adding information for 87 units with high capacity, in countries with large shares of missing values (many in Germany); and (2) imputing data for 148 units in various countries where imputation was feasible (many in China). The second part of the procedure did not turn out to affect our measure of peak capacity much and our analyses therefore rely on extended WEPP data without imputation.[2]

National sample selection

Defining peaks of capacity and generation, and episodes of generation decline

Over the course of history, coal power **capacity** in a country can experience periods of growth or stagnation followed by periods of decline and new periods of growth. In our method, we seek to differentiate such transient local peaks of coal capacity from 'true' peaks, which occur at the highest level of capacity and are followed by at least 10% decline before the end of the time-series. For example, in South Africa capacity declined slightly between 1993 and 1994 before it continued to increase until the end of the end of the time-series (Fig. 2). We might therefore have perceived 1993 as the peak year, which would have been 'false'.[3] Thus, we code the absence of peak coal capacity in South Africa.

We code peaks in **generation** following the same method as for capacity. For example, in Japan, coal capacity has not peaked, but coal power generation decreased by 11.9% from 2015 and therefore we code a peak in generation. However, electricity generation from coal power significantly fluctuate (e.g. due to weather

[1] We have checked units that are planned, under construction and delayed after construction start, in countries that we eventually classify as cases of failed capacity. There are three planned units in Australia. Two of them are for a plant named Mount Piper, but these plans have been withdrawn. The third unit is planned for a plant named Shine Energy. The Shine Energy project is uncertain because it is still at the feasibility stage and the operating company does not have experience with coal power, but government officials have expressed support. The proposed 1 TW unit will contribute to a 3% increase in Australia's total coal capacity, compared to the current level of operating coal capacity. Another unit is planned in Finland, for a plant named Myllynummi, but this unit is only supposed to have a capacity of 60 MW (3% of operating capacity in 2020) [37]. GEM Wiki. *Mount Piper Power Station*. 2019 15.01.2021]; available from https://www.gem.wiki/Mount_Piper_Power_Station. GEM Wiki. (2020). *Collinsville (Shine Energy) power station*. Retrieved 04.03.2021 from https://www.gem.wiki/Collinsville_(Shine_Energy)_power_station

[2] The only difference between the imputed and non-imputed data is that capacity peaks in 1994 in Germany according to the imputed data and in 1995 according to the non-imputed data. The imputed and non-imputed capacity data correlate at 0.9999.

[3] False capacity peaks occur in Brazil (2013), Chile (2017) and Romania (2015), and false generation peaks occur in Kazakhstan (2013), South Korea (2018), Russia (2008), South Africa (2007), Sri Lanka (2017), Thailand (2013) and Turkey (2018).

Table 1. Hypotheses and independent variables

Hypothesis	Reasoning
Faster growth in electricity generation correlates negatively with the probability of peaking coal	Faster growth of electricity demand delays coal destabilization by making governments more concerned about security of supply and weakening the competition between coal and other technologies [18–20]
Increased dependence on imported coal correlates positively with the probability of peaking coal	Dependence on imported coal may speed up destabilization for energy security reasons while the presence of domestic coal strengthens the coal sector and perpetuates lock-in [7, 26–28]
Increased total energy import dependence correlates positively with the probability of peaking coal	Concerns over energy security may favor coal power as established mature technology [26–28]
Increased share of coal in total generation correlates negatively with the probability peaking coal	Larger coal sectors may be more difficult to destabilize [7, 15, 31, 32]
Increased age of power plant fleet correlates positively with the probability of peaking coal	Older power plant fleets are more likely to peak due to higher probability of power plant retirement [15, 31, 32]
Larger electricity generation correlates positively with the probability of peaking coal	Larger countries may have more capacities to destabilize coal sectors [34]
Increased GDP per capita correlates positively with the probability of peaking coal	High income stimulates public preferences for cleaner energy, makes it easier to develop competing technologies and increases the government capacity to mitigate negative consequences of phase-out through ‘just transition’ policies [21–25]
Decreased political corruption correlates positively with the probability of peaking coal	Corruption and lack of transparency may perpetuate lock-in by ensuring continuous support to the coal sector even after it is economically non-competitive [5, 7, 8, 11, 26, 33]
Stronger electoral democracy correlates positively with the probability of peaking coal	High quality of governance facilitates development of new technologies and transparent political debate about the future of coal [5, 7, 8, 11, 26, 33]
Time (year) correlates positively with the probability of peaking coal	With passage of time, competing technologies become more widely available and societies may get more concerned with the adverse effects of coal on climate and the environment [20]

Table 2. Descriptive statistics

	Obs	Mean	Std. Dev.	Min	Max
Peak capacity	1822	0.1	.1	0	1
Total generation, 5 yr growth (%)	1822	29.5	34.5	−69.1	690.5
Total generation, peak (100 TWh)	1822	5.2	12.6	0	71.3
Total generation, share of coal (%)	1822	36.4	27.1	0	164
Coal-based generation, share of imports (%)	1822	42.4	132.3	0	5377.3
Total generation, share of imports (%)	1822	26.6	28.8	0	305.4
GDP per capita (1000 USD)	1822	14.4	12.9	.3	52.7
Electoral democracy (0-100 scale)	1822	62.2	26.8	5.5	91.2
Political corruption (0-100 scale)	1822	60.6	27.9	2	96.6
Capacity-weighted mean age (years)	1822	16.5	9.3	1	47.9
Year	1822	30.6	14.4	1	55

Note: The year-variable that we include in our models ranges from the first to the last in-sample year, whereas the scale is relabeled in illustrations so that 1 = 1965 and 55 = 2019.

variation) and therefore we limit statistical analysis to peaking capacity.

Independent variables

Our independent variables are gathered by the Varieties of Democracy (V-dem) institute [38, 39][4], the World Bank [via the Standard Quality of Government dataset; 40][5], and the International Energy Agency [41][6]. The capacity weighted mean age of power plants is based on WEPP [35]. Descriptive statistics are available in Table 2.

[4] Electoral democracy and political corruption.
[5] GDP per capita.
[6] Total generation, 5-year growth in total generation, share of coal in total generation, share of imported fuels in total generation, share of imported fuel in coal-fired generation.

Results

Peak capacity, peak generation and significant generation decline episodes

We code 22 episodes of peaking coal capacity in the sample countries (Table A2). As shown in Fig. 2 and Fig. A1, peak capacity is always followed by or occurs concurrently with peaking generation and, in most cases, significant generation decline (as for example in Australia, Austria and Belgium). In several countries generation peaks and declines without a capacity peak, meaning that coal power plants generate less and less electricity without being actually retired. Most of such cases involve rather recent declines in generation (i.e. after 2010: Brazil, Bulgaria, Chile, Colombia, Israel, Japan, Mexico, Serbia). In these cases, capacity might peak in the future, which has precedence in cases like Germany, where 11 years passed between the beginning of

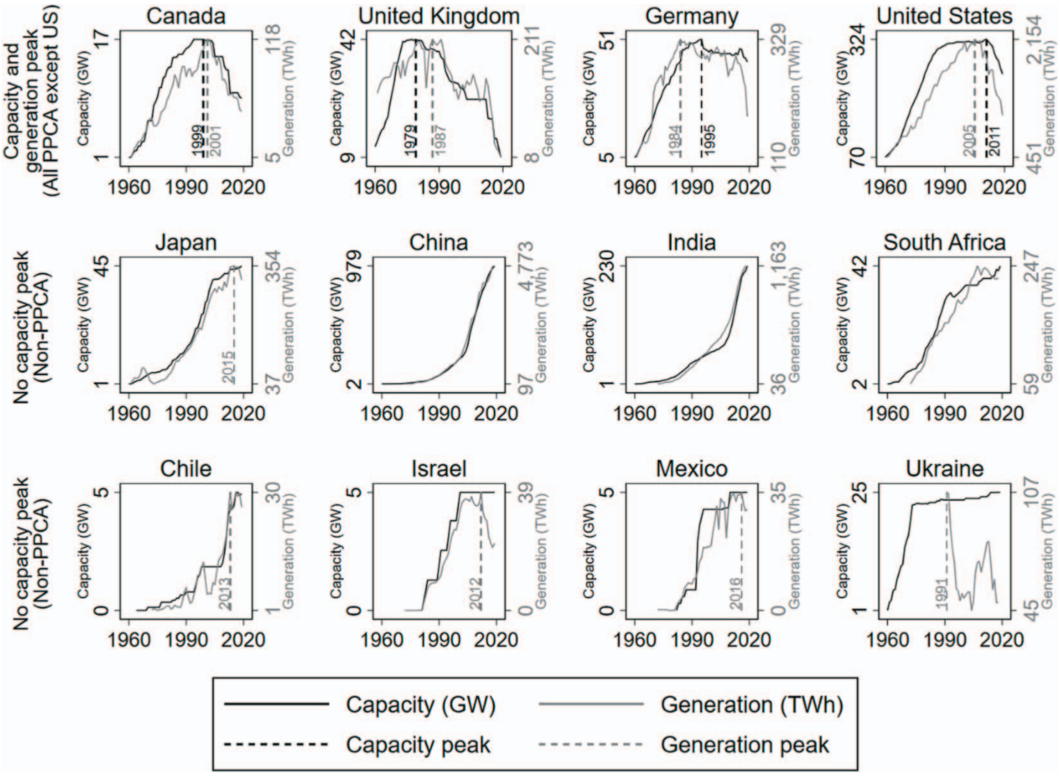

Figure 2. Coal capacity and generation (1960–2020) with peak capacity and generation indicated, selected countries. *Note*: Fig. A1 in the Appendix provides the same information for all sample countries. The key statistics underlying Fig. 2 and Fig. A1 are reported in Table A1 in the Appendix.

generation decline and peaking capacity. Generation decline not accompanied by peaking capacity also occurs when they coincide with war or radical regime change (Colombia, Mexico, Ukraine, Uzbekistan). In this case demand for electricity rapidly drops but power plants are not necessarily retired.

Besides generation decline in recent years or during the crises, there are only three countries where coal-based electricity generation peaked and declined but the installed capacity did not peak: Poland (generation peak in 2006), Romania (2007) and Zimbabwe (1991). The Zimbabwean case is more understandable since the generation decline is less pronounced and capacity did not increase after generation peaked. Moreover, the capacity weighted mean age of coal units in Zimbabwe was 9 years at the time of peaking generation and we should not expect so young power plants to retire even if they stopped generating. Romania and Poland are more remarkable cases, as coal power capacity remained stable in Romania despite massive generation decline (from 25 TWh in 2011 to 16 TWh in 2018), and coal power capacity in Poland even increased (from 31 GW in 2015 to 34 GW in 2019) despite considerable generation decline. The age of coal power plants in Poland and Romania were not lower than in other countries where capacity peaked (Romania: 28 years; Poland: 29 years; other peak cases after 2000: 27 years). Thus, it seems that coal power is especially locked-in in these countries. We will soon examine if the high share of coal in Poland (99% at peak) and lower anti-corruption in Romania (28) and Zimbabwe (18)[7] may explain this lock-in.

Peaking coal capacity and the membership in the PPCA

The members of the PPCA (formed in 2016) currently include 47 countries that have pledged to phase out unabated coal power. Do these pledges precede or immediately follow peaking call capacity? Nineteen of the PPCA members do not operate any coal power plants or operate only the small ones.[8] Figure 3 shows that in countries with considerable coal sectors, PPCA membership and peaking coal capacity strongly overlap. Most of the capacity peaks (18 of 21) have occurred among PPCA members and most of the PPCA members have experienced peaking coal capacity (18 of 21). The direction of causality of this relationship may be inferred from the timing of peak capacity: over 90% of PPCA countries experienced peak coal at least 5 years before joining the alliance; 75%, at least 10 years before; and 50%, at least 20 years before. Yet, this does not mean that the PPCA is without purpose—the organization may contribute to consolidating and accelerating phase out processes even if does not contribute to the initiation of phaseout, and it may contribute to initiation in the future if they attract new members where coal is not already declining [see 8].

There are five PPCA member countries where coal power capacity has not yet peaked: Israel, Mexico, Chile, Montenegro and Ukraine. Israel used to have its power supply entirely dominated by imported coal, but that started to change with the discovery of domestic gas reserves in the early 2000s. Since then its coal power generation has steadily declined, but its two coal power plants with nameplate capacity 2.25 GW each are still considered

[7] The mean corruption score among peak cases after 2000 was 83.

[8] Albania, Angola, Costa Rica, Croatia, El Salvador, Ethiopia, Fiji, Latvia, Liechtenstein, Lithuania, Luxembourg, Marshall Islands, North Macedonia, Peru, Senegal, Switzerland, Tuvalu, Uruguay and Vanuatu.

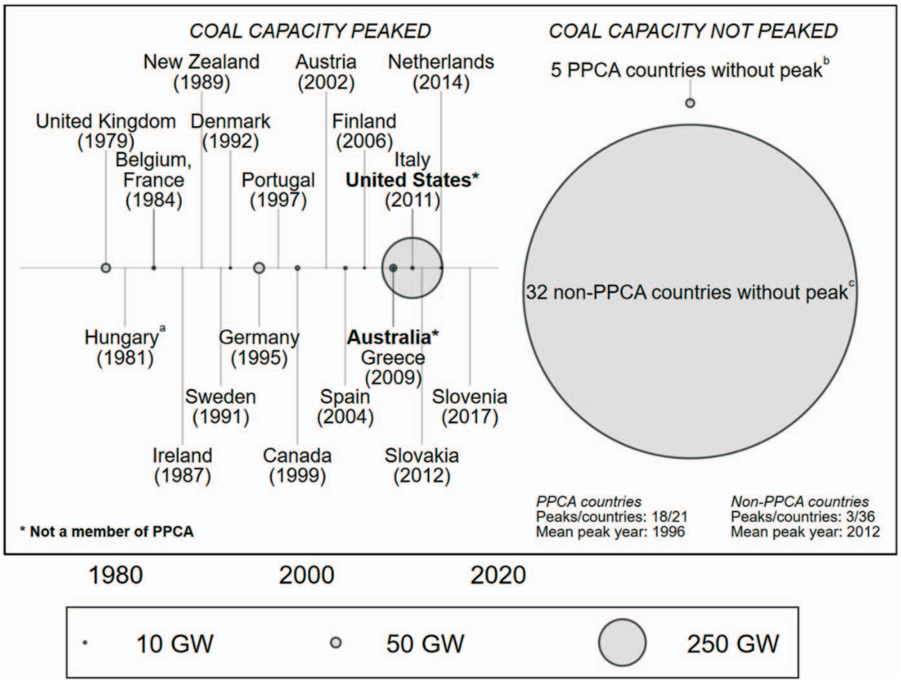

Figure 3. Distribution of peak capacity over time and countries with and without PPCA membership. [a]Hungary is excluded from the regression analysis because of missing data. [b]Chile, Israel, Mexico, Montenegro, Ukraine. [c]Argentina, Bosnia and Herzegovina, Botswana, Brazil, Bulgaria, Cambodia, China, Colombia, Guatemala, India, Indonesia, Japan, Kazakhstan, Korea, South, Laos, Malaysia, Mongolia, Morocco, Philippines, Poland, Romania, Russia, Serbia, South Africa, Sri Lanka, Thailand, Turkey, Uzbekistan, Vietnam, Zimbabwe.

too young to retire (one was built in the early 1980s and the other between 1990 and 2000). Israel pledged to stop its coal power generation (possibly by converting its coal power plants to gas) by 2025. It is thus unlikely that PPCA has significantly affected the imminent peak of coal power in Israel. Mexico does not specify a date for its coal phase-out. Chile has coal phase-out date set for 2040, although in Glasgow it promised to 'bring it forward'. Ukraine, that has recently experienced difficulties with importing Russian coal for its power sector, declared 2035 as the phase-out date for the state-owned coal power plants and its biggest operator declared 2040 as the coal phase-out date. Montenegro pledged retiring its only coal power plant that provides 40% of electricity in the country by 2035.

There are only two countries—Australia and the United States—where coal power capacity has peaked but did not join the PPCA. This might be due to both political considerations in these countries, or their high heterogeneity, with some regions very heavily dependent on coal.

When and where does coal power capacity peak?

It would be reasonable to assume that the cases of peaking coal power become more frequent over time due to increasing concerns over adverse effects of coal use as well as wider availability of substitutes. However, Fig. 3 shows that starting from around 1980, the cases of peaking coal power are relatively evenly distributed over time with four to five cases occurring in each of the four decades: the 1980s, 1990s, 00s, and 2010s. Yet, it is difficult to eyeball the functional form of time's correlation with capacity peaks since our sample is unbalanced.[9] To better understand the relationship between time and peak capacity, we conduct regression analyses with non-parametric, linear, squared and cubic functions of time (Table A4), which shows that the probability of peaking coal power after 1980 changes little over time, and that the linear function fits the data reasonably well. We have therefore used a linear function of time in our regression models, and we have estimated these models with the complementary log–log link function, which is appropriate for discrete time-event data [42, 43].

Table 3 presents regression models where we examine how different characteristics of energy systems, and political and economic development relate to capacity peaks. The different models in this table include GDP per capita, political corruption and electoral democracy separately due to high correlation between the variables (Model 1, 2, 4; Model 6 includes neither of these three predictors) (Table A3).[10] Model 3 accounts for a curvilinear relationship between the share of coal in electricity production and capacity peak, and Model 5 considers an interaction between the share of coal in electricity production and the share of imported coal.[11]

9 The number of observations per year varies from 35 to 55, or from 8 to 39 excluding (censored) post-peak observations.

10 Correlations: GDP per capita – political corruption (.75); GDP per capita – electoral democracy (.68); political corruption – electoral democracy (.7). See also the correlation matrix in Figure A2 and the variance inflation factors in Table A3. Figure A2 shows that the correlation between 5-year growth of total generation and capacity-weighted mean years of coal power units correlate above 0.5, and that capacity-weighted mean years correlates above 0.5 with year. We have therefore run robustness tests where we examine the effect of 5-year growth of total generation without controlling for capacity-weighted mean years (not included in the paper; excluding capacity-weighted mean years does not affect the 5-year growth of total generation coefficient or standard error much), and we interpret effects of capacity-weighted mean years and year with caution. All VIF scores are acceptable (i.e. below 2).

11 We include the square of coal share in Model 3 to achieve an acceptable link-test result, and we examine the interaction between coal share and share of imports in coal because it is plausible that a domestic coal industry exerts more influence than a foreign based one (we examined the interaction with GDP per capita and Electoral democracy as control variables as well, but we only present the strongest result, which we achieved with Political corruption as the control variable).

Table 3. Results of the regression analysis

	(1) b/se	(2) b/se	(3) b/se	(4) b/se	(5) b/se	(6) b/se
Total generation, 5 yr growth (%)	0.96***	0.92***	0.92***	0.94***	0.94***	0.97***
	(0.01)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)
Total generation, peak (100 TWh)	0.94**	0.97*	0.97**	0.97*	0.97**	1.00
	(0.02)	(0.01)	(0.01)	(0.02)	(0.02)	(0.02)
Total generation, share of coal (%)	0.99	0.97***	1.00	0.98**	0.97***	0.99
	(0.01)	(0.01)	(0.04)	(0.01)	(0.01)	(0.01)
Coal-based generation, share of imports (%)	0.99*	0.98***	0.99*	0.99	0.98**	1.00
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)
Total generation, share of imports (%)	1.01	1.02**	1.01	1.01	1.00	1.01
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Capacity-weighted mean age (years)	1.04	0.99	0.99	1.05	1.05	1.04
	(0.06)	(0.03)	(0.03)	(0.05)	(0.05)	(0.04)
Year	0.99	1.03	1.02	1.03	1.03	0.99
	(0.04)	(0.02)	(0.03)	(0.03)	(0.03)	(0.02)
GDP per capita (1000 USD)	1.11***					
	(0.02)					
Electoral democracy (0-100 scale)		1.39***	1.38***			
		(0.13)	(0.13)			
Political corruption (0-100 scale)				1.10***	1.10***	
				(0.02)	(0.02)	
Total generation, share of coal (%) # Total generation, share of coal (%)			1.00			
			(0.00)			
Total generation, share of coal (%) # Coal-based generation, share of imports (%)					1.00**	
					(0.00)	
Constant	0.00***	0.00***	0.00***	0.00***	0.00***	0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)
AIC	185	175	176	182	182	220
BIC	235	225	231	231	237	264
HL-test	0.14	0.78	0.12	0.22	0.11	1.21
Link-test	0.94	1.01**	1.01*	0.92	0.93	0.47**
N	1822	1822	1822	1822	1822	1822

*$P < 0.1$, **$P < 0.05$, ***$P < 0.01$. *Note*: Complementary log–log regression models of capacity failure; Exponentiated coefficients; Robust standard errors in parentheses show goodness-of-fit test; Link-test = Tukey's goodness-of-link test (adapted to account for robust standard errors).

The probability of peaking coal capacity decreases under faster electricity demand growth and it is lower in countries with larger electricity generation. The probability, moreover, increases when GDP per capita, freedom from political corruption, and electoral democracy increases.

Models 1–5 in Table 3 indicate that the probability of capacity peak decreases by 3–6% when the size of electricity system (at its historic maximum) increases by 100 TWh. In some models, the share of coal in total electricity generation and share of imports in coal-based generation also lowers the probability of peaking coal capacity, whereas the share of imports in total generation has the opposite effect, at statistically significant levels. Further robustness tests, however, indicate that these effects are highly sensitive to model specifications and thus can be attributed to suppression (see Table A8). Moreover, we do not find significant effects of the capacity-weighted mean age of power plant units or year.

Figure 4 illustrates how the predicted probabilities of capacity peaks change when the key independent variables change by one standard deviation and all other variables are held constant at mean values.[12]

- A one standard deviation increase from Slovenia's to New Zealand's levels of GDP per capita, for instance, increases the probability of capacity peak from 1.2% to 4.9%.
- The probability of capacity peaks only increases substantially when the levels of independent variables exceed the mean (e.g. the probability of capacity peaks differs little between low and low-middle income countries, but it is substantially higher in high income compared to high-middle income countries). Similar non-linear effects are observed for electricity demand growth, electoral democracy and political corruption.
- Based on the predicted probabilities at one standard deviation above the mean (below the mean for demand growth), electoral democracy exerts the largest effect (3.9% probability of peak), followed by political corruption (2.8%), electricity demand growth (2.1%) and GDP per capita (1.2%).

[12] Country names indicate countries that are most similar to respective values in year 2018 (e.g. Sri Lanka was the country that ranked closest to the mean of electoral democracy in 2018 (mean and standard deviation values are calculated across all country-years). The asterisk (∗) designates the closest country match that differs by 10% or more from the relevant value (e.g. one standard deviations above the mean of total generation, 5 yr growth is 64.0, and the closest country match is Laos where the variable equaled 75.8). The two top panels are based on Model 1, the bottom-left panel is based on Model 2, and the bottom-right panel is based on Model 4, Table 4. 'Mean + 2∗SD' is omitted for Electoral democracy and Political corruption because these values are outside the scale and therefore less relevant (e.g. two standard deviations above the mean of Political corruption equal s 116.4, whereas the scale goes from 0 to 100), and because the predicted values at these levels of Electoral democracy and Political corruption are very high and very uncertain (i.e. unsuitable for graphical illustration).

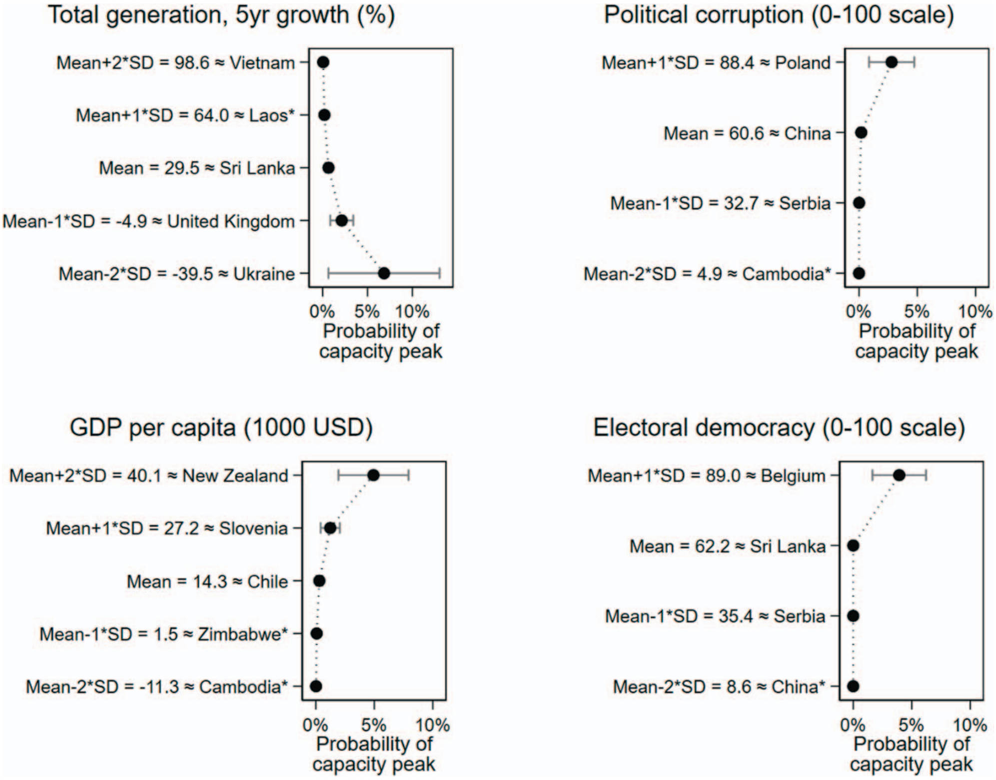

Figure 4. Predicted probabilities of coal peak at standard deviations around mean of respective variables. *Note*: The figure illustrates effects of all variables that have robust, significant effects according to the models in Table 4, except for *Total electricity generation* since this variable fails certain robustness tests (see Table A8 and Table A9). The predicted probabilities of peaking coal capacity are calculated with all variables except one held constant at their respective mean values.

In terms of AIC and BIC, the models with electoral democracy (2, 3) perform slightly better than the ones with GDP per capita (1) and political corruption (4, 5), but all these models perform well compared to a model without GDP per capita, electoral democracy and political corruption (6). The three mentioned predictors are also interrelated and it is therefore difficult to disentangle their individual importance. Our takeaway from this is thus that 'development' is important for peaking coal but further research is required to single out the most important development traits.

Note also that the results in Table 3 indicate that the share of imports in coal-based generation might moderate the effect of share of coal in total generation (Model 5) and that the effect of the latter variable might be curvilinear (Model 3). We examined the moderation effect because we thought that a large domestic coal industry would be more resilient than a large import dependent coal industry, and we examined the curvilinear effect because we were surprised by the null-effect of coal share and we wanted to check if changes at high or low levels of this variable matter for peaking coal. Additional testing, however, shows that the significance of the moderation effect in Model 5 depends on suppression (see Table A7)—and although the curvilinear specification in Model 3 provides an acceptable link-test result, the interaction term is only significant at the 10% level, not necessary with regard to the HL-test, and it worsens the model fit in terms of combined AIC and BIC values. We therefore reject the hypothesized moderated and curvilinear effects, and we will treat Model 1, 2 and 4 as our main models.

Robustness of regression analysis

To examine the robustness of our results, we estimate models that only include year and one other independent variable (Table A8), with fixed country effects, outliers excluded, additional control variables, and excluding forthcoming PPCA countries without peaking coal (Table A9). Table A8 shows that the significance of peak generation and coal share's effects depend on suppression, whereas the significance of other effects do not. Table A9 shows that the effect of political corruption is perhaps not robust to country fixed effects (only significant at the 10% level), whereas the other variables are.[13]

We also consider whether the effects vary over time (i.e. interactions between independent variables and functions of time) but this analysis is uncertain because the sample changes over time (i.e. countries entering and exiting the sample in specific years) (see Table A5). We found one significant time-varying effect—the effect of electricity demand growth stagnates over time—but the interaction with time decreases the model fit and the stagnation is due to several Eastern European and post-Soviet countries entering the sample in the 1990s with very low values 5-year generation growth.[14,15] Moreover, demand growth seems

[13] Fixed effects estimation excludes all countries where peak does not occur, and the results might therefore not be generalizable. Moreover, we exclude 5-year generation growth from fixed effects models that include GDP per capita or Electoral democracy—due to high within-country correlation. The effect of total generation peaks is not estimable with country fixed effects since peak levels are time constant.

[14] Mean 5-year generation growth among in-sample Eastern European and post-Soviet countries during the 1990s: −6.8% (mean value between 1990 and 1995: −15.5%). Mean 5-year generation growth among all in-sample countries during the 1990s: 24.7% (mean value between 1990 and 1995: 25.0%).

[15] One can also argue that we should impose a statistical penalty when we test multiple hypotheses (interactions with linear, log, square, and cubic functions of time), such as Bonferroni adjusted standard errors, and the significance time's interaction with 5-year generation growth vanishes if we do (p-value in collective Wald test of interaction terms: 0.022; adjusted threshold: 0.05/4 = 0.013).

to matter for capacity peaks among Eastern European and post-Soviet countries since demand growth was relatively low when capacity peaked in Slovakia (−3.0%) and Slovenia (7.2%) (the only such countries where capacity has peaked). The time-decaying effect therefore seems to be an artifact of lacking capacity to transform the energy sector in the years after the Soviet and Yugoslav collapses, which happens to coincide with very low levels of demand growth. Altogether, we argue that these results, as well as the limited effect of time itself, indicate that the importance of respective conditions for coal phase-out remain stable over time.

Most of the energy variables exert weak and non-significant effects on capacity peaks, but it is possible that they exert large effects in interaction with each other. Unfortunately, we do not have sufficient data to examine all such interactions. We have therefore reduced the set of independent variables to a few principal component factors to perform this analysis (see Table A6 and Table A7). The energy variables are reduced to two factors, A and B, where A is closest related to 5-year generation growth and capacity-weighted mean age, and B is closest related to the share of coal and share of imports in total generation. GDP per capita, political corruption, and electoral democracy are reduced to one ('development') factor that is almost equally related to each of the latent variables. Regression models based on these factors indicate no significant interactions between energy factors, and the development factor exerts much larger effect on capacity peaks than the energy factors do.

Discussion

Our analysis identifies the overall pattern of peaking coal power, represented in the left pane of Fig. 4. The first country where coal capacity peaked was the United Kingdom in 1979. Since then, coal power peaked in 20 countries, almost equally distributed over the three decades between 1980 and 2010 with the three last cases in 2012, 2014 and 2017. Peaking coal capacity was almost universally followed by decline in coal generation (and by extension – greenhouse gas emissions) (Fig. A1). Moreover, peak capacity universally preceded or co-occurred with **significant** episodes of coal generation decline as defined by Vinichenko, Cherp [34], where coal power declines by more than 5% of the total electricity supply over a decade (Fig. A1).

The literature most commonly mentions two drivers of this decline: the ascend of competing technologies and increasing concerns about environmental and climate impacts of burning coal [18, 19]. Several competing technologies advanced over these decades replacing coal for example nuclear power in in France, gas in the UK and the US, and wind power in the UK and Germany [34].

Our findings provide two important qualifications to this argument. First, while the substituting technologies were available worldwide, coal peaked only in a relatively limited number of countries. This means that advantages of new technologies could only be leveraged in specific socio-economic and political contexts. Secondly, different competing technologies expanded at different periods of time: nuclear power in the 1980s, North Sea gas deposits in the 1990s, shale gas fracking and wind power starting after 2000, and solar power starting after 2010. Yet the number of episodes of peaking coal capacity did not change from one decade to another, eventually decreasing by the late 2010s. This sends the same signal that it is not only the availability of a better technology but also the national conditions that enable peaking coal power.

Peaking coal power may also be caused by the advance of environmental and climate concerns. Indeed, the first cases of peaking coal in Europe coincide with increasing concerns about acid rain in the 1970s. However, the immediate decade following the prominence of such concerns (the 1980s) saw only four cases of peaking coal power. With respect to the climate concerns, the evidence that they were a significant factor is hard to establish. There was no acceleration of peaking coal capacity cases either following the signing of the UNFCCC in 1992, the signing of the Kyoto protocol in 1996 or in the last decade when concerns over climate change have intensified and peaking coal capacity cases slowed down. In fact, about one-half of peaking coal cases occurred before the Kyoto protocol and there was not a single case of peaking coal capacity between the Paris Agreement and 2019 (when our time-series end).

At the same time, the Paris Agreement was followed by the establishment of the PPCA, an international climate compact specifically targeting coal power. Our analysis of the relationship between PPCA accession and peaking coal capacity provide a useful insight into the interplay of climate concerns and peaking coal.

We show that nearly all countries where coal has peaked have also joined the PPCA. This signals that the governments of these countries are motivated to phase out coal and it does not rule out that their motivation has been there for years or even decades preceding the formal establishment of the PPCA. This might be one more evidence of a strong connection between coal phase-out and government policies, as also noted in previous qualitative studies [5, 16, 32]. However, this connection may not be one-way and is likely to be confounded by other factors. As we show, in nearly all PPCA countries coal capacity had already peaked, in most cases decades before PPCA was announced. It means that PPCA pledges per se could not be a cause of coal power decline, but rather articulate ongoing processes. As with PPCA, it seems that while all countries with peaking coal are likely to have coal-removal policies, what sets these countries aside are immutable socio-economic and institutional features which enable such policies. We identify three such features: high GDP per capita, slower electricity demand growth and strong electoral democracy going hand in hand with low corruption. We also contribute to understanding to how countries go from what Steckel and Jakob [26] call 'established' coal regimes to coal 'phase-out'.

Higher GDP per capita shapes preferences for cleaner and more advanced forms of energy [20] as well as makes clean energy affordable even if it initially costs more than coal. Wealthier countries also usually lead technology developments be it nuclear [22], offshore oil and gas drilling, fracking, or solar and wind power [25], which speeds up the use of coal power alternatives. Slower electricity demand growth eases energy security concerns, removes the pressure of building more and more of coal power plants, and allows to introduce alternatives at a more relaxed pace after peak coal. Finally, electoral democracy reduces the risk of coal lock-in where the sector persist and expands even beyond the point when it is economically and socially viable.

Figure 5 shows that our models accurately describe the historic developments. Using the statistical models in Table 3, we can calculate a probability of coal peaking in a particular country. We consider such a probability high if it is above 5% in a particular year[16], which translates into ≈20% over 5 years and ≈40% over 10 years. The left pane of Fig. 5 uses different grey tones to display the calculated probability of coal peaking in all countries in the

16 The mean probability of peaking coal in country-years with observed coal peak is 7.1% (standard deviation: 5.4%p).

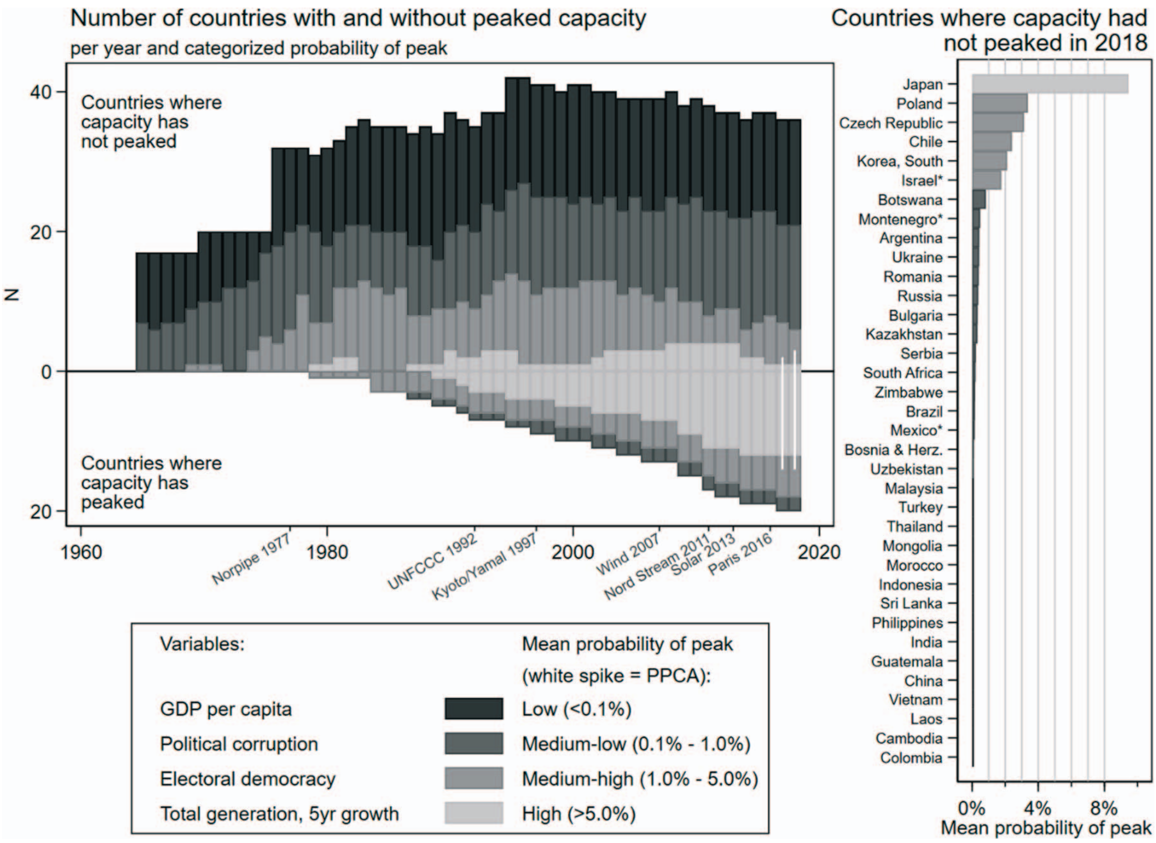

Figure 5. Estimated probabilities of capacity peak by year in countries with and without peak coal. *Note*: Left pane shows a number of countries in the sample before peaking coal capacity (above the horizontal axis) and after peaking coal capacity (under the axis) for each year between 1965 and 2018. Different colors denote the probability of particular countries to peak in a given year based on the row-mean of predicted probabilities from Models 1, 2, and 4, in Table 3. Right pane depicts the annual probability of peaking in a non-peaked countries in 2018. Year 2019 is excluded from the illustration due to incomplete data, which makes the illustration difficult to interpret, but this year is included in the models underlying the illustration.

sample in any given year between 1965 and 2018. It also shows in which countries coal capacity has actually peaked (by displaying the number of such countries under the horizontal axis). The figure illustrates that calculated probabilities of peaking coal capacity generally reflect the observed pattern of coal capacity peaks. In most of the countries where the capacity peaked, the annual probability of peaking exceeds 5% and, in contrast, in the majority of the countries where coal capacity has not peaked the probability of peaking is less than 1%. Only in one such country (Japan) does it exceed 5% (see the right pane of Fig. 5). Over time the countries where the probability of peaks exceeded 5% have already peaked (or peaked soon thereafter). Although the number of countries with high probability of peak coal is slightly lower in the final years of the time-series, it has been fairly stable since the late 1980s. The number of countries with medium-high probability of peak coal declined from 11 in 2000 to 5 in 2019.

Conclusions

Peaking coal capacity is a precondition for a rapid and substantial decline in the use of coal, which is, in turn, necessary for reaching climate targets. Our paper strengthens this point by showing that peaking capacity strongly correlates with decreasing use of coal in electricity generation. Moreover, and less expected, we show that the political pledges to phase out unabated coal follow rather than precede peaking of coal capacity, sometimes with a lag of a decade or more. We show that historically coal power peaked in wealthy democracies with slow electricity demand growth. Although advances in competing technologies such as nuclear, natural gas and renewable power as well as environmental and climate concerns have likely affected peaking coal capacity, we did not find direct evidence that these factors can explain why coal peaked in some countries but not in others. Moreover, the rise and fall of different competing technologies and climate and environmental concerns over time did not affect the frequency of peak coal capacity episodes, which remained relatively constant between 1980 and 2010 and subsequently declined.

By investigating the historical patterns of peaking coal capacity, our paper advances the understanding of the prospects of world-wide peaking coal capacity. First of all, since most countries with peaked coal capacity joined the PPCA, the fate of coal in these countries is most likely sealed, but as shown previously [7], these countries make up only a small portion of the global coal fleet, which has recently been increasing [8]. Beyond this group, Japan is the only wealthy democracy with declining electricity demand and considerable coal power use, which in part explains why the episodes of peaking coal capacity have recently become rare (Fig. 4, right pane). Japan has not yet made a pledge to phase-out coal power, which confirms our finding that peak coal is a pre-condition for a phase-out pledge even in an advanced economy. Beyond this country, the prospects of imminently peaking coal capacity are much less certain as none of the major coal powers where coal has not yet peaked has the right preconditions.

There are several unfolding trends that can make peaking coal capacity more likely. First, there are obvious advances in wind and solar power, which are now expanding in both developed countries and in emerging markets. However, Cherp, Vinichenko [25] show that the maximum rates of these expansions are still slower than electricity demand growth in most emerging economies. Moreover, the same study finds that the maximum growth rates of wind and solar power are not higher in countries that introduce these sources later, i.e. it is not likely to increase as this technology diffuses to more developing countries. This means that any of these sources on its own is unlikely to trigger peaking coal capacity in developing countries. It is still possible, that together these technologies aided by carbon capture and storage and possibly nuclear power and natural gas may start replacing coal if deployed in a coherent manner. In addition, slowing electricity demand growth, increasing the income levels and advances in functioning democratic governance that can counteract corruption and lock-in could markedly increase the probability of coal peak.

The results that we provide in this paper add reasons to be worried about the recent global decline in democracy and long-term increases in corruption [44; see also Fig. A3]. These changes are not only devastating in their own rights, for the people that are experiencing them. They are also damaging the prospects for coal phase out and achievement of climate targets, which has global ramifications. Our results therefore amplify already urgent calls for democratic reform and anti-corruption around the world, while cautioning against techno-optimism. Technological and market development will likely need to be supplemented by strong policies to trigger worldwide peak coal, but we do not expect this to happen in states with poor mechanisms for accountability and transparency.

Further research can provide more informative and confident findings by examining the effects of political regulations such as the EU ETS and national emission standards as well as carbon prices and bilateral energy cooperation [45]. Our conclusions will be strengthened if effective regulations only occur under ideal circumstances, in wealthy well-functioning democracies where coal has become uncompetitive and unreliable, and other findings can provide valuable nuances. This might be feasible with Sommerer and Lim's [46] extension of the ENVIPOLCON data [47, 48]. Further research should also consider design-based methods for causal inference, potentially leveraging external shocks to energy supply, economic and political performance to validate the correlational evidence in our analysis. Such research designs may be feasible with cases related to the Russian invasion of Ukraine and the following interruptions in Russian gas exports to Europe.

SUPPLEMENTARY DATA

Supplementary data are available at *Oxford Open Energy* online.

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CONFLICTS OF INTEREST

All authors declare that they have no conflicts of interest.

AUTHOR CONTRIBUTIONS

O.M.L., J.J. and A.C. jointly conceived and designed the study as well as wrote and revised the paper. O.M.L. carried out most of quantitative analysis.

DATA AVAILABILITY

Some of the data underlying this article were provided by S&P Global and International Energy Agency under licence. This data can only be shared on request to the corresponding author with permission of S&P Global and International Energy Agency. The remaining underlying data are available on request to the corresponding author. Note, however, that neither of the analyses is replicable without data from S&P Global and several analyses require data from the International Energy Agency.

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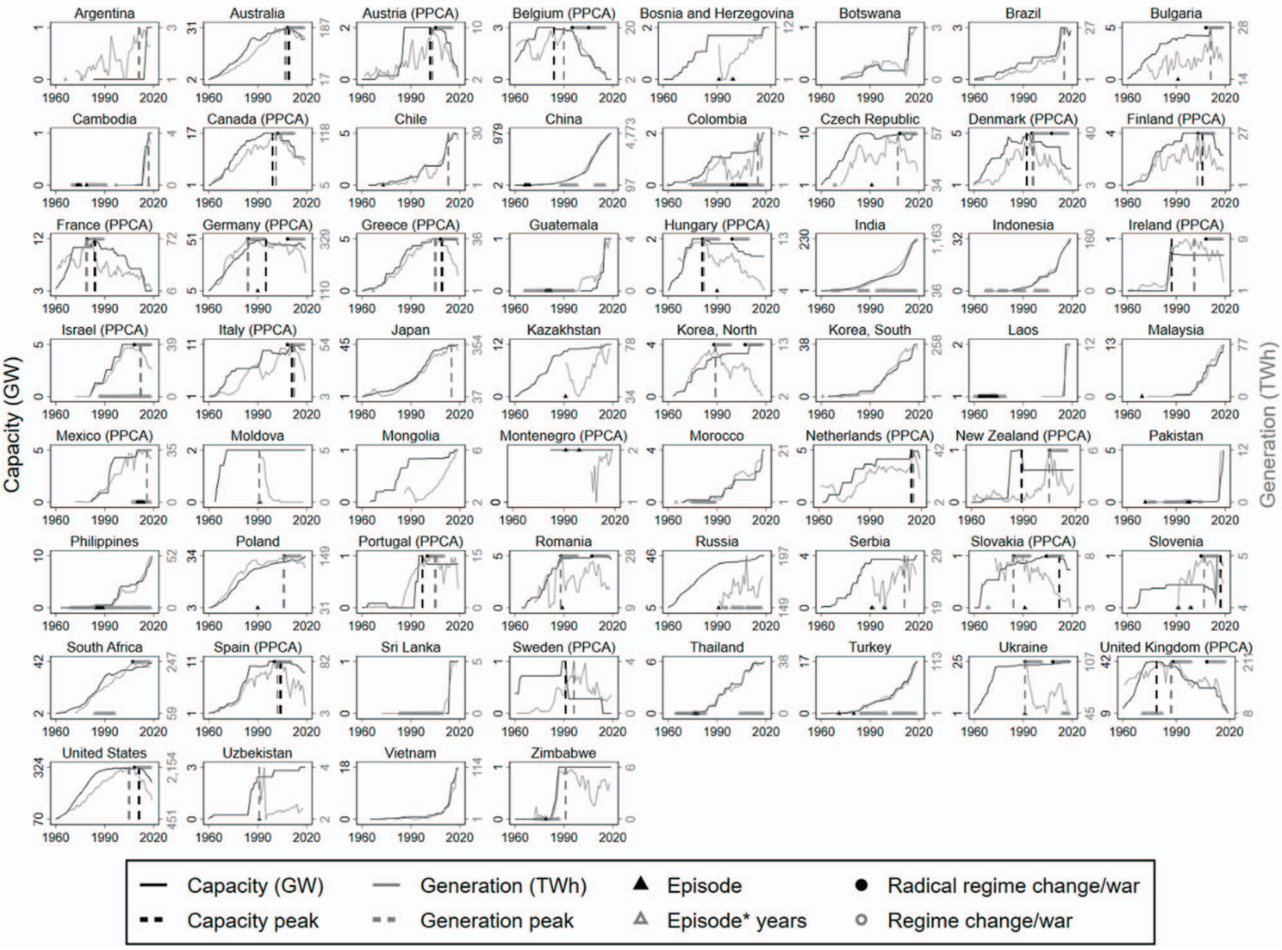

Figure A1. Coal capacity and generation 1960-2020, peak capacity and generation and crisis events (all countries with available data and significant coal sectors). Note: Key statistics underlying this table are reported in Table A1. Episodes (5% < decline in coal-based generation over a decade) are indicated at the top of the y-axes [34], and regime change/war at the bottom. The data for war and radical regime change is from [49], and we have marked events with average magnitude above 3 with dark shade. Capacity and generation peaks overlap (partially) in Australia, Austria, Hungary, Italy, and the Netherlands.

	Total generation, 5yr growth	Total generation, peak	Total generation, share of coal	Coal-based generation, share of imports	Total generation, share of imports	GDP per capita	Political corruption	Electoral democracy	Capacity-weighted mean age
Total generation, 5yr growth									
Total generation, peak	0.072								
Total generation, share of coal	-0.062	0.196							
Coal-based generation, share of imports	-0.023	-0.071	-0.153						
Total generation, share of imports	0.100	-0.184	-0.157	0.389					
GDP per capita	-0.215	0.038	-0.033	0.089	0.205				
Political corruption	-0.076	0.085	0.121	0.056	0.177	0.732			
Electoral democracy	-0.255	-0.163	0.069	0.084	0.123	0.656	0.694		
Capacity-weighted mean age	-0.471	-0.101	0.118	-0.027	-0.260	0.106	-0.077	0.168	
Year	-0.305	-0.025	0.168	0.049	-0.108	-0.159	-0.418	-0.082	0.512

Figure A2. Correlation matrix

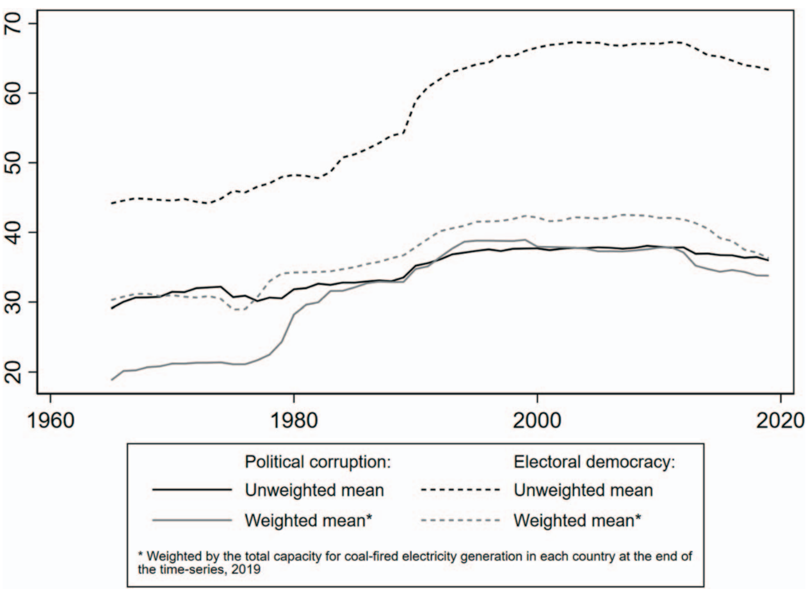

Figure A3. Global mean time-series of democracy and corruptions, restricted to the countries in our sample and weighted by recent coal capacity