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Jewell, J., Vinichenko, V., Nacke, L. et al (2019). Prospects for powering past coal. Nature Climate Change, 9: 592-597. http://dx.doi.org/10.1038/s41558-019-0509-6

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Jewell, J., Vinichenko, V., Nacke, L. and Cherp, A. Prospects for powering past coal. *Nat. Clim. Chang.* **9,** 592–597 (2019).
https://doi.org/10.1038/s41558-019-0509-6
Published version: https://www.nature.com/articles/s41558-019-0509-6

Prospects for powering past coal

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To keep global warming below 1.5°C, unabated coal power should significantly decline by 2030[1,2] and in most scenarios cease by 2050[1,3]. The members of the Powering Past Coal Alliance (PPCA), launched in 2017 at the UNFCCC Conference of the Parties, commit to "phasing out existing unabated coal power generation and a moratorium on new coal power generation without operational carbon capture and storage"[4]. The Alliance has been hailed as a "political watershed"[5] and a new "anti-fossil fuel norm"[6]. Here we estimate that the premature retirement of power plants pledged by PPCA members would cut 1.6 $GtCO_2$, which is 150 times smaller than globally committed emissions from existing coal power plants. We also investigate the prospect of major coal consumers joining the Alliance by systematically comparing PPCA members to non-members. PPCA members extract and use less coal and have older power plants, but this alone does not fully explain their pledges to phase-out coal power. In addition, the members of the Alliance are wealthier and have more transparent and independent governments. Thus, what sets them aside from major coal consumers such as China and India are both the smaller costs of coal phase-out and the higher capacity to bear these costs.

The PPCA includes 30 national and 22 subnational jurisdictions and covers 4.4% of the global coal capacity. Twenty-four PPCA members do not operate coal power plants nor have they built new power plants since the early 2000s. Two other PPCA members, Belgium and Scotland phased-out coal power already in 2016. We find that most PPCA members pledge to retire coal plants when their average age approaches the average coal plants lifetimes and that these pledges are in line with recent trends (Table 1, Supplementary Figure 1). Moreover, the number of newly constructed coal power plants in PPCA countries have declined since 1990 (Supplementary Figure 2) and several PPCA members planned to phase-out coal power already before the launch of the Alliance[7–11]. The Netherlands is a clear outlier to this trend with a pledge to retire three coal plants commissioned in 2015[12].

How many coal power plants would be retired prematurely as a result of PPCA pledges depends on the assumed plant lifetimes. Since the lifetimes have been recently rising (Supplementary Figure 3), for our reference estimate we use national average lifetimes since 2000 (Table 1). Given these lifetimes, the PPCA pledges would lead to premature retirement of 46% of coal power plants in PPCA members or 2% of the global coal power capacity.

Emissions avoided as a result of premature retirement depend on assumed plant lifetimes, emission factors, efficiencies and load factors, as well as on what substitutes coal power. Under our reference estimate, which assumes national average lifetimes and load factors, technology-specific efficiencies (Methods) and zero-emission substitution, PPCA pledges result in 1.6 $GtCO_2$ avoided emissions between 2019 and 2050. Over 70% of the avoided emissions are in four countries: Italy, the Netherlands, Israel and Canada (Supplementary Table 1). Italy, the Netherlands, Israel and Hawaii are the only four jurisdictions where the cumulative avoided emissions are larger than their current annual CO_2 emissions. Beyond 2050, the PPCA pledges would result in an additional 0.1 $GtCO_2$ of avoided emissions concentrated in South Chungcheong, South Korea.

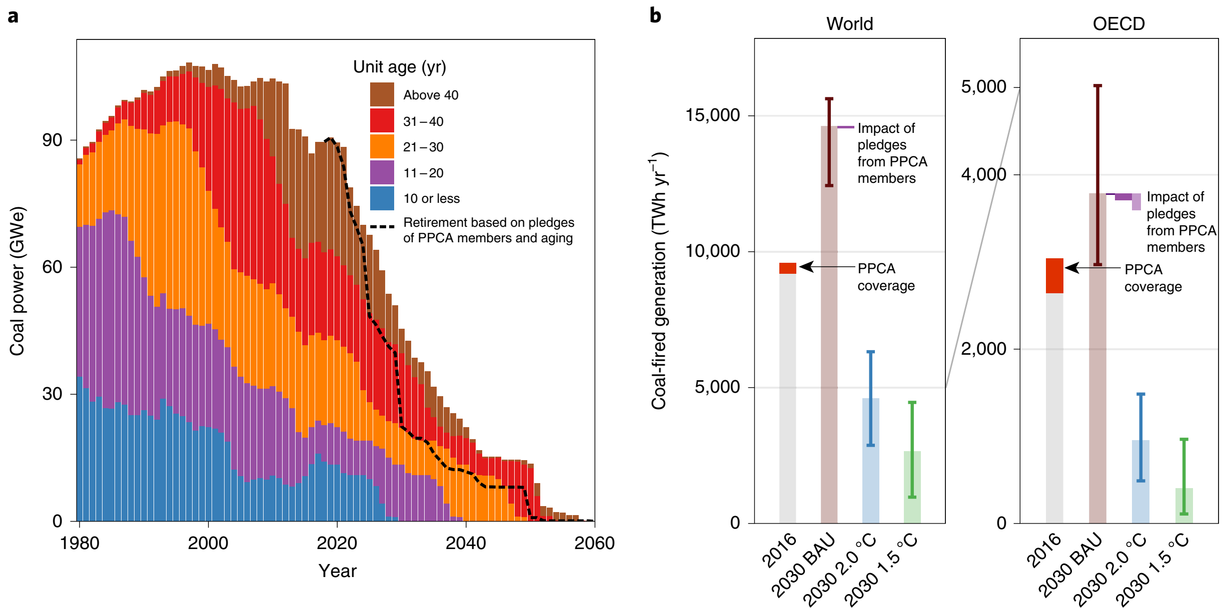
The two largest uncertainties of this estimate are plant lifetimes and coal power substitutes. Under the standard plant lifetime range (30-50 years[13,14]), the avoided emissions would be 0.5-2.5 $GtCO_2$ and under the widest reported lifetime range (20-60 years[15]) – 0.1-4.5 $GtCO_2$ (Supplementary Text 1, Supplementary Figure 4, Supplementary Table 3). Varying the plant efficiencies and load factors by 10% leads to a variation from the reference estimate by +/- 0.3 $GtCO_2$. Finally, if coal power is substituted not by low-emission technologies or demand reduction but instead by natural gas, the avoided emissions would drop in half.

These estimates can be compared to the globally committed emissions from currently operating coal power plants, which are estimated at 206 $GtCO_2$ under a 40-year lifetime, 296 $GtCO_2$ under a 50-year lifetime[15] and therefore at ca 242 $GtCO_2$ under 44-year lifetime (the lifetime in our reference estimate). This is approximately 150 times larger than the reference effect of the PPCA pledges (see Supplementary Table 3 for other lifetime assumptions). The PPCA pledges would reduce annual coal-fired generation by 94 TWh by 2030 (17-230 TWh given lifetime uncertainty) compared to the scenario with no premature retirement. This can be contrasted to the expected reductions in annual coal power generation in 2°C scenarios, which is around 10,000 TWh worldwide (2,800 TWh in OECD), and in 1.5°C scenarios – 12,000 TWh worldwide (3,400 TWh in OECD) (Figure 1 – reductions are calculated as differences between medians of Business as Usual and respective scenarios from the IPCC 1.5°C scenario database[16,17]).

Table 1. Pledged phase-out dates, number, capacity and age of coal power in PPCA countries. The pledged phase-out dates are compiled from national sources referenced in Column 2. (Reports of Belgium's 2016 phase-out[18] conflicts with the IEA that still reports a small amount of coal use in electricity in 2017[19]). All power plant age and lifetime data are calculated based on Platts[20]. Average fleet ages are weighted by generation capacity and calculated as of 2019. The theoretical average and minimum ages at phase-out are calculated by adding the 2019 ages to the number of years between 2019 and the phase-out date. The average lifetime is calculated as the mean of plants retiring since 2000 ("-" marks countries with less than four retired plants – see Methods). See Supplementary Table 1 for sub-national jurisdictions.

Country (or state)	Pledge	Number & (GWe) of operating coal power plant units[20]	Weighted average & (minimum) age of existing fleet	Theoretical average & (minimum) age at phase-out	Average lifetime & (minimum retirement age) since 2000
Belgium	phased-out (2016)[18]	-	-	-	-
France	phase-out 2021[18]	51 (3.2)	37 (27)	39 (29)	40 (18)
Austria	phase-out 2022[18,21]	9 (0.8)	36 (20)	39 (23)	32 (29)
Sweden	phase-out 2022[18,21]	3 (0.1)	35 (29)	38 (32)	-
Italy	phase-out 2025[18,21]	34 (10.5)	32 (9)	38 (15)	48 (36)
U.K.	phase-out 2025[18,21]	45 (15.3)	47 (28)	53 (34)	44 (34)
Ireland	phase-out 2025[18]	3 (0.9)	33 (32)	39 (38)	-
Canada	phase-out 2030[22]	33 (9.1)	33 (5)	44 (16)	41 (33)
Denmark	phase-out 2030[18]	9 (2.5)	33 (21)	44 (32)	40 (33)
Finland	phase-out 2030[18,21]	20 (2.6)	39 (25)	50 (36)	-
Netherlands	phase-out 2030[18,21]	6 (4.8)	10 (3)	21 (14)	36 (28)
New Zealand	phase-out 2030[23]	9 (0.5)	36 (25)	47 (36)	-
Portugal	phase-out 2030[18]	6 (1.9)	30 (24)	41 (35)	-
Israel	phase-out 2030[24]	10 (4.9)	28 (18)	39 (29)	-
Mexico	no specific date[25]	18 (5.5)	25 (9)	-	-
Angola, Costa Rica, El Salvador, Ethiopia, Fiji, Latvia, Liechtenstein, Lithuania, Luxembourg, Marshall Islands, Niue, Senegal, Switzerland, Tuvalu, Vanuatu	No operating coal power plants	-	-	-	-

Figure 1. Impact of the PPCA pledges. Panel (a) shows the historical and projected age structure of the coal fleet for PPCA members (both national and subnational). The solid bars show the historical age structure and the future projection based on historically observed lifetimes with no new construction (see Methods). The dashed line adds additional premature retirements in accordance with the PPCA pledges (Table 1 and Supplementary Table 1). See Supplementary Figure 5 for the projected age structure under alternative mean lifetimes. Panel (b) shows the impact of PPCA pledges on the global and OECD coal power generation in the business as usual (BAU) and climate stabilization scenarios from ref. 16,17 where the bar height is the median value and the error bar is the full range in the scenarios (see Methods). The OECD panel shows the reference, low and high estimates of the PPCA impact depending on the assumed plant lifetimes.

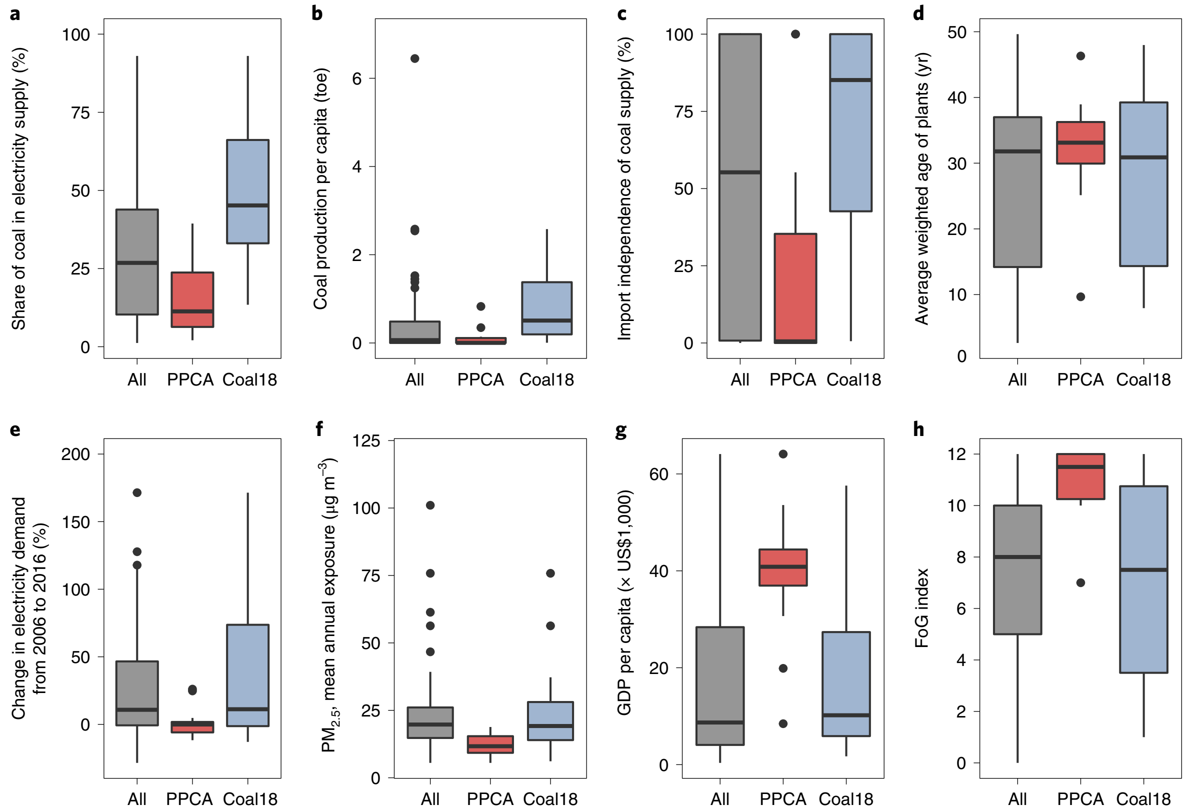


To examine the prospects of additional countries joining the PPCA, we focus on the 69 countries (including 14 PPCA members) that currently produce at least 1% of their electricity supply from coal (see Methods). Of the greatest relevance to climate mitigation is the likelihood for the largest coal consumers, 18 countries which together account for over 90% of coal-based power (Coal18 – Supplementary Tables 4, 5), to join the PPCA.

To systematically compare PPCA members with other countries, we examine national characteristics potentially affecting the likelihood of coal power phase-out (Supplementary Table 6, Supplementary Text 2). Figure 2a illustrates that PPCA members have smaller shares of coal in electricity supply, particularly compared to Coal18 countries. Thus, it is easier for PPCA countries to substitute coal power with other technologies, especially given their lower electricity demand growth (Figure 2e). Additionally, PPCA countries produce less coal (Figure 2b) and rely more on coal imports (Figure 2c), which means that coal phase-out would have a smaller effect on mining employment, coal-dependent regions, and energy security, which could suffer if domestic coal is replaced by imported fuels or electricity[26,27]. Furthermore, fewer PPCA countries have young coal fleets (Figure 2d) associated with higher risks of stranded infrastructure assets[13] and resistance from power plant owners[26].

In addition to facing lower barriers to coal phase-out, PPCA members have higher capacities to overcome these barriers, i.e. higher GDP per capita (Figure 2g) and functioning of government (FoG) index, which reflects the absence of undue influence on elected government, government transparency, and checks against political corruption[28] (Figure 2h). These characteristics enable PPCA members to more effectively formulate and implement coal phase-out policies (Supplementary Text 2). Exposure to air pollution in PPCA countries is *lower* than in both Coal18 and the rest of the world (Figure 2e), thus air pollution is not likely a direct driver of PPCA membership (Supplementary Text 3). Due to the high correlation and interdependence between explanatory variables (Supplementary Figure 6), identifying key drivers of PPCA membership requires additional statistical analysis.

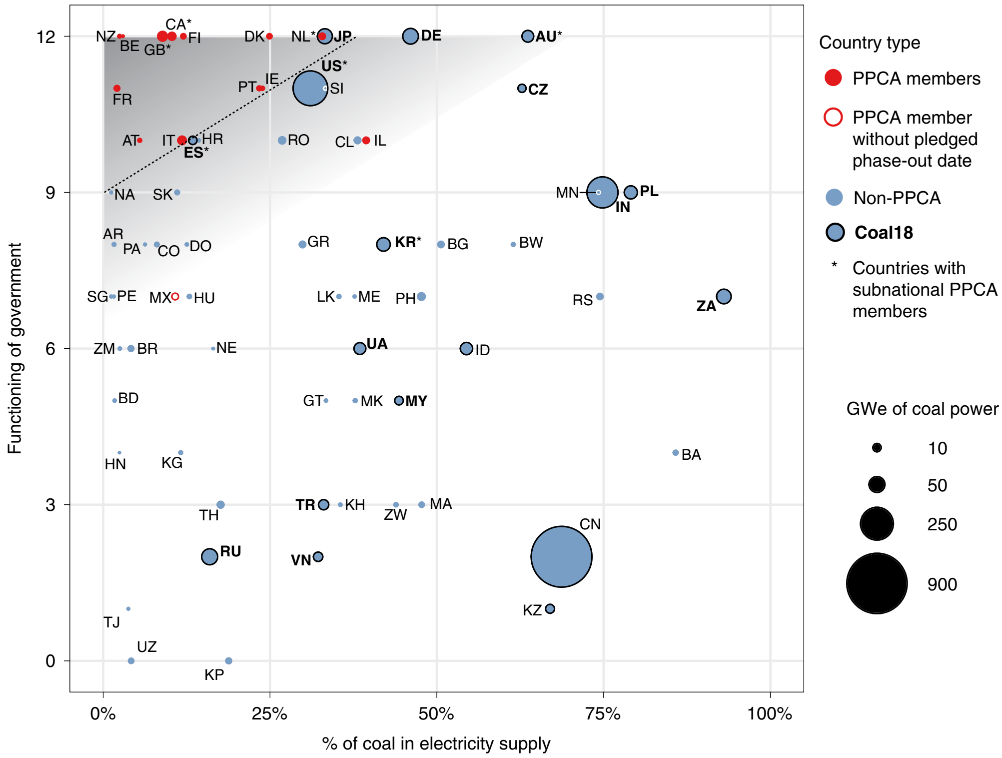
Figure 2. Difference between PPCA and Coal18 countries. Boxes represent interquartile ranges for the respective variables and country groups; thick lines within boxes represent medians; vertical lines and dots represent data points outside the interquartile ranges. Panel (a) shows share of coal in electricity supply. Panel (b) shows coal production per capita. Panel (c) shows import independence of coal supply. Panel (d) shows the average age of coal power plant units. Panel (e) shows the change in electricity demand (2006-2016). Panel (f) shows air pollution. Panel (g) shows GDP per capita. Panel (g) shows Functioning of government. See Methods for data sources and calculations.



To evaluate which variables probabilistically explain a country's membership in PPCA, we conduct a multivariate logistic regression analysis using PPCA membership as a binary dependent variable and 11 independent variables including 8 shown in Figure 2 plus EU membership, share of non-hydro renewables and share of coal in non-transport final energy use (Methods, Supplementary Table 6, Supplementary Text 2). According to this analysis, FoG and GDP per capita have a significant positive effect on PPCA membership (Supplementary Tables 7, 8 and 9). The strength of the coal sector – measured by coal production per capita, coal share in electricity generation and in non-transport final energy use – have a significant negative effect on PPCA membership, especially when considered collectively. Air pollution has a paradoxical *negative* effect on PPCA membership and the effect of the remaining five variables is considerably less pronounced (Supplementary Table 10). The best-fit model with fewest explanatory variables includes the share of coal in electricity and FoG (Supplementary Tables

7, 8 and 9, Supplementary Text 3). The effect of these two variables on PPCA membership is illustrated in Figure 3.

Figure 3. Functioning of Government index and share of coal in electricity generation in PPCA members, Coal18 and other countries. The size of the circles indicates the current coal power capacity. Coal18 countries are bolded and circled in black (Supplementary Tables 4 and 5). Countries with subnational units which have joined the PPCA are marked with an asterisk (Supplementary Table 1). The dashed line and the shaded area illustrate the results of the logistic regression analysis. The area to the left and above the dashed line shows the predicted probability of belonging to the Alliance above 50% according to Model 1.4 (Supplementary Table 7). The shaded area shows where the probability of belonging to the Alliance is at least 5%. See Methods for definition and calculation of variables.



According to this analysis, the five Coal18 countries with a greater than 5% probability of joining PPCA are Spain, Germany, Japan, the US, and Australia. Spain gets 13% of its electricity supply from primarily imported coal and has an old power plant fleet. It recently announced an agreement to shut down all coal mines by the end of 2019[29] and its National Climate and Energy plan states that coal plants will not supply electricity beyond 2030[30].

Germany, which has coal power capacity similar to all PPCA members combined, a higher share of coal in electricity than any of the PPCA members (46%), a younger fleet (30 years weighted average age), and produces about one-half of its coal domestically[19], has recently formulated a plan to phase-out coal power by 2038 or 2035[31] and has signaled interest in joining the PPCA[32]. Similarly to the PPCA countries, Germany plans to close older plants in the coming decade: the units proposed to close in 2022 will be on average 46 years old and in 2030 – 41 years old, as compared to the recent average lifetime of 41 years. However, the final stage of the phase-out would break with this pattern by closing many of the recently-constructed power plants. The average age of the remaining units, comprising about 1/3 of the current capacity, would be 30 years in 2038 (Supplementary Figure 7, Supplementary Text 4). An evaluation planned for 2032 may reverse this decision or accelerate it to 2035. The German coal exit would avoid 0.6-1.6 GtCO_2 emissions between 2019-2050 depending on the final phase-out date and how much coal will be substituted by natural gas. The plan recommends a provision of €40 bln in aid to affected regions plus compensation to affected companies, electricity users and workers[33–35]. It is not yet determined how much of this aid would be additional to already existing programs. However, the magnitude of the potential commitments indicates the scale of the challenge of implementing a politically acceptable coal phase-out[36,37] (Supplementary Text 4).

Another Coal18 country similar to the PPCA members is Japan: it has both coal share and FoG almost identical to that of the Netherlands, as well as an older power plant fleet relying entirely on imported coal. While Japan abandoned its plans for coal phase-out following the downward revision of its nuclear power targets after the Fukushima accident[38,39], the Environment Minister recently announced it will oppose new construction of coal plants[40]. The US and Australia share some of the PPCA countries' characteristics, have subnational units which have joined the PPCA (Supplementary Table 1), and have been reducing coal power generation[19]. However, both countries are major coal producers (e.g. Australia produces about 15 times more coal per capita than Canada)[19] and the current administrations in both countries are pro-coal[41,42]. The other 12 countries similar to the PPCA members have smaller power plant fleets and even if all of these joined, it would only increase the capacity under PPCA from 4.4 to 5.3% of the global total.

Our analysis highlights a difference between PPCA members and major coal users in emerging Asian economies, where the shift away from coal is most critical for keeping global warming under 1.5°C or 2°C[1,13]. For example, the median age of coal power fleets across PPCA countries is 33 years compared to

12 years in China (46% of global coal capacity), 14 years in India (11%), 12 years in Indonesia (1.4%), and 8 years in Vietnam (0.7%) (Supplementary Table 4). The electricity demand change in 2006-2016 was 116% in China, 90% in India, 87% in Indonesia, and 171% in Vietnam while in PPCA countries it was 1.5% on average. China in particular has large coal production (about 1.5 times per capita larger than Canada)[19], supplies 69% of its electricity from coal, but at the same time has much lower GDP per capita and FoG than PPCA countries. Thus, the lack of China's promise to phase-out coal power and its recently reactivated construction of coal power plants[43] are not surprising, despite certain steps to stabilize coal use[44,45]. China and some other Coal18 countries do seek to reduce coal power, e.g. through co-firing with biomass or partial substitution with natural gas, even though a nation-wide coal power phase-out is not currently on their agenda (Supplementary Table 5).

Our analysis contributes to a broader understanding of the global climate governance – centered on the Paris agreement – which involves "shallow" coordination between countries guided by national interests rather than by joint gains[46]. One common suggestion for deepening climate cooperation is with climate clubs whereby a group of countries jointly commit to stronger climate mitigation[46–48]. The literature suggests that access to clean technologies, reduced air pollution and similar benefits could incentivize countries to join climate clubs[46,48]. By analyzing the PPCA we provide a new perspective to this debate. Our analysis shows that it is not the benefits of PPCA membership but the costs of phase-out and capacities to bear these costs that differentiate PPCA members from non-members. Specifically, countries pledge to phase-out coal only when potential stranded assets, employment losses, regional impacts and other costs are lower. The exceptions are the Netherlands and Germany, which makes it especially important to analyze the lessons and the feasibility of replicating the mechanisms of these countries' coal phase-out elsewhere (see ref. 49 for emerging discussion on Germany).

We also show that lower costs of coal's demise are not sufficient to trigger phase-out pledges. A small coal sector and aging power plants provide a space for policy choice to either accelerate phase-out or to prop a declining coal sector with extra government support. The difficult process of coal phase-out is more likely to be pursued by independent and transparent governments in wealthy countries which have capacities to bear substantial political, social and economic costs, as Germany's case illustrates. Therefore, even the declining competitiveness of coal[50,51] will not automatically lead to its demise, particularly in non-liberalized markets with governments under influence from the coal sector. On the contrary, such governments may choose to boost the use of uncompetitive coal through favorable regulations and supportive subsidies as in some post-Soviet countries[52–54]. Returning to the more general question of why countries join climate clubs, our findings indicate that the affordable "entrance fee" may matter more than lucrative "membership benefits".

References

1. Climate Analytics. Implications of the Paris Agreement for Coal Use in the Power Sector. 42 (2016).
2. Luderer, G. *et al.* Residual fossil CO2emissions in 1.5-2 °c pathways. *Nat Clim Chang* **8**, 626–633 (2018).
3. Allen, M. *et al. Global Warming of 1.5°C Summary for Policymakers.* (2018).
4. Government of Canada. Powering Past Coal Alliance: Declaration and Member List. (2018). Available at: https://www.canada.ca/en/services/environment/weather/climatechange/canada-international-action/coal-phase-out/alliance-declaration.html.
5. Carrington, D. 'Political watershed' as 19 countries pledge to phase out coal. *The Guardian* (2017).
6. Green, F. Anti-fossil fuel norms. *Clim Change* 1–14 (2018). doi:10.1007/s10584-017-2134-6
7. Climate Action. All of the UK ' s remaining coal plants will shut down by 2025. *Climate Action* (2018). Available at: http://www.climateaction.org/news/all-of-the-uks-remaining-coal-plants-will-shut-down-by-2025. (Accessed: 17th March 2019)
8. Littlecott, C., Burrows, L. & Skillings, S. Summary - Insights from the UK coal phase out experience. *E3G* (2018). Available at: https://www.e3g.org/library/summary-insights-from-the-uk-coal-phase-out-experience. (Accessed: 17th March 2019)
9. Brittlebank, W. France to end coal production by 2023 - Climate Action Programme. *Climate Action* (2016). Available at: http://www.climateactionprogramme.org/news/france_to_end_coal_production_by_2023. (Accessed: 17th March 2019)
10. Government of Portugal. The Government wants to eliminate coal production before 2030. *Portuguese Republic* **November**, (2016).
11. Huuhtanen, M. Finland Plans To Phase Out Coal Use In Energy Production By 2025. *Phys Org* (2016). Available at: http://www.huffingtonpost.com/2012/10/02/finland-coal-use-phase-out-2025-energy_n_1932444.html?utm_hp_ref=green%5Cnhttp://www.huffingtonpost.com/2012/10/02/finland-coal-use-phase-out-2025-energy_n_1932444.html?view=print&comm_ref=false. (Accessed: 17th March 2019)
12. Wynn, G. *The Dutch Coal Mistake: How Three Brand-New Power Plants in the Netherlands Are at Risk Already of Becoming Stranded Assets.* (2016).
13. Johnson, N. *et al.* Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technol Forecast Soc Change* **90**, 89–102 (2015).
14. Edenhofer, O., Steckel, J. C., Jakob, M. & Bertram, C. Reports of coal's terminal decline may be exaggerated. *Environ Res Lett* **13**, 24019 (2018).
15. Davis, S. J. & Socolow, R. H. Commitment accounting of CO_2 emissions. *Environ Res Lett* **9**, (2014).
16. Huppman, D. *et al. IAMC 1.5°C Scenario Explorer and Data hosted by IIASA (release 1.0). Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis* (2018). doi:10.22022/SR15/08-2018.15429
17. Rogelj, J. *et al.* Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. in *Special Report on Global warming of 1.5°C (SR15)* (Intergovernmental Panel on Climate Change, 2018).
18. Beyond Coal. *Overview: National coal phase-out announcements in Europe.* (2018).
19. IEA. *World energy balances. IEA World Energy Statistics and Balances (database).* (2018).
20. Platts. World Electric Power Plants Data Base. (2017).
21. Industry Briefing. Europe energy Europe coal phase outs gather pace. *Economist Intelligence Unit* (2017).
22. Government of Canada. Coal phase-out: the Powering Past Coal Alliance. (2018). Available at: https://www.canada.ca/en/services/environment/weather/climatechange/canada-international-action/coal-phase-out.html. (Accessed: 18th April 2018)

23. ABC News. NZ signs up to phase out coal power by 2030. *Radio New Zealand* (2017).
24. State of Israel Ministry of Israel. *Energy Economy Objectives for the Year 2030*. (2018).
25. Secretaría de Energía. *Prospectiva del Sector Eléctrico 2017-2031*. (2017).
26. Spencer, T. *et al.* Climate Policy The 1.5°C target and coal sector transition: at the limits of societal feasibility The 1.5°C target and coal sector transition: at the limits of societal feasibility. (2017). doi:10.1080/14693062.2017.1386540org/10.1080/14693062.2017.1386540
27. Helm, D. Energy policy: Security of supply, sustainability and competition. *Energy Policy* **30**, 173–184 (2002).
28. Freedom House. *Freedom in the world 2018: Methodology*. (2018).
29. Neslen, A. Spain to close most coalmines in € 250m transition deal. **3**, (2018).
30. Ministry of Ecological Transition for the Government of Spain. *Draft of the integrated national energy and climate plan 2021-2030*. (2018).
31. German Ministry of Economy and Energy. *Commission 'Growth, Structural Change and Employment' (Kommission 'Wachstum, Strukturwandel und Beschäftigung')*. (2019).
32. Darby, M. Germany ready to join global coal phase- out alliance: environment minister. *Climate Change News* (2019).
33. Zeit Online. Many billions for Coal Exit (Viele Milliarden für den Kohleausstieg). *Zeit Online* (2019).
34. Wehrmann, B. RWE substantiates claims for billion-euro coal plant compensation. *Clean Energy Wire* (2019).
35. Cembalest, M. *Eye on the market: Annual Energy Paper*. (2019).
36. Schultz, S. Germany should phase-out coal by 2038 at the latest (Deutschland soll bis spätestens 2038 aus der Kohle aussteigen). *Spiegel Online* (2019).
37. Schultz, S. What will the agreement of the Coal Exit bring (Was die Einigung zum Kohleausstieg bringt). *Spiegel Online* (2019).
38. Normile, D. Bucking global trends, Japan again embraces coal power. *Science (80-)* **360**, 476–477 (2018).
39. Cherp, A. & Jewell, J. Energy policy: Renewables targeted before Fukushima. *Nature* **533**, (2016).
40. Toda, M. & Kawamura, T. Japan to rule out coal-fired plants as international criticism rises. *The Asahi Shimbun* (2019).
41. Krapp, P. Australian government backs coal in defiance of IPCC climate warning. *The Guardian* (2018).
42. Trump, D. Remarks by President Trump at the Unleashing American Energy Event. *The White House* (2017).
43. Shearer, C., Yu, A. & Nace, T. *Tsunami Warning: Can China's central authorities stop a massive surge in new coal plants caused by provincial overpermitting?* (2018).
44. Xu, M. & Stanway, D. China to cut coal use, curb steel in 2018-2020 pollution plan | Reuters. *Reuters* (2018).
45. Department of Climate Change and National Development & Reform Commision of China. *China's First INDC Submission. UNFCCC* (2015).
46. Keohane, R. O. & Victor, D. G. Cooperation and discord in global climate policy. *Nat Clim Chang* **6**, 570–575 (2016).
47. Victor, D. G. *Global warming gridlock: Creating more effective strategies for protecting the planet*. (Cambridge University Press, 2011).
48. Hovi, J., Sprinz, D. F., Sælen, H. & Underdal, A. Climate change mitigation: A role for climate clubs? *Palgrave Commun* **2**, (2016).
49. Reitzenstein, B. A. & Popp, R. A role model for European coal phase out ? Five lessons from the German Coal Commission. *E3G Blog* (2019). Available at: https://www.e3g.org/library/a-role-model-for-european-coal-phase-out-five-lessons-from-the-german-coal. (Accessed: 6th May 2019)
50. Gray, M., Ljungwaldh, S., Watson, L. & Kok, I. *Powering down coal: Navigating the economic and financial risks in the last years of coal power*. (2018).
51. Gimon, E., O'Boyle, M., Clack, C. T. M. & McKee, S. *The coal cost of crossover: economic viability of existing coal compared to new local wind and solar resources*. (2019).
52. The Government of the Russian Federation. *Master Plan for Siting Electricity Facilities up to 2035: Decree 1209*. (2017).
53. The Government of the Russian Federation. *Energy Strategy of Russia for the period to 2035*. (2017).
54. The Government of Ukraine. *National plan for reduction of emissions from large combustion facilities. Approved by the Cabinent of Ministers on 08.11.2017, No 796-p*. (2017).

Data availability

The data file for regression analysis are available within the Supplementary Information. Data for figures are available from the corresponding author upon request.

Competing interests

The authors declare no competing interests.

Author contributions

J.J. conceived the study. J.J., A.C., and V.V. designed the research. J.J., V.V., and L.N. carried out the research. All authors analyzed the results. J.J., A.C., and V.V. wrote the paper.

Acknowledgements

This work was supported by the Research Council Norway under the Contractions project grant agreement no. 267528/E10. A.C. received support from CEU's Intellectual Themes Initiative Political Economy of Energy Transitions Project.

Methods

Data sources

We compiled pledged phase-out dates for PPCA members from national and sub-national sources (see Table 1 and Supplementary Table 1)[18,21–23,25,55–57]. All power plant data are from the World Electric Power Plant Database from S&P Global Platts[20]. (We used the S&P Global Platts database rather than the EndCoal tracker[57] because Platts has historical data from before 2000 which allowed us to calculate historical retirement ages – e.g. Supplementary Figure 3). All other energy data are from the International Energy Agency (IEA) for the year 2016[19] unless specified otherwise. Economic data are from the World Bank and for the year 2016[58] and the Functioning of Government data is from Freedom House for the year 2006[28]. We were not able to obtain economic data for North Korea, which would otherwise be in our sample for statistical analysis, thus we excluded it. The scenario data are from the IPCC's 1.5°C report[16,17].

For the Coal18 countries, we evaluate whether there are coal phase-out plans in by: searching for "Country name + coal plan" and "Country name + coal phase-out" and consulting the Nationally Determined Contribution[59] and most recent National Communications[60] submitted to the United Nations Framework on Climate Change since the Paris Agreement or the National Energy and Climate Plans submitted to the European Commission[61] (Supplementary Table 5).

Calculating power plant age profiles and average retirement age

To calculate the average age of the existing fleet, we only include plants which are classified as operating (Status = OPR). We calculate the age of each plant by subtracting the year of its construction from 2019. We then take the average (weighted by nameplate capacity). To calculate the "theoretical average & (minimum) age at phase-out", we add the number of years from the pledged phase-out date and 2019 to the current average age of the existing fleet.

Average power plant lifetimes are calculated for each PPCA member and Germany as a mean across all retired power plants for which retirement information is available since 2000. For countries with fewer than 4 data-points, a mean across all power plants lifetimes in PPCA countries (42 years) is used; for subnational jurisdictions with fewer than 4 data-points, national averages are used if they have 4 data-points or more, and global averages are used otherwise. We use a similar procedure to estimate standard deviations of retirement ages.

These data are used to estimate the share of power plants which would be retired prematurely due to the pledges from PPCA members (Table 1 and Supplementary Table 1). We assume that plant retirement age follows a normal distribution with historical means and standard deviations. For our reference estimate, we use national and subnational historic retirement ages and standard deviations calculated as described above. In future scenarios, all operating plants start retiring from 2019, and the retirement date of a plant is determined by its expected lifetime in 2019, which is estimated using truncated normal distribution (Supplementary Figure 8). It ensures that plants already past the respective national average age do not retire immediately at the start of the period – they still have a positive expected lifetime determined by the remaining "tail" of the distribution.

In the phase-out scenario, in additional to the business as usual retirement described above, all plants surviving to the respective national, state, or provincial phaseout year are retired in that year. For Germany, the phase-out scenarios correspond to the multi-stage coal phase-out plan proposed by the Coal Commission[31] (Supplementary Text 4). For our sensitivity analysis, we also use fixed average lifetimes for all plants in all PPCA members (20, 30, 40, 50, and 60 years), applying the same truncated normal distribution retirement procedure and using the standard deviation of plant lifetimes in all PPCA countries scaled proportionally to the average lifetime (so that the ratio of the standard deviation to the mean remains constant). In this analysis, we include national, state and provincial PPCA member pledges.

Calculating avoided emissions from plant retirement

To calculate the avoided emissions from premature retirement, we calculate the avoided generation from each prematurely retired plant by multiplying its capacity by the number of years between the premature and the baseline retirement dates and by the load factor. We use average national load factors for 2007–2016 by dividing coal-fired power plant output[19] by installed coal capacity[20]. For states and provinces, we use national load factors[19] by installed coal capacity[20] for each year. For states and provinces, we use national load factors.

We then apply technology-specific efficiencies to the power output of each plant to estimate coal consumption (in energy units) using the average between two different references (see Supplementary Table 11)[62,63]. We then use emission rates for the thermal content of different coal types for power plants with known fuel types to estimate avoided emissions (Supplementary Table 12)[64]. For plants with unknown fuel type, we use 95.3 kg/MBTU which is the average across all currently operating plants with known fuel type, weighted by installed capacity. Finally, total avoided emissions are calculated by summing across all plants between 2019 and 2050 (at which point all coal power plants in PPCA member countries with pledged phase-out date would be retired).We then apply worldwide technology-specific efficiencies (differentiating between sub-critical, super-critical and ultra supercritical generation technologies) to the power output of each plant to estimate coal consumption (in energy units) using the average between two different references (see Supplementary Table 11)[62,63]. Where the technology is not indicated, sub-critical technology is assumed. We then use emission rates for the thermal content of different coal types for power plants with known fuel types to estimate avoided emissions (Supplementary Table 12)[64]. For plants with unknown fuel type, we use 95.3 kg/MBTU which is the average across all currently operating plants with known fuel type, weighted by installed capacity. Finally, total avoided emissions are calculated by summing across all plants between 2019 and 2050 (at which point all coal power plants in PPCA member countries with pledged phase-out date would be retired). For calculating potential emissions from natural gas in case it substitutes coal power we use the US average efficiency of gas-fired power plants in 2007-2017 (43%)[65] and the CO_2 emission factor for gas 53.07 kg/Mbtu[65].

Scenario comparison

In Figure 1 (panel b), we compare how coal generation changes under the PPCA pledges to climate scenarios from the literature[16,17]. For the "BAU" or Business as Usual scenarios, we selected all scenarios which had, "Current policies", "No policies", "Baseline", or "BAU" in their name or definition. For the "2°C" scenarios, we selected all scenarios in the Categories: "Higher 2C" and "Lower 2C". For the "1.5°C" scenarios, we selected all scenarios in the Categories: "1.5C low overshoot", "1.5C high overshoot" and "Below 1.5C".

Variable definition for comparative analysis and logistic regression

Selection of variables for logistic regression and comparative analysis is explained in Supplementary Text 2. The following is the list of variables in our logistic regression and data sources:

- **Coal.Share** – share of coal in electricity supply in 2016. Calculated as a ratio of electricity produced from coal to the total domestic electricity supply. Data source: ref. 19.
- **Prod.PC** – coal production per capita, toe/person, in 2016. Data sources: coal production – ref. 19, population – ref. 58**.**
- **Coal.TFC** – share of coal in non-transport final energy consumption. Calculated as share of coal in total final energy consumption excluding the transport sector (i.e. capturing coal use in industry, residential and public and commercial sectors) in 2016. Transportation sector was

excluded to avoid the extent of transport sector affecting the final results. Data source: ref. 19.

- **Coal.Indep** – import independence of coal supply. Calculated as a ratio of domestic coal production to the total domestic supply of coal. If the ratio is greater than one (i.e. the country is a net coal exporter), the indicator equals one by definition (meaning "full independence of supply"). Data source: ref. 19.
- **Demand10** – change in electricity demand over 10 years (2006–2016). Calculated as an absolute difference between the total electricity demand in 2016 and 2006 divided by the total electricity demand in the base year (2006). Data source: ref. 19.
- **Age** – weighted (by installed capacity) average age of operating coal-fired power plants. Plant age is as of 2019. Data source: ref. 20.
- **NHR.Share** – share of non-hydro renewables in total electricity supply in 2016. Data source: ref. 19.
- **PM2.5.Exp** – air pollution, measured as mean annual exposure to PM2.5 ($\mu g/m^3$), in 2016. Data source: ref. 58.
- **GDP.PC** – GDP per capita (in 1 000 current USD) in 2016. Data source: ref. 58.
- **FoG** – Functioning of government as measured by an index published by Freedom House, which measures on the scale from 0 to 12 the absence of undue influence on elected authorities, effectiveness of safeguards against political corruption, and openness and transparency of government operation. Data source: ref. 28.

Logistic regression analysis

We conduct a multivariate statistical analysis using a two-sided logistic model to analyze which variables best predict PPCA membership and which countries are most likely to join in the future. The binary outcome variable is PPCA membership. Our sample includes the 68 countries which supply at least 1% of their electricity from coal and for which all our independent variables are available (this excludes North Korea, for which there was no GDP data available). Though PPCA membership of other countries using negligible quantities of coal power is symbolically important, its tangible impacts on climate mitigation are likely to be insignificant.

In the first step we analyze all possible models (2036) including at least two of the 11 explanatory variables. Models where PM2.5.exp is statistically significant show its unexpected *negative* correlation with PPCA membership. This is in contrast to the presumed causal mechanism and thus possibly indicates a model deficiency. PM2.5.exp is therefore excluded from further analysis (Supplementary Text 2, Supplementary Text 3).

In the second step we analyze all possible models (1013) involving a combination of at least 2 of the remaining 10 variables. These machine-generated models are ranked by the Akaike information criterion (AIC) which estimates the goodness of fit and also rewards model parsimony by penalizing additional independent variables[67]; a lower AIC means better model fit. In addition, we test how many 'false predictions' of membership in PPCA each model produces (a prediction is a false negative if an actual PPCA member has less than 50% of probability to be a PPCA member according to a given model and false positive if a non-member is predicted by the model to be a member with higher than 50% probability – Supplementary Table 7).

This machine-generated procedure follows the general logic of step-wise regression using backwards elimination, starting with a model containing all of our independent variables and then testing a number of reduced models by dropping statistically insignificant variables one-by-one and testing different variable combinations (as illustrated in Supplementary Table 7)[68].

The best-fit parsimonious model resulting from this procedure includes FoG, GDP.PC, Prod.PC, Coal.TFC and Coal.Share; the best-fit model with only two variables, includes Coal.Share and the FoG (models 1.3 and 1.4, Supplementary Table 7, 8 and 9). We also use the likelihood ratio test[69] to make sure that no significant information is lost when dropping variables from the best-fit and 2-variable model (i.e. that the variables dropped from the full model are not statistically significant collectively). Finally, to investigate collective statistical significance of the variables characterizing the coal sector (Coal.Share. Coal.TFC, and Prod.PC) and which highly correlate with each other (Supplementary Figure 6) we conduct an additional likelihood ratio test[69] focused on these variable (Supplementary Text 3).

Limitations

Our paper focuses on the impact and potential diffusion of a specific policy measure: deliberate, nation-wide, time-bound, universal phase-out of unabated coal power. We do not analyze other policies (e.g. carbon tax) that can reduce emissions from coal power or indirectly lead to closure of coal power plants. We also do not analyze potential closures of coal power plants due to market dynamics, technological change, and other factors not explicitly reflected in deliberate phase-out policies.

In our reference estimate of avoided emissions, we presume that phased-out coal generation will be compensated by nearly-zero carbon measures such as electricity demand reduction or, in a sensitivity estimate, by natural gas power. However, we do not analyze the whole range of substitution options, some of which may lead to much higher emissions. This can occur, for example, as a result of a "waterbed effect" when decline in coal generation in PPCA countries could lead to an increase in coal generation elsewhere either because of a drop in coal prices or due to an increase in opportunities to export coal-based electricity to those countries.

On the other hand, our analysis may underestimate the potential effect of PPCA by not including the cancellation of planned or possible coal power plants. Though we show that the majority of PPCA countries have not built many new coal power plants in the last two decades (and thus are unlikely to have had many concrete plans for construction) we could not obtain reliable and systematic information on how many coal power plants were cancelled during the planning stage, when and whether the membership in PPCA could have played any role.

With respect to explaining PPCA membership and discussing its potential for its further expansion our first limitation stems from our focus on nation-states. Explaining PPCA memberships of sub-national jurisdictions as well as private corporations would require a different explanatory framework and different variables. The second limitation is more generally connected with statistical analysis which identifies correlation between variables rather than causal relationships. Although we base our variable selection on plausible causal mechanisms and a rich theoretical and empirical literature (Supplementary Text 2), validating these mechanisms would require detailed case-study research.

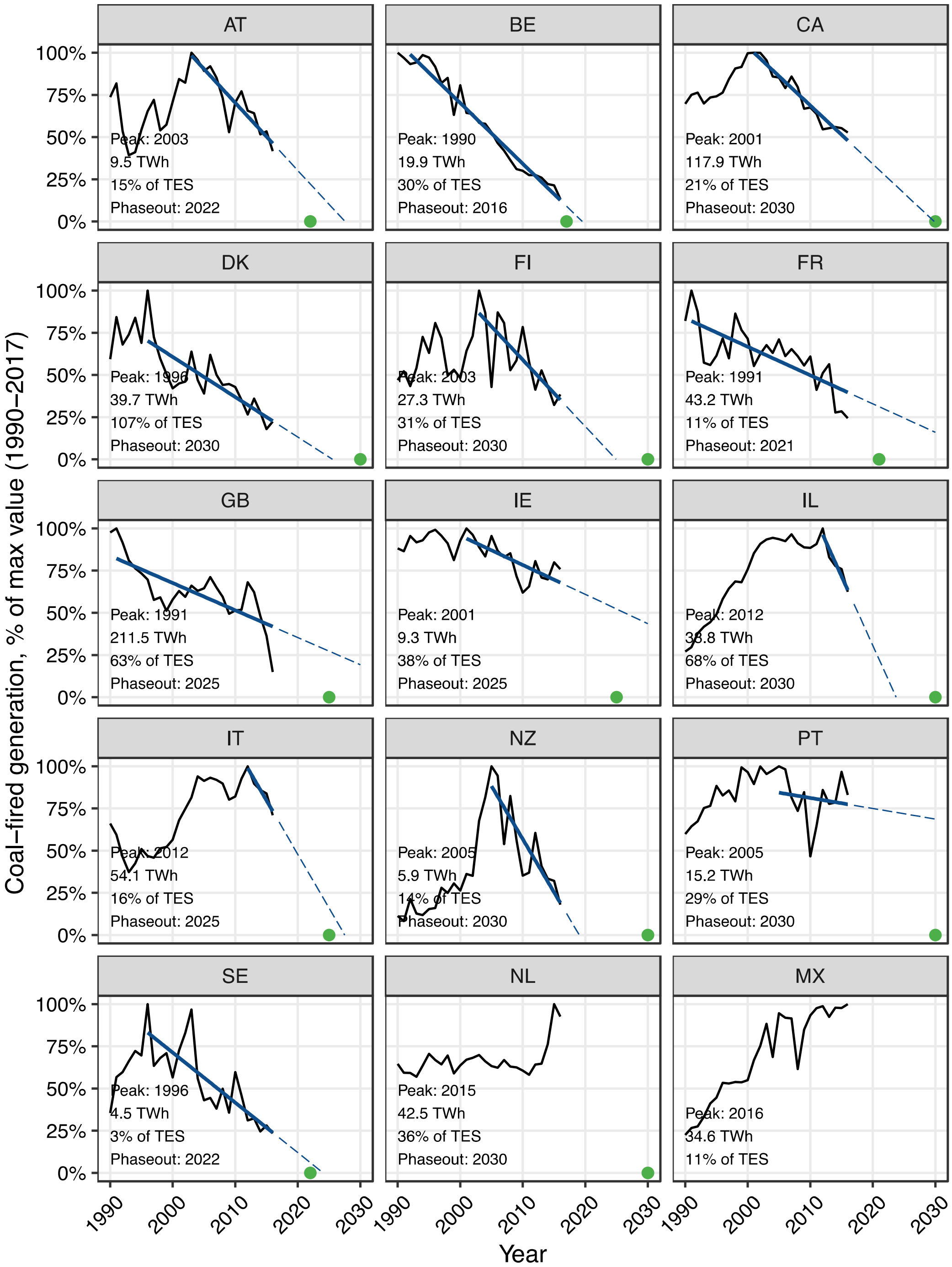
Methods References

16. Huppman, D. *et al. IAMC 1.5°C Scenario Explorer and Data hosted by IIASA (release 1.0). Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis* (2018). doi:10.22022/SR15/08-2018.15429
17. Rogelj, J. *et al.* Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. in *Special Report on Global warming of 1.5°C (SR15)* (Intergovernmental Panel on Climate Change, 2018).
18. Beyond Coal. *Overview: National coal phase-out announcements in Europe.* (2018).
19. IEA. *World energy balances. IEA World Energy Statistics and Balances (database).* (2018).
20. Platts. World Electric Power Plants Data Base. (2017).
21. Industry Briefing. Europe energy Europe coal phase outs gather pace. *Economist Intelligence Unit* (2017).
22. Government of Canada. Coal phase-out: the Powering Past Coal Alliance. (2018). Available at: https://www.canada.ca/en/services/environment/weather/climatechange/canada-international-action/coal-phase-out.html. (Accessed: 18th April 2018)
23. ABC News. NZ signs up to phase out coal power by 2030. *Radio New Zealand* (2017).
25. Secretaría de Energía. *Prospectiva del Sector Eléctrico 2017-2031.* (2017).
28. Freedom House. *Freedom in the world 2018: Methodology.* (2018).
55. Paulos, B. Washington State leaves coal behind, but not its workers. *energytransition.org* (2018).
56. Darby, M. Chile declares start of coal power phase-out. *Climate News* (2018).
57. EndCoal. Global Coal Plant Tracker. *Coal Swarm* (2018). Available at: https://endcoal.org/tracker/. (Accessed: 20th April 2018)
58. World Bank. World Bank Open Data. (2018).
59. UNFCCC. NDC Registry. (2019). Available at: https://www4.unfccc.int/sites/ndcstaging/Pages/Home.aspx. (Accessed: 5th March 2019)
60. UNFCCC. National Communication submissions from Non-Annex I Parties. (2019). Available at: https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/national-communications-and-biennial-update-reports-non-annex-i-parties/national-communication-submissions-from-non-annex-i-parties. (Accessed: 3rd May 2019)
61. European Commission. National Energy and Climate Plans. (2019). Available at: https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/governance-energy-union/national-energy-climate-plans. (Accessed: 5th March 2019)
62. Katzer, J. *et al. The Future of Coal: An interdisciplinary MIT study.* (Massachusetts Institute of Technology, 2007).
63. Hardisty, P. E. *et al.* Life Cycle Greenhouse Gas Emissions from Electricity Generation: A Comparative Analysis of Australian Energy Sources. *Energies* **5**, 872–897 (2012).
64. US Energy Information Administration. Carbon Dioxide Emission Coefficients. *Environment* (2016). Available at: https://www.eia.gov/environment/emissions/co2_vol_mass.php. (Accessed: 16th January 2018)
65. EIA. Table 8.1 Average operating heat rate for selected energy sources. (2018). Available at: https://www.eia.gov/electricity/annual/html/epa_08_01.html. (Accessed: 26th March 2019)
66. Juhrich, K. *Emission situation. CO_2 emission factors for fossil fuels.* (2016).
67. Cleves, M., Gould, W., Gutierrez, R. & Marchenko, Y. *An introduction to survival analysis using Stata.* (Stata Press, 2010).
68. Myers, R. H. *Classical and modern regression with applications.* (Duxbury Thomas Learning, 1990).
69. Kleinbaum, D. & Klein, M. *Logistic regression: A self-learning text.* (Springer US, 2010).

Supplementary Information: Prospects for powering past coal

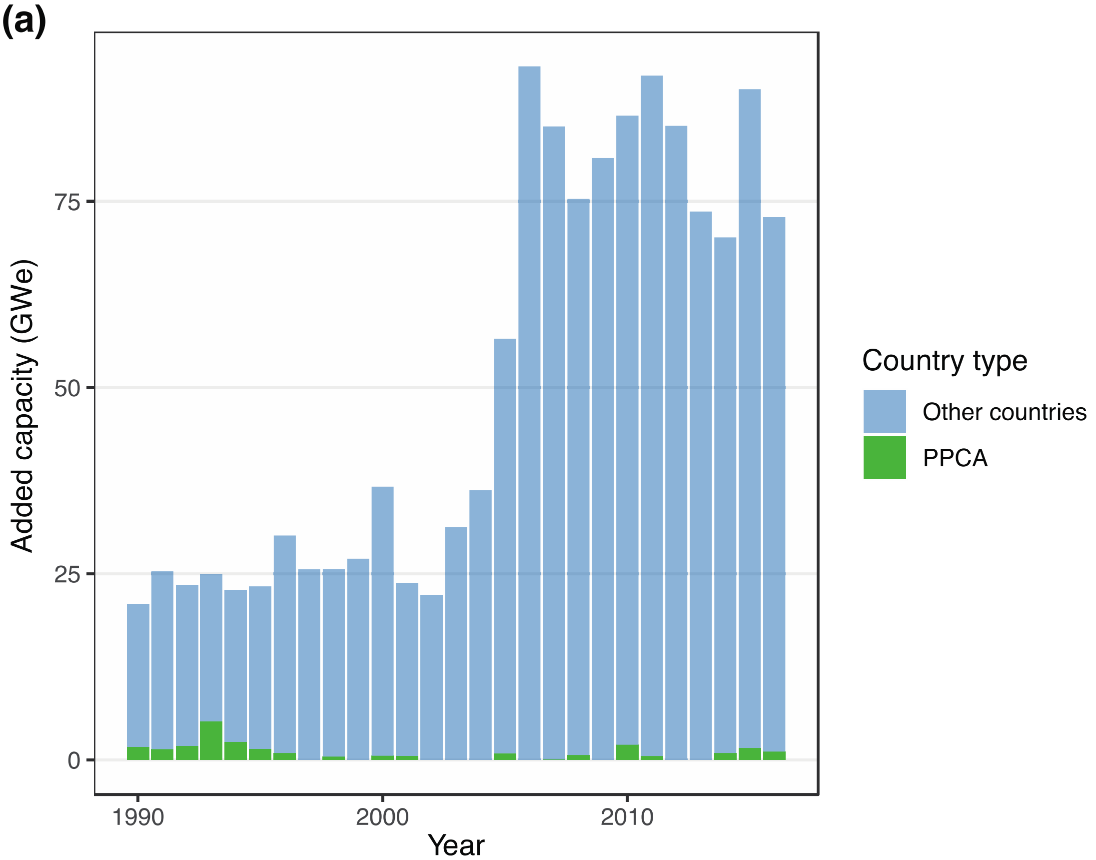
Supplementary Figures

Supplementary Figure 1. Historical trends of coal power generation in PPCA countries. Includes countries with at least 3% of electricity supply from coal in any year since 1990. Each graph shows the change in coal generation since 1990, normalized to the maximum value for that country. The trend-line is calculated from the year when coal generation peaked (or 1990 if the peak was prior to 1990) and the green dot represents the pledged phase-out date. The text indicates peak year, peak annual coal-based generation, and peak percent of coal power in total electricity supply (TES). Most PPCA countries pledge to phase-out coal power in line with historical trends. Data from IEA[1]. Pledge date from Table 1 (none for Mexico).

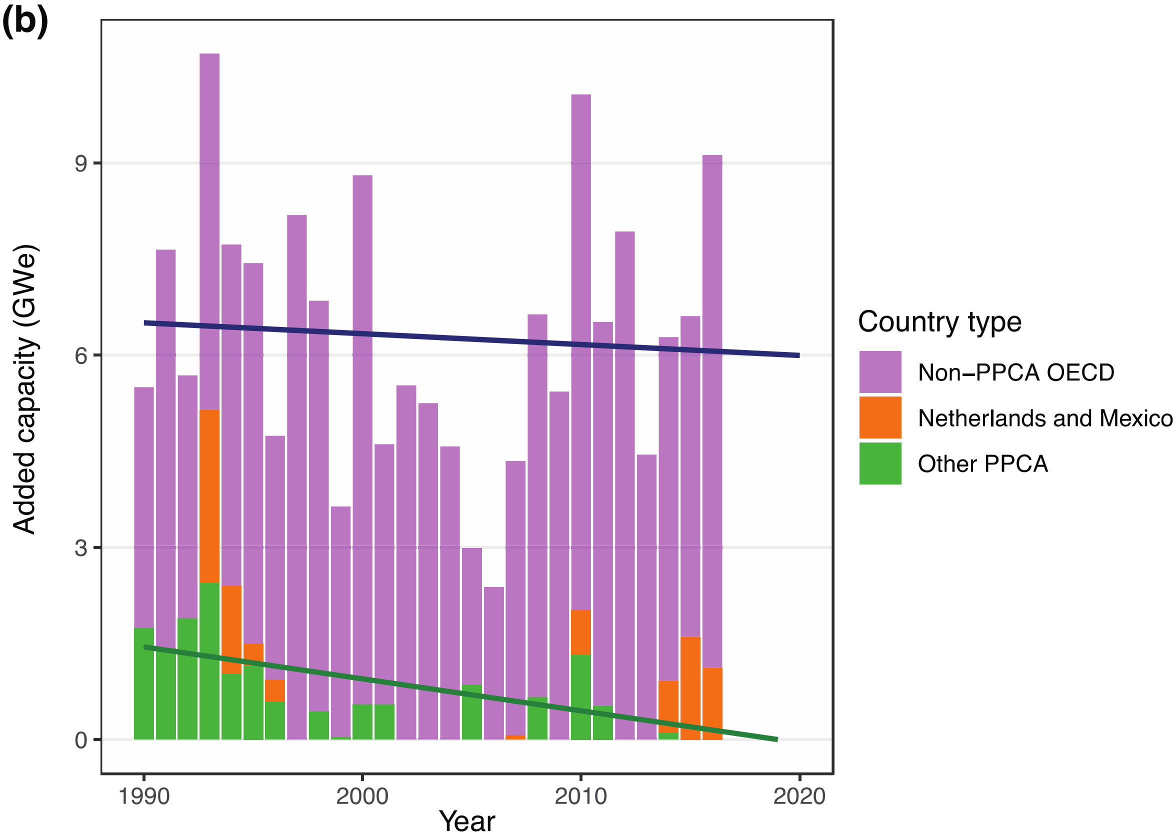


Supplementary Figure 2. New coal power plant construction since 1990. Panel (a) shows PPCA members and all other countries. Panel (b) shows PPCA members (with the Netherlands and Mexico separate) and OECD countries which are not PPCA members with linear trends of construction since 1990 projected through to 2020.

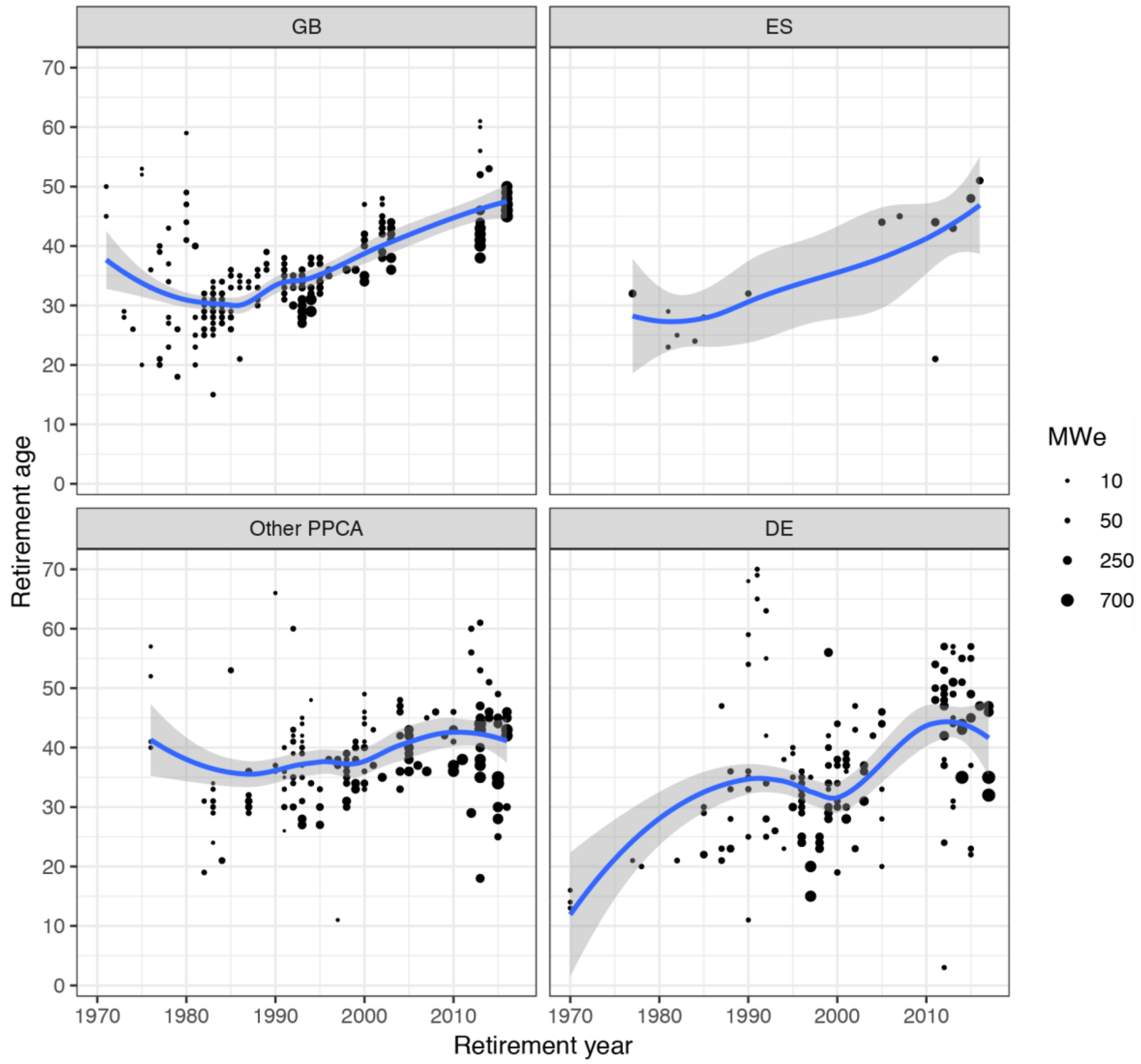
(a)



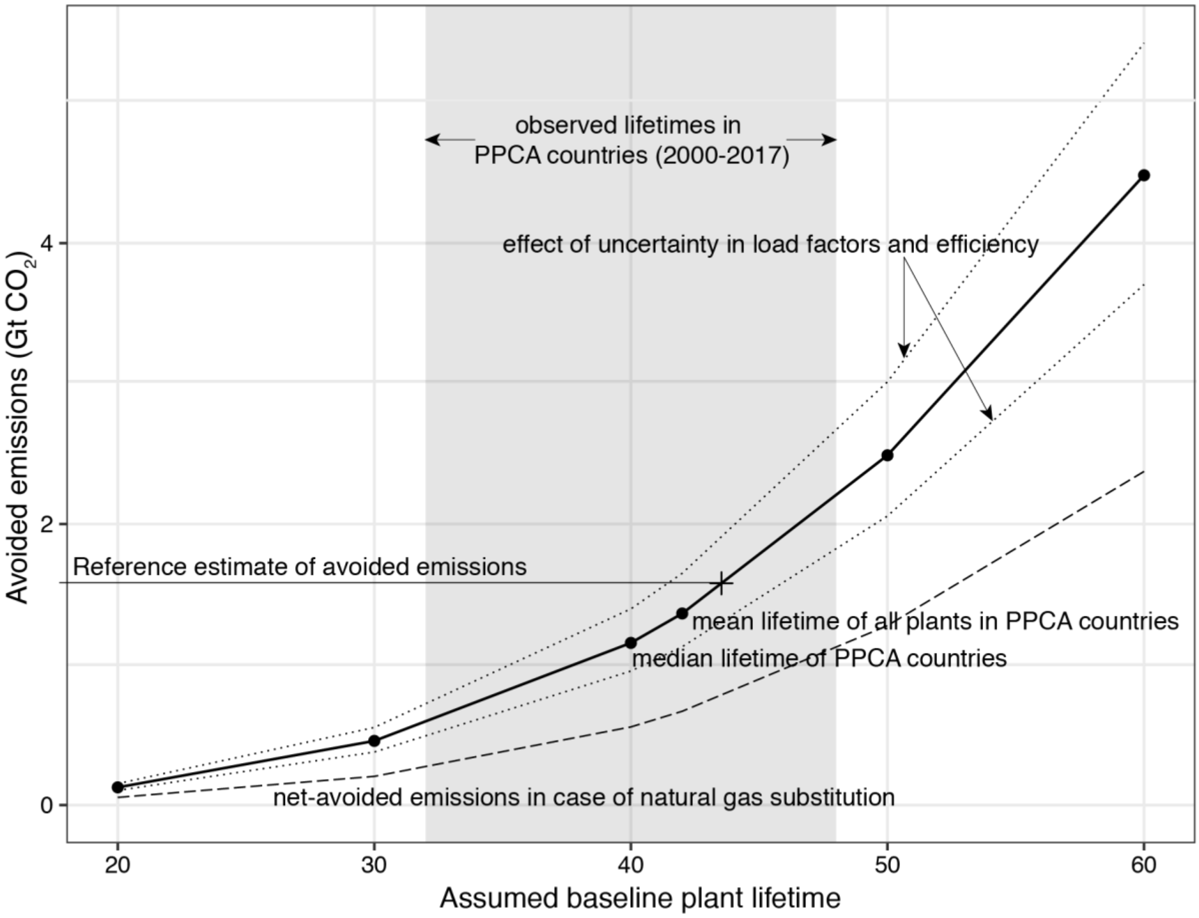
(b)



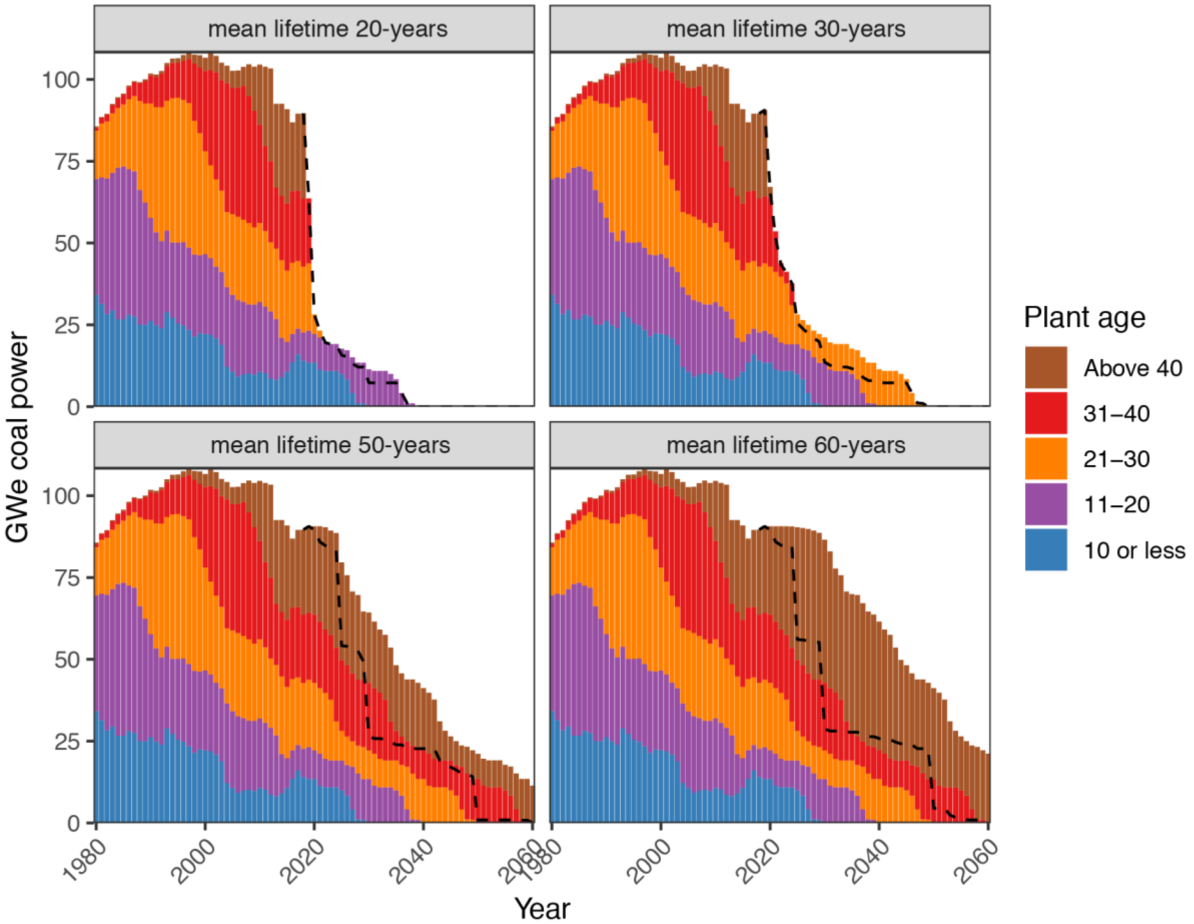
Supplementary Figure 3. Retirement ages of coal power plants in PPCA countries, the UK, Spain and Germany in 1990-2019. Data are from Platts[2]. The trend line shows time-dependent averages through local polynomial regression fitting[3].



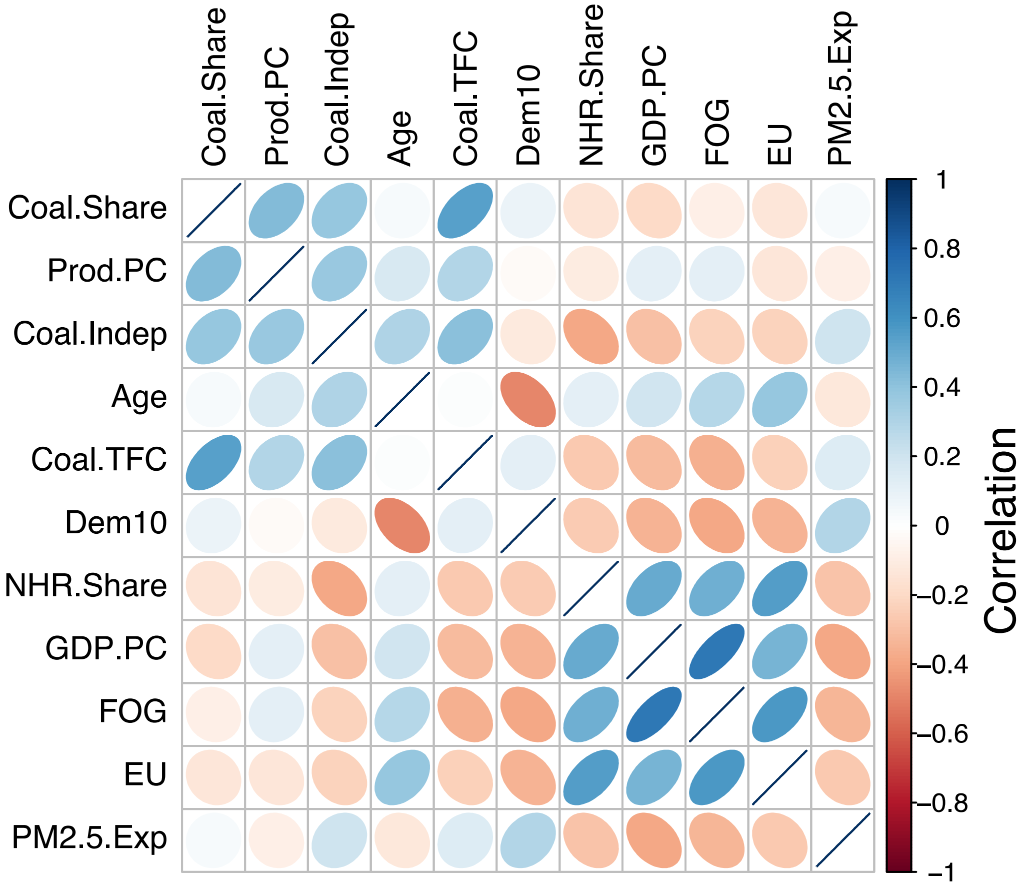
Supplementary Figure 4. Sensitivity analysis for avoided emissions. The horizontal line and the cross represent the reference estimate based on national lifetimes and reference load factors and efficiencies. The solid line shows how avoided emissions depend on different mean lifetime assumptions. The upper dotted line shows how the avoided emissions would change with 10% higher load factor and 10% lower efficiency and the lower dotted line shows how the avoided emissions would change with 10% lower load factor and 10% higher efficiency. The dashed line shows how the central estimate of avoided emissions would change if coal power is replaced with natural gas instead of zero-emission sources. The shaded area shows the range of observed average lifetimes in PPCA countries. See also Supplementary Table 3, the main text, and Supplementary Text 1 for more on the sensitivity analysis.



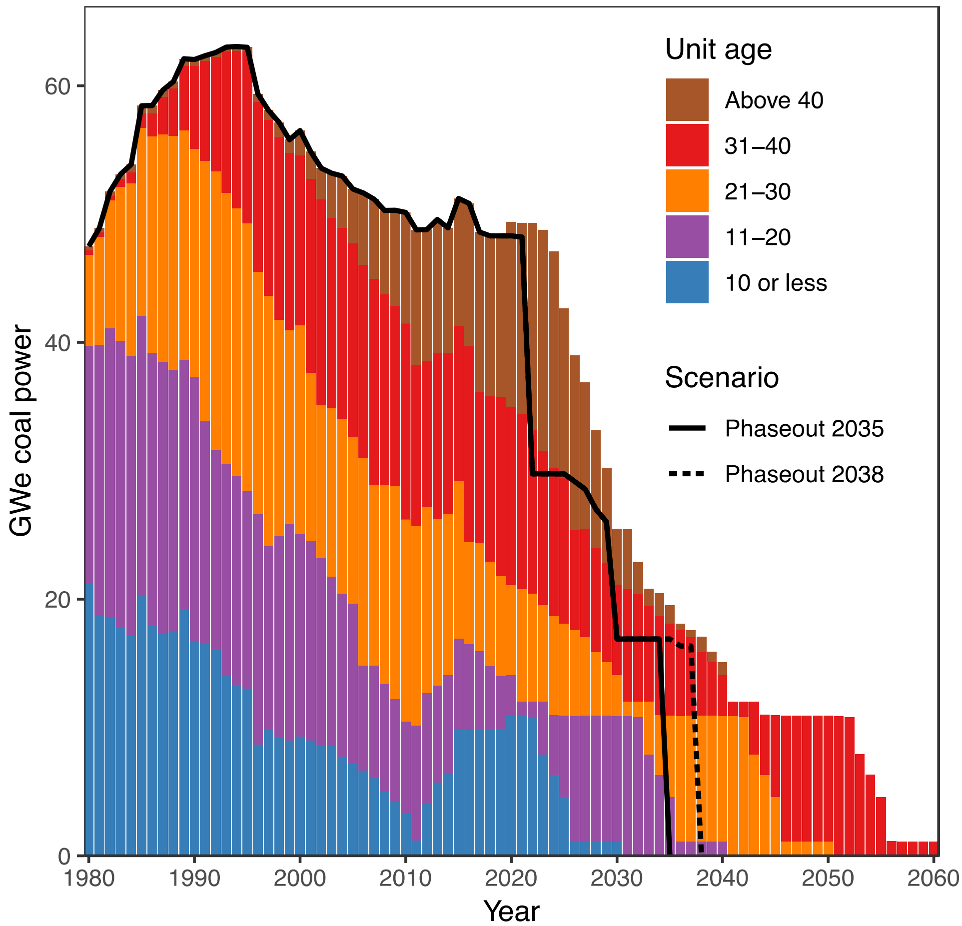
Supplementary Figure 5. Coal power plant fleet under different mean lifetime assumptions with and without retirements forced by PPCA pledges. Future retirements in the baseline (color bars) and forced by PPCA pledges (dashed line) follow the truncated normal distribution procedure we describe in Methods and illustrated in Supplementary Figure 8.



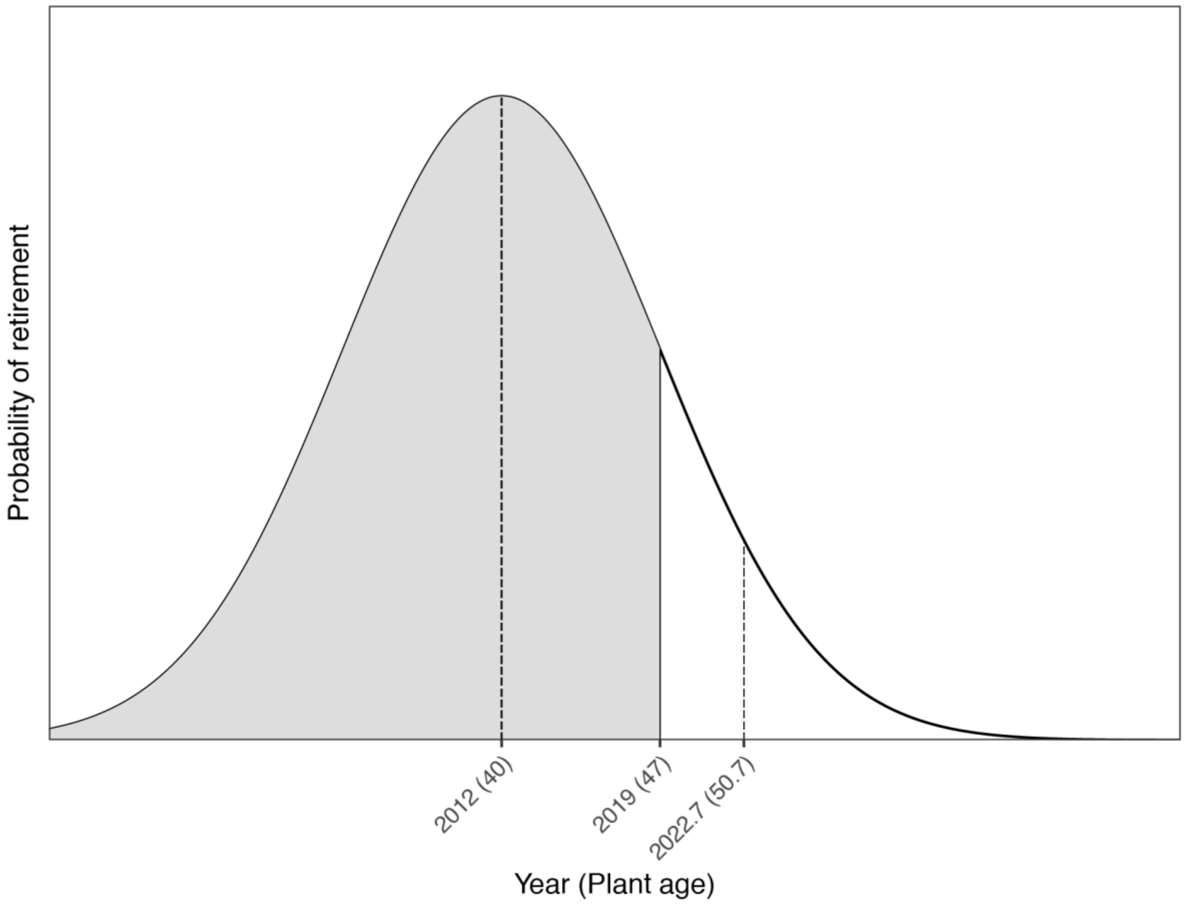
Supplementary Figure 6. Correlation matrix for independent variables. The color and shade of each cell in the matrix indicates the sign and the value of correlation between the two corresponding variables. We used ref. 4,5 for calculation and visualisation of correlation.



Supplementary Figure 7. Capacity of coal power plants in Germany in the baseline and the two phase-out scenarios, 1960-2060. Color bars indicate historical and projected capacity by age cohort. Black lines indicate the proposed phase-out scenarios. Projected capacity is calculated by the method described in the Method section of the main text and Supplementary Text 4 for 2019-2060 for the baseline and the two phase-out scenarios. Historical capacity is based on ref. 2 and phase-out scenarios on ref. 6. The figure shows the new construction in Germany after 2010 and also that the bulk of premature coal power plant retirements is planned for either 2035 or 2038 (see Supplementary Text 4). Baseline does not include new construction except Datteln 4 commissioned in 2020.



Supplementary Figure 8. Using truncated normal distribution to estimate expected plant lifetime. In the example, the average retirement age for an illustrative group of power plants (e.g. in a particular country) is 40 years with a standard deviation of 7 years. The illustrative plant was launched in 1972 and has survived to 2019, when it was 47 years, which is past the average lifetime. The expected lifetime of this plant is determined by the part of the normal distribution starting in 2019 – the truncated normal distribution (unshaded area under the curve). For this particular plant the expected retirement year is approximately 2023 (2022.7). In our projections of future baseline retirement, we will retire this plant in 2023 when it will be ca 51 years old rather than immediately in 2019 (when it already exceeds the mean retirement age).



Supplementary Tables

Supplementary Table 1. Cumulative avoided emissions for PPCA members. Includes PPCA members with non-zero avoided emissions in the reference estimate.

	Cumulative avoided emissions 2019-2050 in $MtCO_2$ based on…					
Jurisdiction	**Reference estimate (based on national lifetime)**	**20-year lifetime**	**60-year lifetime**	**National lifetime, 10% higher load and lower efficiency**	**National lifetime, 10% higher load and lower efficiency**	**Annual CO_2 emissions in 2017[7–9]**
Italy	423.1	27.7	695.9	377.8	512.0	355.5
Netherlands	374.5	92.5	520.0	334.4	453.1	164.0
Israel	168.9	0.0	564.0	150.8	204.3	66.6
Canada	149.7	5.6	744.9	133.7	181.1	572.8
New York (US)	85.2	0.0	100.2	76.0	103.0	164.5
France	81.8	0.0	265.1	73.1	99.0	356.3
Washington (US)	54.6	0.0	70.2	48.7	66.0	81.0
United Kingdom	45.3	0.0	619.8	40.4	54.8	384.7
Ireland	30.4	0.0	136.9	27.2	36.8	39.7
Portugal	26.1	0.0	200.5	23.3	31.5	54.9
Hawaii (US)	24.5	0.0	29.1	21.9	29.6	18.5
Oregon (US)	20.8	0.0	34.7	18.6	25.2	37.9
Connecticut (US)	19.4	0.0	21.6	17.3	23.5	34.4
Balearic Islands (Spain)	19.0	0.0	41.6	16.9	23.0	-
Denmark	17.7	0.0	150.3	15.8	21.4	34.6
Finland	17.2	0.0	135.8	15.3	20.8	46.0
South Chungcheong, (South Korea)	14.9	0.0	39.3	13.3	18.0	-
Sweden	7.8	0.0	21.3	7.0	9.4	41.5
Austria	4.0	0.0	65.6	3.5	4.8	69.9
New Zealand	0.1	0.0	32.5	0.1	0.1	36.0

Supplementary Table 2. Phase-out dates and the capacity, number and age of coal power plant units of subnational members. The pledged phase-out dates are compiled from national sources as referenced in Column 2. All power plant and lifetime data are calculated based on Platts[2]. Average fleet ages are weighted by generation capacity and calculated as of 2019. The theoretical average and minimum ages at phase-out are calculated by adding the 2019 ages to the number of years between 2019 and the phase-out date (see Methods). The average national lifetimes are calculated as the mean of plants retiring since 2000.

Jurisdiction **Country** **State or Province** ***City***	**Pledge**	**Number & (GWe) of operating coal plant units**[2]	**Average & (minimum) age of existing fleet**	**Average & (minimum) age at phase-out**	**Average lifetime & (minimum retirement age) since 2000**
Australia	*none*	70 (24.2)	32 (7)	-	43 (31)
Australian Capital Territory	no operating plants	-	-	-	-
City of Melbourne	no operating plants	-	-	-	-
City of Sydney	no operating plants	-	-	-	-
Canada	phase-out 2030[10]	33 (9.1)	33 (5)	44 (16)	41 (33)
Alberta	phase-out 2030[11]	15 (5.7)	32 (8)	43 (19)	see above
British Columbia	no operating plants	-	-	-	-
City of Vancouver	no operating plants	-	-	-	-
Ontario	no operating plants	-	-	-	-
Quebec	no operating plants	-	-	-	-
Netherlands	phase-out 2030[12,13]	6 (4.8)	10 (3)	21 (14)	36 (28)
City of Rotterdam	*no additional phase-out date*	1 (0.8)	5 (5)	16 (16)	see above
Spain	*none*	35 (10.2)	37 (22)	-	43 (21)
Balearic Islands	phase-out 2025[14]	4 (0.5)	30 (22)	37 (29)	see above
South Korea	*none*	107 (34.2)	17 (2)	-	35 (34)
South Chungcheong	phase-out 2050[15]	28 (16.2)	17 (2)	46 (33)	see above
UK	phase-out 2025[12,13]	45 (15.3)	47 (28)	53 (34)	44 (34)
Scotland	phased out 2016[16]	-	-	-	-
Wales	*no additional phase-out date*	4 (1.6)	44 (40)	50 (46)	see above
US	*none*	901 (282.4)	41 (5)	-	53 (1)
California	phased-out (2016)[17]	-	-	-	-
City of Los Angeles	no operating plants	-	-	-	-
New York	phase-out 2020[18,19]	8 (1.1)	44 (32)	45 (33)	see above
Connecticut	phase-out 2021[20]	1 (0.4)	51 (51)	53 (53)	see above
Hawaii	phase-out 2022[21]	1 (0.2)	27 (27)	30 (30)	see above
City of Honolulu	no operating plants	-	-	-	-
Washington	phase-out 2025[22]	4 (1.4)	46 (43)	52 (49)	see above
Oregon	phase-out 2030[23]	1 (0.6)	39 (39)	50 (50)	see above
Minnesota	no plan for full fleet[24]	29 (4.3)	43 (13)	-	see above

Supplementary Table 3. Effect of uncertainties on avoided emissions benchmarked against globally committed emissions from coal. Columns 2-4 show emissions avoided as a result of PPCA pledges ($GtCO_2$) under the given assumptions about coal power plants lifetime, loads, and efficiency if coal power is replaced by zero-carbon sources. The shaded row shows the reference estimate based on national average lifetimes. Column 5 shows the estimate with reference load and efficiency under different lifetime assumptions if coal is replaced by natural gas. Column 6 shows committed emissions from existed coal power plants worldwide under given lifetime assumptions.

Lifetime	Reference load and efficiency	10% higher load & lower efficiency	10% lower load & higher efficiency	Replacement with natural gas	Coal power committed emissions[25]
20-year mean	0.1	0.2	0.1	0.05	66.2
30-year mean	0.5	0.6	0.4	0.2	128.3
40-year mean	1.2	1.4	1.0	0.6	206.1
42-year mean	1.4	1.7	1.1	0.7	
National average	**1.6**	1.9	1.3	0.8	
50-year mean	2.6	3.0	2.1	1.3	295.7
60-year mean	4.5	5.4	3.7	2.4	390.3

Supplementary Table 4. Coal18 countries and the percent of global installed coal capacity and global coal-fired generation. All power plant age data are calculated based on Platts[2]. Average ages are weighted by generation capacity and calculated as of 2019.

Country	% of global installed coal-fired capacity[2]	% of global coal-fired generation[1]	Number & (GWe) of operating coal plant units[2]	Average & (minimum) age of existing fleet in 2019	Under construction GWe (Number of units)[2]
China	46.1 %	44.2 %	3018 (915)	12 (2)	91 (147)
US	14.2 %	14.1 %	901 (282)	41 (5)	0.02 (1)
India	11.3 %	11.5 %	1328 (223)	14 (2)	53 (105)
Russia	2.6 %	1.8 %	472 (51)	40 (3)	0.2 (4)
Germany	2.4 %	2.8 %	196 (48)	30 (3)	1 (1)
Japan	2.2 %	3.6 %	161 (44)	24 (3)	2 (4)
South Africa	2.1 %	2.4 %	126 (41)	34 (2)	7 (9)
South Korea	1.7 %	2.4 %	107 (34)	17 (2)	6 (7)
Poland	1.6 %	1.4 %	524 (32)	39 (3)	4 (5)
Indonesia	1.4 %	1.4 %	225 (27)	12 (2)	9 (38)
Ukraine	1.2 %	0.6 %	125 (25)	48 (5)	0.2 (1)
Australia	1.2 %	1.7 %	70 (24)	32 (7)	-
Turkey	0.9 %	1.0 %	103 (17)	18 (3)	2 (3)
Vietnam	0.7 %	0.6 %	53 (14)	8 (2)	10 (18)
Kazakhstan	0.6 %	0.7 %	124 (12)	39 (3)	2 (3)
Malaysia	0.6 %	0.7 %	21 (11)	12 (2)	3 (4)
Spain	0.5 %	0.4 %	35 (10)	37 (22)	-
Czech Republic	0.5 %	0.5 %	160 (9)	43 (4)	1 (4)
Total	**91.8%**	**91.9%**	**7749 (1819)**	**21 (2)**	**191 (354)**

Supplementary Table 5. National coal power plant plans for Coal 18 countries.

Country	Plan
Australia	**No phase-out plans** Australia's INDC does not mention coal[26] however the 7th NC from 2017 states that there is a "withdrawal from coal-fired generation" with more than 2 GWe coal-fired electricity assumed to be retired after 2020 replaced by existing coal generation and some gas[27]. Australia has had carbon pricing which compromised the competitiveness of coal, and most argue that at this point renewables competes with coal-fired installations but the current government is a coal supporter[28]. This is illustrated by the Australia prime minister's rejection of recommendations from the IPCC's 1.5°C report saying Australia was committed to coal power[29].
China	**No phase-out plans** China's INDC plans to "control total coal consumption", "enhance" clean coal, and improve coal efficiency[30]. China's 2020 Air Pollution Action Act plans for steps to curb coal use[31], however recent analysis shows recently-reactivated construction of coal plants[32].
Czech Republic	**No phase-out plans** An NGO lobbying for coal phase-out across Europe reports that no coal phase-out is under discussion in the Czech Republic[33], however the country's National Climate and Energy plan submitted to the European Commission plans for decreasing the proportion of coal in the energy mix in favor of nuclear[34].
Germany	**Proposed phase-out plan by 2038 or 2035** In January 2019, the commission for 'growth, structural change and employment' published a report outlining a multi-stakeholder compromise on a multi-stage plan for phase-out of coal power plants in Germany by 2035 at the earliest and 2038 at the latest[6]. See: Supplementary Text 4. Proposed coal phase-out in Germany.
India	**No phase-out plans** India's INDC states "coal will continue to dominate power generation in the future"[35]. India's National Electricity Plan includes about 90 GWe of coal power expansion from 2017-2027[36].
Indonesia	**No phase-out plans** Indonesia's NDC commits to implementation of clean coal technology in coal power plants[37] and the business as usual in Indonesia's National Climate Communication from 2017 depicts significant growth in coal-fired power (and the development of clean coal technology)[38].
Japan	**No phase-out plans** Neither Japan's INDC[39] nor the most recent NC[40] mentions a reduction in coal power. Japan's 2018 also Strategic Energy Plan does not foresee a decrease in coal power[41,42].
Kazakhstan	**No phase-out plans** Kazakhstan's INDC does not mention coal[43]. The 7th NC from 2017 contains a series of technical activities which was adopted in 2013 including: replacing coal-fired power with gas-fired CHP plants in population centers, an audit of all coal power plants which will continue to run after 2020, and replacing current coal capacities with modern coal power plants[44]. Nevertheless, the NC is clear that coal generation will continue to be the main source of energy until 2030, with a restriction of an increase in its share and growth of coal bed methane.
Korea	**No phase-out plans** Korea's INDC does not mention coal power[45]. According to the 8th Basic Plan for Long-term Electricity Supply and Demand from 2017, the Korean government plans to expand coal power from 36.8 GWe to 39.9 GWe by 2030[46].
Malaysia	**No phase-out plans** Malaysia's NDC does not mention coal[47]. Malayia's NC targets that no new coal power plants to be built after 2025[48].
Poland	**No phase-out plans** According to Poland's National Climate and Energy Plan, "the leading role of coal is planned to be maintained" but its relative share will decrease to 60% in 2030 (from today's 77%) due to energy demand growth, the decommissioning of old coal plants and the implementation of high-efficiency coal technologies[49].

Country	Plan
Russia	**No phase-out plans** Russia's INDC[50] and the 7th NC from 2017[51] do not mention reducing coal power. Russia's Energy Strategy published in 2017 contains measures to protect coal production and does not envision reducing the share of coal in its electricity mix[52]. The Master Plan for power plants construction envisions construction of numerous new coal power plants to replace the aging ones and somewhat increased use of coal in those power plants[53].
South Africa	**No phase-out plans** South Africa's INDC speaks of a "complete transformation of the future energy mix, which is designed to replace an inefficient fleet of ageing coal-fired power plants with clean and high efficiency technology going forward" (including with high-efficiency coal)[54]. However, South Africa's most recent National Communication says that "[c]oal is an important part of South Africa's energy mix and will continue to drive economic and social progress of much of the developing world for the foreseeable future"[55]. South Africa's new Integrated Resource Plan calls for a halt in construction of coal-fired power plants with new demand met by renewables, gas and other sources[56]. However, this plan does not lead to significant reductions in generation capacity by 2030, but the Ministry plans to decommission 28 GW by 2040 and 35 GW by 2050 reducing the proportion of coal-based electricity to 17-42% by 2050 (compared to today's 81%).
Spain	**Possible phase-out by 2030** An NGO lobbying for coal phase-out across Europe reports that no coal phase-out is under discussion in Spain[33], however the country's National Climate and Energy plan submitted to the European Commission states that coal-fired electricity will not supply electricity beyond 2030[57] and the country has already committed to closing all coal mines by the end of 2018[58].
Turkey	**No phase-out plans** Turkey's NDC does not mention coal[59] and the 7th NC includes plans for increasing the use of coal power plants[60].
Ukraine	**No phase-out plans** Ukraine's NDC does not refer to coal[61]. According to the more recent National Emission Reduction Plan for Large Combustion Plants[62], Ukraine's strategy is not to phase-out coal power generation but rather to replace obsolete and inefficient power plants with more flexible and efficient facilities. More specifically it presumes to replace ca 7.1 GW of coal power plants by more efficient ones (of the same or larger capacity) by 2023. Each of these facilities will not be allowed to operate for more than 20,000 hours during 2018-2023. In the second phase of modernisation, additional 11.4 GW of capacity will be replaced by newer plants in 2024-2033. Each of these plants will be allowed to operate for max of 40000 hours within this period.
US	**No phase-out plans** The US NDC pledges significant reduction of emissions from electricity generation resulting primarily from substituting coal by natural gas and other sources[63,64]. A notable reduction of coal use in electricity has been driven by market factors from the late 2010s[65]. The 2015 Clean Power Plan[66] contained measures to accelerate this reduction, but it has been challenged and virtually repealed by the current US Administration[64]. Nevertheless the market-driven reduction of coal use is likely to continue into the future[63].
Vietnam	**No phase-out plans** Vietnam's INDC does not mention coal[67] but Vietnam's 3rd NC from February 2019 states that ultra-super critical coal power generation is the highest priority for the power generation sector[68]. Vietnam's energy plan assumes continued growth and an addition of some 40 GWe of coal-fired power plants between 2015 and 2030[69] though a statement by the Prime Minister in 2016 contradicted these plans and proposed possibly replacing coal with gas[70].

Supplementary Table 6. Key characteristics of all coal-consuming countries and country groups PPCA and Coal 18. (See Methods for data and calculation).

Country group	**All**	**PPCA**	**Coal 18**
Number of countries	68	14	18
EU members	21 (31%)	10 (71%)	4 (22%)
Share of global coal-fired capacity, %	100 %	3.2 %	91.8 %
Share of coal in electricity supply, %	Mean: 29.9% Median: 28.3% SD: 24.5% Range: 1.2-93%	Mean: 15.1% Median: 11.3% SD: 11.8% Range: 2.1-39.4%	Mean: 49.6% Median: 45.2% SD: 22.1% Range: 13.4-93%
Coal production per capita, toe/person	Mean: 0.6 Median: 0.1 SD: 1.7 Range: 0-12.1	Mean: 0.1 Median: 0 SD: 0.2 Range: 0-0.8	Mean: 1.5 Median: 0.7 SD: 2.8 Range: 0-12.1
Share of coal in in non-transport final energy consumption, %	Mean: 7.6% Median: 3.6% SD: 9.3% Range: 0-42.4%	Mean: 2.5% Median: 2.1% SD: 1.8% Range: 0.1-6.8%	Mean: 14.8% Median: 10.9% SD: 12.1% Range: 1.8-42.4%
Independence of coal supply, %	Mean: 51.3% Median: 53.1% SD: 43% Range: 0-100%	Mean: 24.6% Median: 0.5% SD: 36.5% Range: 0-100%	Mean: 67.7% Median: 85.1% SD: 39.3% Range: 0.6-100%
Electricity demand change (2006–2016), %	Mean: 34.3% Median: 11.9% SD: 68.1% Range: -28.5-482.1%	Mean: 1.5% Median: -0.1% SD: 11.2% Range: -11.7-26.1%	Mean: 38.6% Median: 11.2% SD: 51.9% Range: -13-171.4%
Average age of coal-fired plants, years	Mean: 27.2 Median: 31 SD: 13 Range: 2.6-49.6	Mean: 32 Median: 33.1 SD: 8.3 Range: 9.7-46.3	Mean: 27.8 Median: 30.9 SD: 13.1 Range: 7.9-48
Share of non-hydro renewables in electricity supply, %	Mean: 8.8% Median: 6.8% SD: 9.8% Range: 0-51.8%	Mean: 18.2% Median: 16% SD: 12.5% Range: 2.7-51.8%	Mean: 7.4% Median: 6.5% SD: 7.9% Range: 0.1-28.3%
Air pollution (exposure to PM2.5), mkg/m^3	Mean: 26 Median: 19.7 SD: 26.9 Range: 5.5-203.7	Mean: 12.2 Median: 11.7 SD: 4.4 Range: 5.5-18.8	Mean: 24.8 Median: 19.2 SD: 17.6 Range: 6.1-75.8
GDP per capita, 1000 USD	Mean: 17.3 Median: 8.7 SD: 17.6 Range: 0.4-64.1	Mean: 39.2 Median: 40.8 SD: 13.4 Range: 8.5-64.1	Mean: 18.5 Median: 10.2 SD: 17.7 Range: 1.7-57.6
Functioning of government, 0-12	Mean: 7.5 Median: 8 SD: 3.3 Range: 0-12	Mean: 11 Median: 11.5 SD: 1.4 Range: 7-12	Mean: 7.1 Median: 7.5 SD: 3.9 Range: 1-12

Supplementary Table 7. Logistic regression results (selected models) with PPCA membership as dependent variable. Standard errors in parentheses. *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$. "FP" refers to the number of false positives (countries incorrectly predicted as PPCA members); "FN" refers to the number of false negatives (PPCA members incorrectly predicted as non-members). Model 1.1 is the full model with all 10 dependent variables. Model 1.2 illustrates the process of step-wise backward elimination to improve AIC. Model 1.3 is the best-fit model (out of 1013 tested). Model 1.4 is the best model with only 2 variables (see Figure 3 in the main text). Model 1.5 illustrates that replacing FOG with EU in model 1.4 worsens model fit and predictive power.

Model	(1.1)	(1.2)	(1.3)	(1.4)	(1.5)
Observations	68	68	68	68	68
Coal.Share	-4.564(4.967)	-6.407(4.375)	-6.32(4.265)	-9.243(3.931)**	-4.42(3.554)
Coal.Indep	1.369(2.809)	-0.692(1.948)			
Dem10	-3.36(7.195)				
Age	0.017(0.075)	0.014(0.055)			
GDP.PC	0.086(0.048)*		0.072(0.038)*		0.109(0.035)***
FOG	0.884(0.639)	1.222(0.436)***	1.131(0.503)**	1.167(0.373)***	
Prod.PC	-6.216(4.051)	-1.923(2.997)	-3.749(2.205)*		-2.104(1.886)
NHR.Share	6.121(9.287)				
Coal.TFC	-49.485(32.971)	-21.913(19.076)	-37.25(27.065)		-20.297(19.932)
EU	-1.695(2.214)				0.991(1.012)
AIC	43.17	40.56	34.64	36.33	41.76
Prediction FP/FN	3/1	2/3	2/2	1/2	2/5

Supplementary Table 8. Detailed regression results for selected models. Models 1.3 and 1.4 are according to Supplementary Table 7.

Term	**Estimate**	**Std. error**	**Z-score**	**P-value**	**Conf. intervals**
			Model 1.3		
(Intercept)	-11.36	4.75	-2.39	0.017	[-23.33; -4.04]
Coal.Share	-6.32	4.27	-1.48	0.138	[-16.21; 1.39]
GDP.PC	0.0718	0.0383	1.87	0.061	[0.002; .16]
FOG	1.13	0.5	2.25	0.025	[0.31; 2.37]
Prod.PC	-3.75	2.21	-1.7	0.089	[-8.98; -0.16]
Coal.TFC	-37.25	27.07	-1.38	0.169	[-103.16; 6.59]
			Model 1.4		
(Intercept)	-10.49	3.43	-3.06	0.002	[-19.06; -5.13]
Coal.Share	-9.24	3.93	-2.35	0.019	[-18.97; -3.04]
FOG	1.17	0.37	3.13	0.002	[0.59; 2.1]

Supplementary Table 9. Average marginal effects for logistic regression in selected models. Models 1.3 and 1.4 are according to Supplementary Table 7.

Variable	Effect
	Model 1.3
Coal.Share	-0.33
GDP.PC	0.0038
FOG	0.060
Prod.PC	-0.20
Coal.TFC	-1.97
	Model 1.4
Coal.Share	-0.66
FOG	0.083

Supplementary Table 10. Selected illustrative models with PM2.5 exposure included as an independent variable. PPCA membership is the dependent variable. Standard errors in parentheses. **p* < 0.1; ***p* < 0.05; ***p < 0.01. "FP" refers to the number of false positives (countries incorrectly predicted as PPCA members); "FN" refers to the number of false negatives (PPCA members incorrectly predicted as non-members). See Supplementary Text 3 for discussion.

Model	(2.1)	(2.2)	(2.3)
No	68	68	68
Coal.Indep	4.656(3.188)		3.772(3.066)
GDP.PC	0.136(0.057)**	0.081(0.039)**	0.116(0.048)**
Prod.PC	-11.135(5.254)**	-5.117(2.153)**	-9.467(4.764)**
PM2.5.Exp	-0.357(0.154)**	-0.276(0.135)**	-0.304(0.128)**
Coal.TFC	-43.634(28.771)	-42.234(27.091)	
Dem10		-3.178(3.059)	
AIC	33.39	34.62	34.67
FP/FN	3/2	1/2	2/4

Supplementary Table 11. Technology-specific production efficiencies for coal plants.

Technology	Katzer et al.[71]	Hardisty et al.[72]	Average
Subcritical	34.3%	33%	33.7%
Supercritical	38.5%	41%	39.8%
Ultra-supercritical	43.3%	43%	43.2%

Supplementary Table 12. Emission factors for different types of coal[73].

Coal by type	Kilograms CO_2/Million Btu
Anthracite	103.70
Bituminous	93.30
Subbituminous	97.20
Lignite	97.70

Supplementary Texts

Supplementary Text 1. Sensitivity analysis

We conduct a sensitivity analysis on (1) the percent of prematurely retired plants from the pledges of PPCA members, (2) the avoided emissions from PPCA pledges and (3) the reduction of coal-fired generation in 2030.

For the percent of prematurely retired plants (1), our findings would change if we varied the assumed coal power plant lifetime on either the lifetimes. This would range between 11-68% under a standard lifetime uncertainty range of 30 to 50 years[74,75], and between 7-87% under the widest assumed lifetime range of 20 to 60 years[76] (Supplementary Text 1).

For the avoided emissions (2), we test the sensitivity of our results to the assumed plant lifetimes, plant efficiencies and load factors, as well as what would substitute coal generation (Supplementary Figure 4 and Supplementary Table 3). For calculating the premature retirement, for the central estimate, we use the average national plant lifetimes since 2000 which ranges from 32 to 48 years (see Table 1 and Methods). We conduct a sensitivity analysis of avoided emissions on the assumed power plant lifetime of both the standard[77,78] and widest range[25] in the literature (Supplementary Figure 4 and Supplementary Table 3). We also compare the results of this sensitivity to calculations on committed emissions with different coal power plant lifetimes (Supplementary Table 3).

We also conduct a sensitivity analysis of estimated of avoided emissions to the assumptions about power plant efficiencies and load factors (2). For the reference estimate, we use nationally-calibrated load factors and technology-specific power plant efficiencies (Methods). We vary both power plant efficiencies and load factors by +/-10% to cover any potential change in these parameters. Our estimate of variance of power plant efficiency is based on analysis of US EPA data for capacities and output of different power plants[79] with which we determined that the mean efficiency is 32% with a standard deviation of 2.4% and a full range of 24-41%. For load factors, scenarios for future developments vary from no change[80] to an initial increase of some 10% through 2035 followed by a decrease through until 2050[81], thus we also varied load factors by +/-10%.

Finally, for the reduction in 2030 coal-fired generation (3), we test how varying the assumed lifetimes affects coal-fired generation in 2030 (Figure 1). For the minimum estimate, we use a 20-year lifetime and for our maximum estimate, we use a 60-year lifetime.

Supplementary Text 2. Selecting explanatory variables for PPCA membership

We used a systematic approach for identifying variables that could potentially explain PPCA membership and predict future expansion of the Alliance. We looked for variables that would:

- be linked to specific mechanisms plausibly supporting or blocking a political decision to phase-out coal;
- could be consistently measured for the 68 countries in our sample (i.e. PPCA and other countries using non-trivial amounts of coal for electricity production);
- would not duplicate other variables used in our analysis including our dependent variable (membership in PPCA).

Committing to phase-out the use of coal in electricity generation is a political decision by a nation state. Political decisions concerning energy use are influenced by state goals, domestic special (non-state) interests, and international policy diffusion. How these diverse inputs into the policy process are combined depends on motivations, capacities and interactions of the state and other relevant actors[82–84].

Motivations for energy policies can arise from **state energy goals** which include first and foremost the need to maintain a secure supply-demand balance[85]. How coal phase-out affects this goal depends on the share of coal in electricity supply, whether coal is domestically-produced or imported and whether and how fast electricity demand is increasing. The availability of domestic coal reserves and other electricity generation technologies may also affect this goal. Other state goals relevant to the energy sector may include climate change mitigation, air pollution reduction, and economic development.

In addition to state energy goals, domestic policies are shaped by **vested interests**, including those opposing coal phase-out policies because they may be particularly hurt by lost employment, stranded assets and slowed economic development in coal producing regions[86]. The resistance of the coal sector to phasing-out coal support policies like coal subsidies or preferential purchasing agreement schemes for coal power has been documented in the UK[87], Germany[88–91], and South Africa[92]. There may also be domestic interests supportive of coal phase-out through citizens or organizations concerned by air pollution or climate change or even specifically targeting coal (through organizations like Beyond Coal[33] and Coal Swarm[17]). Additionally, there can be economic interests potentially competing with coal like new renewables. However, these are usually more diffuse interests which tend to be less influential in policy change processes[93].

International policy diffusion would involve imitation, harmonization with, learning from or coercion by other states or international organizations. Apart from the PPCA itself, the European Union's Council of Ministers has recently reached a deal to end coal subsidies[94], the European Parliament recently passed a resolution calling Member States to phase-out coal as an energy source by 2030[95] and there are also a number of decarbonization targets which indirectly support coal phase-out and thus may facilitate diffusion of coal phase-out policies, especially given very strong political and economic ties between EU members.

Finally, **capacities** of the state can be sub-divided into economic and institutional[96]. By economic capacities we mean the ability of the society to pay the costs of coal phase-out (e.g. compensation to plant owners and support to regions dependent on mining, compensation and retraining of the work-force, mobilizing investments for electricity supply infrastructure that would replace coal, etc.). Wealthier countries have been shown to lead development of new energy technologies[82] and promote stricter environmental policies. An example of why economic capacity is important is a recent estimate of large costs of adjustment measures recommended by the German "Coal exit" commission[97] or similar costs in Spain[58] which we cite in the text.

"**Institutional capacity**" (sometimes also referred to as "political capacity") is the capacity of a country's institutions to implement specific policies. It was first introduced in Ikenberry's seminal study of the differences in national responses to the 1970s-1980s oil crises[96]. Political capacity has generic elements of the ability to formulate and implement any policies (e.g. the human and financial resources of government agencies), that is closely correlated (but not identical) to GDP per capita. For example, relatively rich energy exporting countries (sometimes called 'petro-states') are widely viewed as having lower political capacities. In a more specific sense, institutional capacity enables integrating and balancing different domestic interests and international influences. Governments of stable democratic countries with low levels of corruption are better able to formulate and see through decisions serving state interests and to take into account state goals and disperse political interests (e.g. citizens concerns with air pollution or climate change) rather that concentrated vested interests (e.g. of coal sector).

Based on these premises we have identified the following variables and associated hypotheses, which can potentially explain coal phase-out (see Methods in the main text for data sources and exact definition of each variable):

1. Higher **share of coal in electricity generation** is expected to **decrease** the likelihood of PPCA membership through increasing the costs of coal phase-out (deploying other energy sources and technologies to substitute lost coal capacity and potentially compensating stranded coal assets) and also increasing political resistance from coal-centered socio-technical regimes (e.g. plant workers and owners).
2. Higher **production of coal per capita** is expected to **decrease** the likelihood of PPCA membership since it increases the strength of socio-technical regimes centered on coal and most likely resisting its phase-out. It also increases the costs of coal power phase-out in the form of stranded assets and potential compensation to affected communities.
3. Higher **share of coal in non-transport final energy consumption** (i.e. in buildings, heating, and industry) is expected to **decrease** the likelihood of PPCA membership for the same reason as coal production: because it is associated with the strength of coal-centered socio-technical regimes.
4. Higher **import dependence of coal supply** is expected to **increase** the likelihood of PPCA membership**.** Phasing out imported coal is easier because it won't risk energy security and it would not face resistance from domestic coal extraction industry.
5. Higher **electricity demand growth** is expected to **decrease** the likelihood of PPCA membership because countries would need not only to substitute lost coal power capacity but also deploy additional capacities to address the extra electricity demand.
6. Higher **age of power plants** is expected to **increase** the likelihood of PPCA membership**.** Retiring older power plants would lead to a smaller amount of stranded assets and thus less resistance to coal phase-out.
7. Higher **use of non-hydro renewable electricity technologies** is expected to **increase** the likelihood of PPCA membership**.** Deployment of new renewables such as solar and wind signals both political commitment to decarbonisation and political and socio-technical capacity for energy transition and would therefore be associated with higher probability of coal phase-out.
8. Higher levels of **air pollution** are expected to **increase** the likelihood of PPCA membership through increased pressures on the government from affected citizens and communities.
9. Higher **GDP per capita** is expected to **increase** the likelihood of PPCA membership since wealthier societies would be less sensitive to potential increase in electricity prices if coal is substituted by more expensive sources and because richer states would have more resources to compensate potential losers of prematurely closed coal power plants.
10. More **transparent and independent governance** is expected to **increase** the likelihood of PPCA membership**.** We use the Functioning of Government (FoG) index to express this characteristic. FoG is a combined measure of (1) the absence of undue influence on elected government, (2) government transparency, and (3) checks against political corruption[98]. The importance of the government policies in supporting the persistence of the coal sector has been highlighted in the UK[87], Germany[88–91], and South Africa[92]. Governments free from corruption are potentially more capable on following through state goals, taking into account (typically dispersed) public concerns about air pollution and climate change and resisting (typically concentrated) lobbying pressures of pro-coal

interests. They are also more likely to conceive and implement effective phase-out policies e.g. by effectively compensating the losers of coal phase-out.

11. **EU membership** is expected to **increase** the likelihood of PPCA membership. EU member countries subscribe to EU-wide policies to limit the use of coal, for example the recent deal on ending coal subsidies[94] and the call by the European Parliament to end coal power by 2030[95] as well as to more general decarbonisation targets and to learn from other EU members (e.g. the UK and Germany) which have been pursuing controlled reduction of coal use.

Naturally, the complex mechanisms that can lead to a decision to phase-out coal could also be explained by other variables. However, many such variables cannot be used for systematic and rigorous comparison across countries. Some key variables which we have considered but not analyzed include:

National coal reserves. Although this variable can signal availability of coal, costs of extractions and transportation significantly vary across countries and thus coal may be less available even for countries with large (but expensive to extract and/or remote) resources. Russia and Ukraine are examples of such countries. Coal use and coal production per capita are better proxies of the attractiveness of producing domestic coal.

Availability of substitutes for coal power. Although this variable could signal how easy it is to replace coal with other sources, there are significant problems with consistently measuring and comparing it across countries. First, coal can be replaced by a variety of sources including oil, natural gas (either domestic or imported), nuclear power, and renewables (including hydro power, solar, wind, biomass etc.) as well as electricity demand reduction. In case of PPCA, replacing unabated coal with CCS-equipped plants is also explicitly mentioned. Various countries have different potentials and capacities of using different sources technologies and it may be difficult to compare, say, a country with large shale gas reserves with a country that has capacity to build nuclear power plants or large energy saving potential. Secondly the 'availability' of all these technologies and sources is also difficult to measure in a consistent manner: some may depend on geographic features of countries while others – on their technological and economic capacities. However, the aggregate measure of all these various resources and technologies is the use of non-coal sources in the electricity mix, which is inverse to the existing variable of the share of coal. In other words, countries that have smaller shares of coal presumably have larger availability of non-coal sources and vice-versa.

We consulted the Global CCS Institute's Global Status of CCS Report 2015[99] to compare the prospects of CCS deployment in PPCA and non-PPCA countries at the time immediately preceding the formation of the Alliance. The data in the report do not indicate any systematic differences in either CCS-related policies, geographic conditions for CCS deployment or actual CCS projects between PPCA and non-PPCA members. This industry group identifies the UK and Canada (PPCA members) as well as Australia, US, Japan and China (non-PPCA members) as potential leaders of CCS deployment in terms of potential, policies and projects. Moreover, PPCA members include several countries with low interest in CCS and no active projects like Sweden, France, and Italy.

Civil society activism. It is difficult to consistently compare the strength and effectiveness of civil society activism (that is often anti-coal but may also be in defense of pro-coal interests) across different political cultures. However, by measuring the Functioning of Government index we approximate the level of democracy in a country (i.e. how acceptable is civil activism) and the receptiveness of governments to citizens voices and concerns.

Coal subsidies and other government policies. This variable could signal government commitment to the coal sector, but it will also introduce a circularity in the analysis. Phasing-out coal subsidies is often a crucial part of coal phase-out and PPCA membership, while their persistence is a clear sign that no phase-out is planned. In other words, this is a result of a clear phase-out policy not an explanation in our study.

Supplementary Text 3. Regression analysis results and additional tests

Within the regression analysis we first produced 2036 models with 11 independent variables (see Methods and Supplementary Text 2). All of the models that include air pollution (PM2.5 concentration) as a significant variable feature paradoxical results, in which this variable has an unexpected *negative* effect on PPCA membership (Supplementary Table 10). This effect does not reflect any of the presumed causal mechanisms although it can be speculated that low air pollution may be an indicator of stronger air pollution control and other environmental policies, (typically found in wealthy well governed countries), which may eventually support coal phase-out. Since effective statistical models should not include variables not linked to meaningful causal mechanisms, we excluded the air pollution variable from further analysis.

For the remaining 10 variables, we once again produced 1013 machine-generated models and identified the 10 and 20 best-fit models based on their AIC. The variables which found significant (at least at 10% level) in all of these models include:

1. **FoG** (significant in 10 out of 10 best models and 18 out of 20 best models);
2. **GDP per capita** (significant in 7 out of 10 best models and 12 out of 20 best models);
3. **Coal production per capita** (significant in 5 out of 10 best models and 8 out of 20 best models);
4. **Coal share in electricity production** (significant in 3 out of 10 best models and 8 out of 20 best models);
5. **Coal share in non-transport final energy consumption** (significant in 1 of the 10 and 20 best models).

All these five variables are also present in our best-fit model (Model 1.3 in Supplementary Table 7, Supplementary Table 8 and Supplementary Table 9) with Functioning of Government, GDP per capita and Coal production per capita being significant variables. In other words, we show that these five variables found in the best-fit model consistently show up as significant in a limited subset of best-fit models, which is not the case for other tested variables.

Among these five variables, Functioning of Government reflects political factors, GDP per capita reflects economic factors and the remaining three variables reflect closely intertwined techno-economic factors characterizing the production and use of coal. Due to the limited number of data-points, we were not able to disentangle the effect of individual coal-related variables. However, we were able to demonstrate their collectively significance (and hence the role of the coal sector) with certainty. We tested the collective significance of these three variables using the likelihood ratio test[100] which compares a full model that includes these variables and a reduced model with these variables omitted. The test indicates that these characteristics of the coal sector are collectively significant at the 0.15% level. Even two of these variables: coal production per capita and coal share in electricity production are still collectively significant at the 5% level.

The presence and significance of the five variables in the best-fit models stands in stark contrast to the remaining 5 variables which we use in regression analysis.

6. **Average age of coal power plants** appears as significant first in the model ranked **82** by AIC and is present but not significant in the model ranked 5 by AIC;
7. **Share of non-hydro renewables** appears as significant first in the model ranked **186** by AIC and is present but not significant in the model ranked 12 by AIC;
8. **Change in electricity demand in 2006-2016** appears as significant first in the model ranked **251** by AIC and is present but not significant in the model ranked 14 by AIC;
9. **EU membership** appears as significant first in the model ranked **258** by AIC and is present but not significant in the model ranked 13 by AIC;
10. **Coal independence** appears as significant first in the model ranked **274** by AIC and is present but not significant in the model ranked 4 by AIC.

Based on this analysis we concluded that the first five variables provide better explanation of PPCA membership than the last five. Naturally, our statistical analysis explores correlations and not causations and although we aimed to identify plausible causal mechanisms, our results should be validated and elaborated by other methods (e.g. case-studies) to improve their robustness.

Supplementary Text 4. Proposed coal phase-out in Germany

In January 2019, the German Commission for growth, structural change and employment ("Wachstum, Strukturwandel und Beschäftigung", here: the Commission) published its final report outlining a compromise on the phase-out of coal-fired power plants in Germany[6]. The members of the Commission which included representatives of the coal industry, workers, policy makers, environmental advocacy groups, representatives of regions with coal industries, and scientists agreed on phasing out coal-fired power generation by 2038.

The Commission recommended that by 2022, the net capacity of coal-fired power plants is reduced from the current 47 GWe to 15 GWe lignite and 15 GWe hard coal capacity. By 2030, this should be further reduced to 9 GWe lignite and 8 GWe hard coal capacity. The "open clause" of the report provides the possibility for an acceleration of the final phase-out to 2035 or for re-evaluating its feasibility in 2032. Thus, the coal power phase-out timeline in Germany includes the following elements[6]:

- **30. June 2020.** Develop a plan for the retirement of lignite power plants in agreement with the power plant owners. If the plan is not reached by this date the government should enforce a plan by law. The agreement should contain financial compensation and social acceptability.
- **2022. Reduce the generation capacity to 15 GWe lignite and 15 GWe hard coal** through retirement or retrofitting (increased CHP) and switching the grid backup capacity (ca 2.3 GW) from coal to natural gas.
- **2023.** Evaluation of measures realized so far
- **2025.** Intermediate step: reduce annual emissions by 10 $MtCO_2$ through an "innovation project"
- **2026.** Evaluation of measures realized so far
- **2029.** Evaluation of measures realized so far
- **2030**. **Reduce the generation capacity to 9 GWe lignite and 8 GWe hard coal** through retirement
- **2032.** "Öffnungsklausel" (open clause): evaluate whether coal phase-out can be realized already in 2035 and whether the phase-out is realistic in general.
- **2035 (earliest) – end of 2038 (latest).** Complete phase-out.

This plan stipulates the bulk of the premature retirement to occur in either 2035 or 2038 (see Supplementary Figure 7).

The plan is generally acknowledged to be technologically and economically feasible[101]. However, the cost of the plan is uncertain. Financial support for regional development and structural change in affected areas in line with the Commission's recommendations is estimated to amount to 40 billion €[97]. In its scale, this aid is comparable with the structural aid provided to Eastern Germany following Germany's unification in the 1990s[97]. While there are already concrete proposals on the timeline and the recipients of these funds[102], there are also uncertainties of how much of these will be additional to the already existing programs[103,104]. Further compensations to stabilize electricity prices for private consumers and the industry and support for workers are also envisioned[105–107].

Additionally, the Commission recommended that the government achieves a compromise with the owners of prematurely retired power plants. This most likely will involve compensations determined through negotiations[6]. The utility RWE has demanded compensation of 1.2-1.5 bln € for each prematurely retired GWe and the shares of the company have risen in expectations of this compensation[108,109]. Some are criticizing this as an expensive political gesture since many coal-fired plants are relatively old and would likely be decommissioned soon in any case[101]. The legal obligation of the Government to pay compensations for foregone profits has also been questioned[110]. Compensation is also a critical aspect in negotiations with Uniper, regarding the question whether its new power plant Datteln 4, currently under construction, will be connected to the grid. This hard coal power plant with a net capacity of 1.1 GWe was planned to be connected in 2011 but protests from environmental advocacy groups as well as technical issues led to a delay of the project. The current planned start date is 2020[111,112].

The report does not explicitly specify how coal-fired power generation will be substituted. While Germany keeps increasing its renewable electricity capacity and takes measures to reduce electricity demand, it is also expanding its capacities to generate power from natural gas. Germany is likely to build two liquified natural gas terminals in the foreseeable future[113,114]. Additionally, the Nord Stream 2 pipeline is to be completed in November 2019[115].

Age of retirement

The average age of retirement of coal power plants in Germany in 2000-2017 is 41 years. For our calculations, we assume that the plans will be retired according to the 'truncated normal distribution' procedure described in the main text Methods and illustrated in Supplementary Figure 8. This ensures that units which are already older than the recent average lifetime are not retired en-masse at the starting point of the projection. We calculate capacities separately for lignite and hard coal power plants.

We determine the necessary reductions from these baseline capacities to reach the targets proposed by the Commission (15 GWe lignite and 15 GWe for hard coal each in 2022 and 8 GW hard coal and 9 GW lignite in 2030 as well as zero in 2038 or in 2035 for both fuels). We then retire plants until the target is reached, starting from the oldest operating plants and also plants with unspecified type of coal (in 2022 only). This means that:

- in 2022, 18.4 GWe of coal power capacity with the weighted average unit age of 46 years and the minimum age of 37 years would be retired;
- in 2030, 9.1 GWe of coal power capacity with the weighted average unit age of 41 years and the minimum age of 35 years would be retired;

- in 2038, 16.9 GW of coal power capacity with the weighted average unit age of 30 years and the minimum age of 22 years would be retired; if this retirement is accelerated to 2035, the weighted average age will be reduced to 27 years and the minimum – to 19 years.

Avoided emissions

To calculate avoided coal-fired power generation and CO_2 emissions of this proposal, we follow the same method as for the PPCA members (see Methods) taking into account the retirement timeline outlined above. To estimate the upper boundary of avoided emissions, we conduct sensitivity analysis with the final phase-out in 2035 and Datteln 4 never entering operation (but its emissions counted as avoided). The avoided emissions under these assumptions would be **1609 $MtCO_2$**. If phase-out is completed by 2038 and Datteln 4 operates between 2020 and 2038, the avoided emissions would be **1301 $MtCO_2$.** If in addition, all of the avoided generation are substituted by natural gas, the avoided emissions would be **644 $MtCO_2$.**

References

1. IEA. *World energy balances. IEA World Energy Statistics and Balances (database).* (2018).
2. Platts. World Electric Power Plants Data Base. (2017).
3. Cleveland, W., Grosse, E. & Shyu, W. Local regression models. in *Statistical Models* (eds. Chambers, J. & Hastie, T.) (Wadsworth & Brooks/Cole, 1992).
4. Rummel, R. J. *Applied Factor Analysis*. (Northwestern University Press, 1988).
5. Wei, T. & Simko, V. *R package 'corrplot': Visualization of a correlation matrix (Version 0.84)*. (2017).
6. German Ministry of Economy and Energy. *Commission 'Growth, Structural Change and Employment' (Kommission 'Wachstum, Strukturwandel und Beschäftigung')*. (2019).
7. Boden, T., Marland, G. & Andres, R. *Global, Regional, and National Fossil-Fuel CO2 Emissions*. (2017). doi:10.3334/CDIAC/00001_V2017
8. UNFCCC. National Inventory Submissions. (2017). Available at: https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories/submissions-of-annual-greenhouse-gas-inventories-for-2017/submissions-of-annual-ghg-inventories-2014. (Accessed: 1st June 2018)
9. US EPA. *State CO2 emissions from fossil fuel combustion*. (2018).
10. Government of Canada. Coal phase-out: the Powering Past Coal Alliance. (2018). Available at: https://www.canada.ca/en/services/environment/weather/climatechange/canada-international-action/coal-phase-out.html. (Accessed: 18th April 2018)
11. Government of Alberta. *Phasing out coal pollution*. *Climate Leadership Plan* (2018).
12. Beyond Coal. *Overview: National coal phase-out announcements in Europe*. (2018).
13. Industry Briefing. Europe energy Europe coal phase outs gather pace. *Economist Intelligence Unit* (2017).
14. Beetz, B. Spain's Balearic Islands proposes ambitious 100% renewable energy law. *PV Magazine* (2018).
15. Chen, H. Korean Province to phase out coal: implications for Asia. *National Resource Defense Council* (2018). Available at: https://www.nrdc.org/experts/han-chen/korean-province-phase-out-coal-implications-asia. (Accessed: 5th December 2018)
16. Scottish Government. Scottish Government joins clean power group. *Scottish Government* (2018). Available at: https://www.gov.scot/news/powering-past-coal-alliance/. (Accessed: 13th March 2019)
17. EndCoal. Global Coal Plant Tracker. *Coal Swarm* (2018). Available at: https://endcoal.org/tracker/. (Accessed: 20th April 2018)
18. KallanishEnergy. New York moves to end coal- fi red power plants by. *Kallanish Energy* (2018).
19. Henry, D. NY gov aims to phase out coal by. *The Hill* (2018).
20. Opalka, B. New England's last coal-fired power plants face uncertain futures. *Energy News* (2018).
21. Yerton, S. Oahu's cheapest source of power is about to go away. *Honolulu Civil Beat* (2017).
22. Paulos, B. Washington State leaves coal behind, but not its workers. *energytransition.org* (2018).
23. 78th Oregon Legislative Assembly. *No Title*. (2016).
24. Orr, I. Minnesota plans to retire 1,829 MW of coal and replace it with 7,200 MW of wind, solar, and gas. *American Experiment* (2018).
25. Davis, S. J. & Socolow, R. H. Commitment accounting of CO_2 emissions. *Environ Res Lett* **9**, (2014).
26. Government of Australia. *Australia's Intended Nationally Determined Contribution to a new Climate Change Agreement*. (2015).

27. Government of Australia. *Australia's 7th National Communication on Climate Change: A Report Under the United Nations Framework Convention on Climate Change*. (2017).
28. Jotzo, F., Mazouz, S. & Wiseman, J. *Coal Transitions in Australia. Preparing for the looming domestic coal phase-out and falling export demand.* (2018).
29. Krapp, P. Australian government backs coal in defiance of IPCC climate warning. *The Guardian* (2018).
30. Department of Climate Change and National Development & Reform Commision of China. *China's First INDC Submission. UNFCCC* (2015).
31. Xu, M. & Stanway, D. China to cut coal use, curb steel in 2018-2020 pollution plan | Reuters. *Reuters* (2018).
32. Shearer, C., Yu, A. & Nace, T. *Tsunami Warning: Can China's central authorities stop a massive surge in new coal plants caused by provincial overpermitting?* (2018).
33. Europe Beyond Coal. *Overview: National coal phase-out announcements in Europe, Coal phase-out status November 2018*. (2018).
34. *Czech Republic National Climate and Energy Plan*. (2019).
35. *India's Intended Nationally Determined Contribution: Working Towards Climate Justice*. (2016). doi:10.1017/CBO9781107415324.004
36. Central Electricity Authority. *National Electricity Plan*. (2018).
37. *First Nationally Determined Contribution Republic of Indonesia*. (2016).
38. Spencer, T. *et al.* Climate Policy The 1.5°C target and coal sector transition: at the limits of societal feasibility The 1.5°C target and coal sector transition: at the limits of societal feasibility. (2017). doi:10.1080/14693062.2017.1386540org/10.1080/14693062.2017.1386540
39. Government of Japan. *Submission of Japan's Intended Nationally Determined Contribution (INDC)*. (2015).
40. Government of Japan. *Japan's Seventh National Communication Under the United Nations Framework Convention on Climate Change*. (2017).
41. Government of Japan Ministry of Economy Trade and Industry. *Strategic Energy Plan*. (2018).
42. Normile, D. Bucking global trends, Japan again embraces coal power. *Science (80-)* **360**, 476–477 (2018).
43. Republic of Kazakhstan. *Intended Nationally Determined Contribution: Submission of the Republic of Kazakhstan*. (2015).
44. Ministry of Energy of the Republic of Kazakhstan, United Nations Development Programme in Kazakhstan & Global Environment Facility. *Seventh National Communication and third Biennial report of the Republic of Kazakhstan to the UN Framework Convention on Climate Change*. (2017).
45. Republic of Korea. *Submission by the Republic of Korea Intended Nationally Determined Contribution*. (2015).
46. Korean Ministry of Trade Industry and Energy. Ministry announces 8th Basic Plan for Electricity Supply and Demand. (2017). Available at: http://english.motie.go.kr/en/tp/energy/bbs/bbsView.do?bbs_seq_n=605&bbs_cd_n=2&view_type_v=TOPIC&&currentPage=1&search_key_n=&search_val_v=&cate_n=3. (Accessed: 13th November 2018)
47. The Government of Malaysia. *Intended Nationally Determined Contribution of the Government of Malaysia*. (2015). doi:10.1007/s13398-014-0173-7.2
48. Ministry of Energy Science Technology Environment and Climate Change. *Malaysia Third National Communication and Second Biennial Update Report To the UNFCCC*. (2018). doi:ISBN 978-967-13297-4-0
49. Ministerstwo Energii. *National Energy and Climate Plan for the years 2021-2030: Objectives and targets, and policies and measures*. (2019).
50. Government of the Russian Federation. The Russian Federation's Intended Nationally Determined Contribution. 3 (2015).
51. Government of the Russian Federation. *Seventh National Communication of the Russian Federation submitted in accordance with Articles 4 and 12 of the United Nations Framework Convention on Climate Change and Article 7 of the Kyoto Protocol*. (2017).
52. The Government of the Russian Federation. *Energy Strategy of Russia for the period to 2035*. (2017).
53. The Government of the Russian Federation. *Master Plan for Siting Electricity Facilities up to 2035: Decree 1209*. (2017).
54. *South Africa 's Intended Nationally Determined Contribution (INDC)*. (2015). doi:10.1002/0471238961.0601141913151418.a01
55. Department of Environmental Affairs Republic of South Africa. *South Africa's Third National Communication under the United Nations Framework Convention on Climate Change*. (2018).
56. Department of Energy Republic of South Africa. Integrated Resource Plan 2018 Final Draft for Public Input. (2018).
57. Ministry of Ecological Transition for the Government of Spain. *Draft of the integrated national energy and climate plan 2021-2030*. (2018).
58. Neslen, A. Spain to close most coalmines in € 250m transition deal. **3**, (2018).
59. Republic of Turkey. *Republic of Turkey Intended Nationally Determined Contribution*. (2015).
60. Republic of Turkey Ministry of Environment and Urbanization, Global Environment Facility & Program, U. N. D. *Seventh National Communication of Turkey under the UNFCCC*. (2018).

61. The Government of Ukraine. *Ukraine first nationally determined contribution*. (2016).
62. The Government of Ukraine. *National plan for reduction of emissions from large combustion facilities. Approved by the Cabinent of Ministers on 08.11.2017, No 796-p.* (2017).
63. EIA. *Annual Energy Outlook 2019 with projections to 2050*. (2019).
64. Greenblatt, J. B. & Wei, M. Assessment of the climate commitments and additional mitigation policies of the United States. *Nat Clim Chang* **6**, 1090–1093 (2016).
65. US Department of State. *Second Biennial Report of the United States of America under the United Nations Convention on Climate Change*. (2016).
66. Environmental Protection Agency. EPA Proposes Affordable Clean Energy (ACE) Rule. (2018).
67. Vietnam Prime Minister. *Intended Nationally Determined Contribution of Viet Nam*. (2015). doi:10.2214/ajr.172.4.10587147
68. Socialist Republic of Viet Nam. *The third national communication of Viet Nam to the United Nations Framework Convention on Climate Change*. (2019).
69. MOIT Vietnam & Embassy of Denmark. *Vietnam energy outlook report*. (2017).
70. Nhu, V. Plans on developing power, coal sectors adjusted. *The socialist republic of Vietnam, Online Newspaper of the Government* (2016).
71. Katzer, J. *et al. The Future of Coal: An interdisciplinary MIT study*. (Massachusetts Institute of Technology, 2007).
72. Hardisty, P. E. *et al.* Life Cycle Greenhouse Gas Emissions from Electricity Generation: A Comparative Analysis of Australian Energy Sources. *Energies* **5**, 872–897 (2012).
73. US Energy Information Administration. Carbon Dioxide Emission Coefficients. *Environment* (2016). Available at: https://www.eia.gov/environment/emissions/co2_vol_mass.php. (Accessed: 16th January 2018)
74. Johnson, N. *et al.* Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technol Forecast Soc Change* **90**, 89–102 (2015).
75. Steckel, J. C., Edenhofer, O. & Jakob, M. Drivers for the renaissance of coal. *Proc Natl Acad Sci* **112**, E3775–E3781 (2015).
76. Davis, S. J. & Socolow, R. H. Commitment accounting of CO<inf>2</inf> emissions. *Environ Res Lett* **9**, (2014).
77. Edenhofer, O., Steckel, J. C., Jakob, M. & Bertram, C. Reports of coal's terminal decline may be exaggerated. *Environ Res Lett* **13**, 24019 (2018).
78. Johnson, N. *et al.* Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technol Forecast Soc Change* **90**, 89–102 (2015).
79. US Environmental Protection Agency. 2018 coal unit characteristics. (2019).
80. International Energy Agency. *World Energy Outlook 2018*. (2018).
81. European Commission. *EU Reference Scenario 2016 - Energy, transport and GHG emissions - Trends to 2050. Energy, transport and GHG emissions - Trends to 2050* (European Union, 2016). doi:10.2833/9127
82. Jewell, J. Ready for nuclear energy?: An assessment of capacities and motivations for launching new national nuclear power programs. *Energy Policy* **39**, (2011).
83. Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E. & Sovacool, B. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Res Soc Sci* **37**, (2018).
84. Cherp, A., Vinichenko, V., Jewell, J., Suzuki, M. & Antal, M. Comparing electricity transitions: A historical analysis of nuclear, wind and solar power in Germany and Japan. *Energy Policy* **101**, (2017).
85. Helm, D. Energy policy: Security of supply, sustainability and competition. *Energy Policy* **30**, 173–184 (2002).
86. Spencer, T. *et al.* The 1.5°C target and coal sector transition: at the limits of societal feasibility. *Clim Policy* **18**, 335–351 (2018).
87. Turnheim, B. & Geels, F. W. Regime destabilisation as the flipside of energy transitions: Lessons from the history of the British coal industry (1913-1997). *Energy Policy* **50**, 35–49 (2012).
88. Frondel, M., Kambeck, R. & Schmidt, C. M. Hard coal subsidies: A never-ending story? *Energy Policy* **35**, 3807–3814 (2007).
89. Pahle, M. Germany's dash for coal: Exploring drivers and factors. *Energy Policy* **38**, 3431–3442 (2010).
90. Storchmann, K. The rise and fall of German hard coal subsidies. *Energy Policy* **33**, 1469–1492 (2005).
91. Jungjohann, A. & Morris, C. *The German coal conundrum*. (2014).
92. Baker, L., Newell, P. & Phillips, J. The Political Economy of Energy Transitions: The Case of South Africa. *New Polit Econ* **19**, 791–818 (2014).
93. Olson, M. *The logic of collective action: public goods and the theory of groups*. (Harvard University Press, 1971).
94. Simon, F. EU forges deal on coal phase-out, with special Polish clause. *Euractiv* (2018). Available at: https://www.euractiv.com/section/electricity/news/eu-hammers-deal-on-coal-phase-out-with-special-polish-clause/. (Accessed: 18th March 2019)
95. European Parliament. *A Europe that protects: Clean air for all*. (2019).
96. Ikenberry, G. J. The irony of state strength: Comparative responses to the oil shocks in the 1970s. *Int Organ* **40**, 105–137 (1986).

97. Schultz, S. Germany should phase-out coal by 2038 at the latest (Deutschland soll bis spätestens 2038 aus der Kohle aussteigen). *Spiegel Online* (2019).
98. Freedom House. *Freedom in the world 2018: Methodology*. (2018).
99. Global CCS Institute. *The global status of CCS 2015: Summary Report*. (2015).
100. Kleinbaum, D. & Klein, M. *Logistic regression: A self-learning text*. (Springer US, 2010).
101. SpiegelOnline. Union politicians warn against 'expensive iconology'. *Spiegel Online* (2019).
102. Stratmann, K. & Witsch, K. Almaier wants to help the coal regions with 40 billion euros of aid through 2038 (Altmaier will den Kohleländern mit 40 Milliarden Euro bis 2038 helfen). *Handelsblatt* (2019).
103. SpiegelOnline. Government plans to decide measures for structural change by the end of May (Regierung will bis Mai Maßnahmen für Strukturwandel beschließen). *Spiegel Online* (2019).
104. Schultz, S. What will the agreement of the Coal Exit bring (Was die Einigung zum Kohleausstieg bringt). *Spiegel Online* (2019).
105. Zeit Online. Many billions for Coal Exit (Viele Milliarden für den Kohleausstieg). *Zeit Online* (2019).
106. Cembalest, M. *Eye on the market: Annual Energy Paper*. (2019).
107. Wehrmann, B. RWE substantiates claims for billion-euro coal plant compensation. *Clean Energy Wire* (2019).
108. Steitz, C. & Käckenhoff, T. Germany's RWE to keep struggling coal-fired plants as exit nears. *Reuters* (2019).
109. Wacket, M. RWE shares up on hopes for higher coal exit compensation. *Reuters* (2019).
110. Bauchmüller, M. & Müller, B. The government is not yet negotiating with energy companies (Regierung verhandelt noch nicht mit Energiekonzernen). *Süddeutsche Zeitung* (2019).
111. Steitz, C. & Käckenhoff, T. Germany's coal exit could mean cash windfall for plant operators. *Reuters* (2019).
112. Uniper SE. Datteln 4. (2018). Available at: https://www.uniper.energy/de/datteln-4. (Accessed: 25th March 2019)
113. Cohen, A. Germany's first LNG terminal is the right move for Europe's energy security. *Forbes* (2018).
114. Reuters. Update 1 - Germany set to have at least 2 LNG terminals - minister. *Reuters* (2019).
115. Johnson, I. Nord Stream 2 gas pipeline to open by November. *Deutsche Welle* (2019).