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Citation for the original published paper (version of record):
Bi, S., Bauer, N., Jewell, J. (2023). Coal-exit alliance must confront freeriding sectors to propel Paris-aligned momentum. Nature Climate Change, In Press.
http://dx.doi.org/10.1038/s41558-022-01570-8

nature climate change

Article https://doi.org/10.1038/s41558-022-01570-8

Coal-exit alliance must confront freeriding sectors to propel Paris-aligned momentum

Received: 27 January 2022

Accepted: 24 November 2022

Published online: 6 February 2023

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The global phase-out of coal by mid-century is considered vital to the Paris Agreement to limit warming well-below 2 °C above pre-industrial levels. Since the inception of the Powering Past Coal Alliance (PPCA) at COP23, political ambitions to accelerate the decline of coal have mounted to become the foremost priority at COP26. However, mitigation research lacks the tools to assess whether this bottom-up momentum can self-propagate toward Paris alignment. Here, we introduce dynamic policy evaluation (DPE), an evidence-based approach for emulating real-world policy-making. Given empirical relationships established between energy-economic developments and policy adoption, we endogenize national political decision-making into the integrated assessment model REMIND via multistage feedback loops with a probabilistic coalition accession model. DPE finds global PPCA participation <5% likely against a current policies backdrop and, counterintuitively, foresees that intracoalition leakage risks may severely compromise sector-specific, demand-side action. DPE further enables policies to interact endogenously, demonstrated here by the PPCA's path-dependence to COVID-19 recovery investments.

Under the Paris Agreement, 175 nations agreed to common-but-differentiated responsibilities toward limiting global warming to 1.5–2 °C above pre-industrial levels[1]. While cost-effectiveness analyses (CEA) by integrated assessment models (IAMs) derive techno-economically and geophysically feasible scenarios to achieve climate targets[2,3], their political feasibility is often scrutinized[4–8]. Sociopolitical barriers are well-acknowledged, either through ex ante 'second-best' policy pathways—for example, delayed action[9,10], regionally differentiated ambition[11] or technological skepticism[12]—or ex post evaluation frameworks blending techno-economic with socio-institutional feasibility[13,14]. However, these scenarios still exogenously distribute policy burdens from the top-down across disparate societies amidst a bottom-up international regime without credible enforcement mechanisms[15,16].

Whereas CEA (acronym definitions in Supplementary Table 5) explores political ambitions needed to achieve stated goals, stated policy evaluation (SPE) illustrates the consequences of maintaining current ambition levels, for example already-implemented national policies (NPi) or nationally determined contributions (NDCs) to Paris[17–19]. Stated policy scenarios are typical reference baselines for cost-effectiveness and policy evaluation analyses (PEA), which assess subsequent mitigation options for their potential contribution to specified targets (Table 1). Conspicuously, these conventional evaluations prescribe policy trajectories from a static perspective[20]. To portray realistic expectations for baseline ambition and subsequent policies, models should instead emulate the bottom-up, contextual nature of climate politics[6,21,22]. Two methodological innovations are necessary to achieve this: (1) to objectively and dynamically quantify policy feasibility[6] and diffusivity[23–25] and (2) harness bidirectional feedbacks between national policy adoption and the global energy economy[7].

Here, we introduce dynamic policy evaluation (DPE), an approach (Table 1) which merges techno-economic and political analyses (Fig. 1)[7,26] of coal phase-out policies. We build on the tradition of IAMs, which derive long-term energy system investment patterns consistent with historical and anticipated socio-economic trends[27–29] and empirical research codifying links between national techno-economic contexts

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https://doi.org/10.1038/s41558-022-01570-8

Table 1 | Approaches to IAM scenario analysis compared

IAM approach	Research question	Coal phase-out insight	Feasibility focus
Cost-effectiveness analysis (CEA)	What policy actions and ambition levels are required to achieve cost-optimal pathways toward an environmental goal (for example, Paris climate targets)?	Coal is often phased out by 2050 in cost-efficient, Paris-compliant, benchmark scenarios[38,39].	Endogenous assessment of a target's techno-economic feasibility given assumptions on future technology and socio-economic developments that may include political feasibility constraints.
Policy evaluation analysis (PEA)	What could a given policy (or policy suite) accomplish towards a stated goal if adopted globally or in a predetermined coalition?	A global coal-exit by ~2050 can account for half the emissions reductions required for the 2 °C Paris climate target[46].	Assessment of long-term impacts of hypothetical policy options with endogenous technological feasibility and exogenous prescription of political feasibility (or global policy adoption).
Stated policy evaluation (SPE)	What are the long-term outcomes if revealed[17] or stated[18,19] ambition essentially remains static over time?	Current PPCA members abate 2.5 $GtCO_2$ of emissions from coal-fired electricity[31].	Assessment of current policies or pledges assumed to be politically feasible but also to remain static. Often used as baseline reference scenarios.
Dynamic policy evaluation (DPE)	Given diverse and fluid national contexts, how does the implied global ambition toward a bottom-up initiative compare to its stated goals? How do the policy's energy system impacts affect the coalition's future growth?	As global systems and national politics co-evolve, where will coal phase-out policies become politically feasible and how much coal can be expected to phase-out by 2050, vis-à-vis the PPCA?	Concurrent endogenous assessment of a policy's techno-economic feasibility via IAM and political feasibility via empirical analysis of IAM scenario data. This interdisciplinary coupling captures reciprocal feedbacks between policy adoption and the energy system, improving realism of future policy uptake and thus emissions.

DPE merges energy-economy models (for example, IAMs), which excel in depicting long-term techno-economic feasibility and research on sociopolitical feasibility, which investigates and formalizes the mechanisms and drivers of climate policy. DPE endogenizes feedbacks between the two disciplines to embed national political dynamics in IAM analyses, improving conventional SPE depictions of baseline policy ambition and opening new doors for research on politically feasible mitigation strategies. We demonstrate DPE on coal phase-outs by soft-coupling the intertemporal optimization IAM REMIND to a logit model but future implementations may also endogenize continuous functions in simulation models, for example.

and political decisions[30–36]. DPE captures the global energy system impacts of emerging policy initiatives in variables computed in stated policy IAM scenarios, feeds them to an empirically derived policy feasibility model and systematically defines policy pathways across regions, sectors and periods for a subsequent scenario (Methods; Extended Data Fig. 3). This feedback loop mimics the co-evolution of energy economics and politics; national energy strategies are influenced by global energy markets, which respond to other states' behaviours. The loop iterates dynamically, allowing governments to endogenously alter course mid-scenario; n.b. our contribution is distinct from the tradition of 'iterating' social science insights with IAMs[4,7,37].

CEA-derived mitigation strategies and international negotiations frequently prioritize the phase-out of coal[38–41], given its low economic value, high emissions factor, readier substitutes and longer-lived capital relative to other fossil fuels[42–45]. The aggregate desirability of abandoning coal is further underscored by PEA demonstrations of the health and environmental benefits[46]. The sociopolitical feasibility, meanwhile, remains underexplored[31,47,48]. As some nations continue to commission coal-fired power plants[34,49–51] (Extended Data Fig. 1), others have formed the Powering Past Coal Alliance (PPCA), an opt-in initiative aspiring to eradicate 'unabated coal-fired electricity' by 2030 in the Organisation for Economic Co-operation and Development (OECD) and by 2050 in developing and emerging economies[52].

While the 48 national PPCA members as of April 2022 comprise just 6.1% of global coal-fired electricity, this has more-than-doubled since 2019[31,52]. However, this political momentum cannot be depicted by techno-economic (Table 1) nor sociopolitical models alone (Fig. 1). Using DPE, we address this uncertainty through the following research questions. Assuming that climate ambitions stagnate otherwise, can this coalition propel Paris-aligned coal-exit diffusion via technology spillovers or does coal leakage prevail in freeriding nations? Does the policy's omission of coal demand in non-electric sectors risk rebound effects, especially within member states (intersectoral, intracoalition leakage)? Finally, how path-dependent is PPCA evolution to near-term coal demand recovery following COVID-19 (ref. 53)?

We define an outcome as sociopolitically feasible if there are actors who have the capacity to realize it in a given context[54]. Thus, feasible policies must align with the imperatives of states that have sufficient capacity to overcome vested interests[6]. For coal-exit pledges, ref. 31 derived a dynamic feasibility space (DFS) to define national probabilities of PPCA accession. The study performed logistic regression on 2,036 permutations of 11 independent variables, establishing that high per capita GDP (GDPpc; state capacity) and low shares of coal in electricity supply (coal-power share; contextual inertia) are robust predictors of PPCA accession[31] (Supplementary Appendix III and Methods).

Given that IAM scenarios coherently depict both inputs and that the DFS is assumed to remain valid over time[6,31], we pioneer the prospective quantification of policy feasibility by coupling the PPCA-DFS with the IAM REMIND[55] (Fig. 1). The COALogit model interface downscales REMIND-computed coal-power shares to the country level (Supplementary Table 4), uses them alongside shared socio-economic pathway SSP 2 (ref. 29) GDPpc forecasts to execute the PPCA-DFS, uses probabilistic thresholds (feasibility frontiers[6]) to define PPCA membership scenarios (Fig. 2) and rescales them to REMIND's region-level for policy application (Methods).

Results

This REMIND–COALogit loop repeats in 2025 and 2045 to simulate OECD and non-OECD PPCA accession, respectively (Extended Data Fig. 4). We model 18 PPCA scenarios altogether, exploring three uncertainties in parallel: feasibility threshold, policy coverage and COVID-19 recovery (Table 2).

We first analyse the energy system impacts of our default 50p scenarios following neutral and brown COVID recoveries, selected because China accedes in the former but not the latter (Fig. 2c,d):

(1) Power-neutral-50p (power-exit policy–neutral recovery–50%-probable coalition)
(2) Power-brown-50p
(3) Demand-neutral-50p
(4) Demand-brown-50p

We analyse sensitivities across each dimension by comparing all PPCA scenarios against benchmarks.

Power-exit

Following a neutral COVID-19 recovery, operating coal-power capacity declines 10% from 2020 to 2025 to 1,850 GW (Supplementary Appendix I). The resulting national coal-power shares and upward-trending GDPpc in SSP2 leads 35 of 38 OECD nations to surpass 50% accession probability by 2025 (Fig. 2b), one REMIND period

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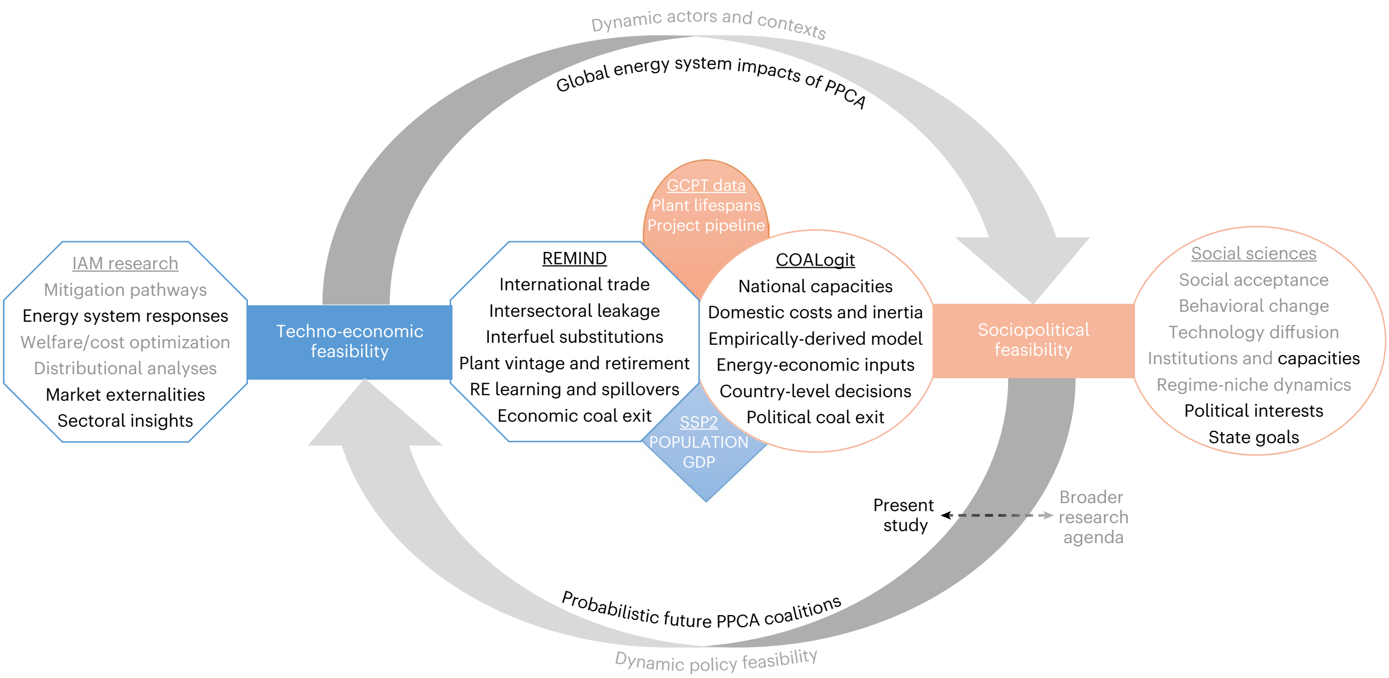

Fig. 1 | DPE: a cyclical interface between techno-economic and sociopolitical analyses. In the present study (inside the cycle; black font), REMIND assesses the impacts of current coal-exit commitments on regional electricity sectors and global energy markets. COALogit downscales regional REMIND coal-power shares to feed the PPCA-DFS, derive national PPCA adoption probabilities and translate them into regionally differentiated policy constraints. Staged accession is simulated by repeating the cycle in 2025 and 2045, the REMIND time-steps preceding each PPCA deadline. Common scenarios of near-term coal capacity (GCPT, Global Coal Plant Tracker) and per capita GDP (SSPs) growth drive both models.

before the 2030 phase-out deadline. COALogit assigns them to the neutral-50p coalition, which completes the power-exit by 2030 in the subsequent OECD-power-neutral-50p REMIND run (Extended Data Fig. 4).

COALogit then assesses the propensity of non-OECD countries to accede before 2050 on the basis of their coal-power shares (from OECD-power-neutral-50p) and GDPpc (from SSP 2) in 2045. A total of 137 of 201 non-OECD nations cross the neutral-50p threshold, so the full power-neutral-50p coalition comprises 182 members representing 82% of 2020 coal-power generation. The REMIND–COALogit cascade's final REMIND run (non-OECD-power-neutral-50p) is fixed to OECD-power-neutral-50p until 2030, giving non-OECD coalition members from 2035 to 2050 to execute the power-exit.

The brown recovery increases coal-fired capacity 13% from 2020 to 2025, to 2,320 GW. Coal-power shares thus deviate from the neutral recovery but GDPpc develops identically. This leads Chile and China to abstain from accession in 2025 and 2045 (Fig. 2d), respectively, so the power-brown-50p scenario includes 44 OECD members (25% of 2020 coal-power generation) and 136 non-OECD (11%).

Coal market response

The power-neutral-50p coalition reduces their total 2020–2100 (henceforth, cumulative) unabated coal-fired electricity demand 38% from NPi-neutral (Fig. 3a). This depresses the global coal market price 8% by 2050, triggering a 54% global coal leakage rate—each joule of coal phased out incentivizes 0.54 J of coal use in other sectors or countries.

Power-brown-50p coalition members reduce their reference cumulative coal-fired electricity by just 24%. China's abstention decreases the policy's intended effect by 80% (791 EJ), while the coal leakage rate rises to 61%. Counterintuitively, 85–90% of coal leakage in either scenario remains within the coalition, into freeriding sectors. Freeriding nations actually reduce their coal-power demand in favour of coal-to-liquids and solids, mirroring the Alliance.

Energy system response

Oil and gas account for two-thirds of the fuel switching during the OECD stage (2020–2030) of the power-neutral-50p scenario (Fig. 3b). After non-OECD members commence their phase-out in 2035, variable renewable energy (VRE) dominates 93% of the primary energy (PE) response. This virtuous cycle of VRE penetration and learning-by-doing spillovers are absent when China abstains from the coalition (power-brown-50p).

However, these spillovers do not diffuse into freeriders, where VRE increases <1% in either scenario. An economy-wide scale-back of end-use electrification (Extended Data Fig. 5), driven by higher near-term power system capital costs and cheaper coal-based solids and liquids, limits VRE deployment. Globally, carbon leakage rates are 54% (power-neutral-50p) and 76% (power-brown-50p) and 90% remains within the coalition in either scenario.

Policy evaluation

Cumulatively, power-neutral-50p precipitates 230 EJ less coal consumption than NPi-default. However, alignment with the cost-efficient 1.5 °C scenario requires another 19,040 EJ reduction, translating to a residual coal-exit ambition gap of 98.8% (Fig. 4a). The climate ambition gap is comparable: 99.2% (3,430 $GtCO_2$). Both gaps in power-brown-50p actually exceed 100%, implying that excessive COVID-era coal investments could overshadow phase-out efforts until mid-century. Unless supplemented with other climate policies, the PPCA's verbatim policy appears inconsequential.

Demand-exit

COALogit returns a demand-neutral-50p coalition identical to power-neutral-50p. These 182 members comprise 81% (OECD, 20% and non-OECD, 61%) of global coal demand in 2020. The demand-brown-50p coalition contains one fewer member than power-brown-50p (Serbia), totalling 179 nations and 32% of 2020 coal demand (OECD, 19% and non-OECD, 13%).

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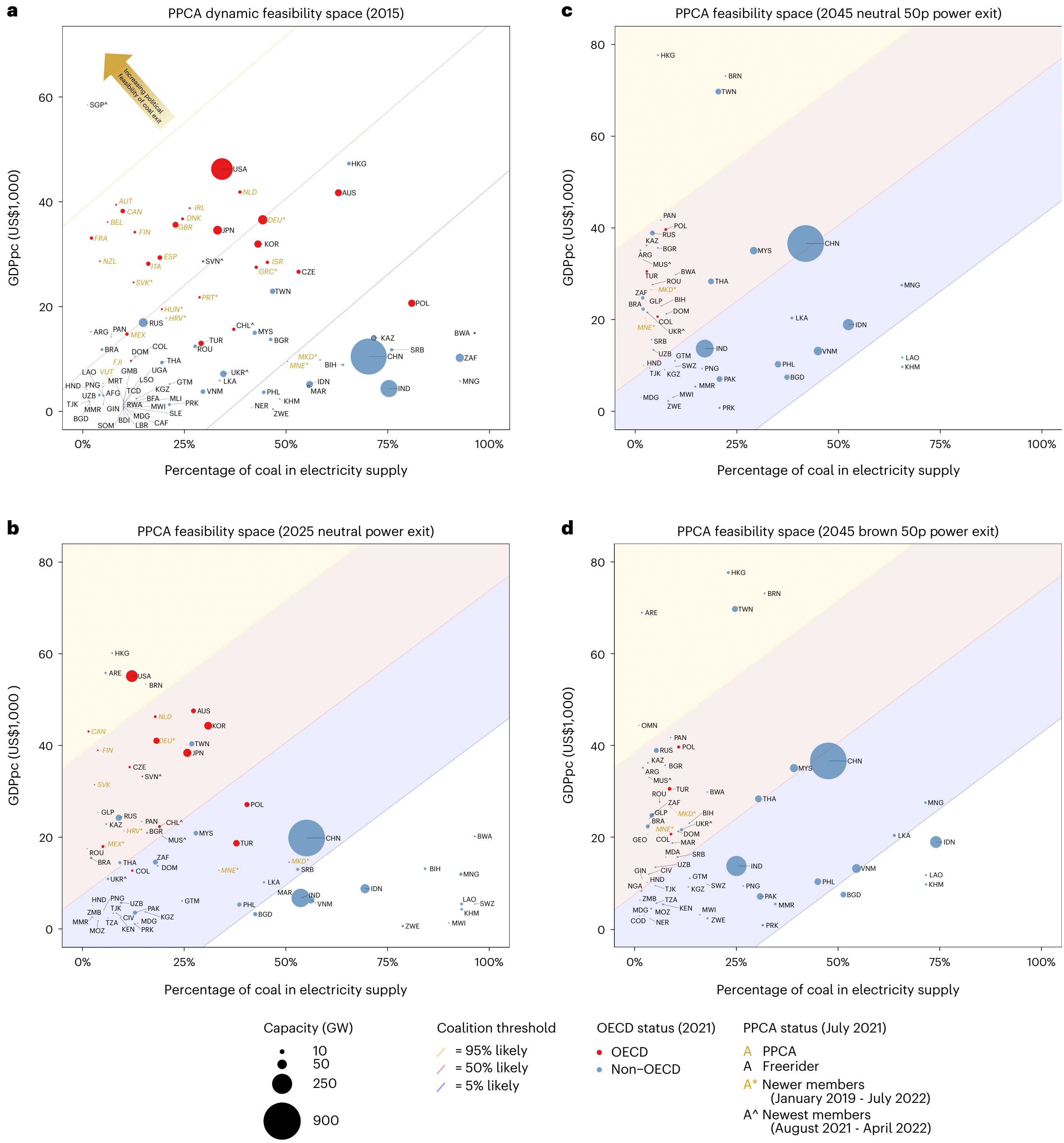

Fig. 2 | Dynamic feasibility of national PPCA accession from COALogit. **a**–**d**, Feasibility space of Alliance membership based on GDPpc and coal-power share in 2015 (**a**), 2025 (**b**) and 2045 (**c**,**d**), depicting nations with >1% coal-power share. The threshold lines, derived from equation (2) (Methods) and shaded areas indicate the probabilistic coalitions analysed here: 95% (presumable), 50% (probable) and 5% (possible). The progression of a single scenario, power-neutral-50p, is depicted in **a**–**c**, while **d** shows how a brown COVID recovery can impact political feasibility. Supplementary Appendix III discusses the empirical model's parametrization and fit to 2015 data (**a**) and Extended Data Fig. 2 sketches a more current (2020) version. Country codes are defined in Table S1 in the Supplement.

Alliance members

Cumulatively, both demand-neutral-50p and demand-brown-50p coalition members phase out over three-quarters of their reference coal consumption. Unabated power constitutes merely 10% of this decline in neutral-50p (3% in brown-50p). Coal-to-liquids account for 67% (77%) and solids for 19% (17%) (Fig. 3c) because under current policies, coal becomes cost-optimal in transport and industry, respectively, once it is outcompeted in electricity. Oil demand surges 21% (24%) accordingly

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Table 2 | Definition and classification of each analysis dimension

Name	Definition	Analysis dimension	IAM mode
95p (presumable)	Real-world PPCA members as of July 2021 (Supplementary Table 1) and nations assigned ≥95% probability of coalition accession by COALogit	Coalition expansion (endogenous PPCA scenario element)	DPE
50p (probable)	Real-world PPCA members plus nations above 50% feasibility threshold		
5p (possible)	Real-world PPCA members plus nations above 5% feasibility threshold		
Power-exit (verbatim PPCA)	PPCA phases out only unabated coal-fired electricity by 2030 in OECD members and 2050 in non-OECD members	Policy ambition (exogenous PPCA scenario element)	PEA
Demand-exit (assume PPCA implies full coal-exit)	PPCA members interpret the policy in good faith to cover all coal consumption. Metallurgical coal (met-coal) is allowed a 10 yr delay (2040 and 2060 deadlines) to reflect inertia to steel sector decarbonization and China's 2060 carbon neutrality pledge		
Neutral	COVID-19 recovery plans reconfirm national historical tendencies in terms of project completion rates and mean plant lifespans in the coal-power sector until 2025: leads to 1,850 GW globally	COVID-19 recovery (exogenous PPCA scenario element)	PEA
Green	Completion rates fall 50% and all shelved preconstruction projects cancelled but plant lifespans unaffected: 1,670 GW		
Brown	Project cancellation rates decline 50% and plants operate 5 yr longer than historical national average: 2,320 GW		
NPi (neutral, green, brown, default)	'National policies implemented,' a revealed-ambition scenario[17] serving as our baseline. We model three variations that fix 2025 coal capacity in REMIND to each COVID recovery (NPi-neutral, NPi-brown and NPi-green) and one which invests cost-optimally without explicit COVID constraints (NPi-default)	Reference scenario	SPE
NDC (neutral, green, brown)	Stated-ambition scenario assuming full compliance with the first-round NDCs to the Paris Agreement[17]. We model three COVID-dependent variations (NDC-neutral, NDC-brown, NDC-green)	Benchmark scenario	SPE
Well-below 2 °C (WB-2C)	A welfare-optimal scenario with >67% likelihood of limiting global mean temperature rise to <2 °C above pre-industrial levels throughout the century. Without COVID constraints	Benchmark scenarios	CEA
Higher than 1.5 °C (Hi-1.5C)	A welfare-optimal scenario with >50% chance of achieving the 1.5 °C target in 2100 with a moderate allowance of temporary mid-century temperature overshoot. No COVID constraints		
1.5 °C	A welfare-optimal scenario with >67% probability of achieving 1.5 °C and a 50% chance of temporary overshoot by <0.1 °C. Sets the upper limit of efficacy indices (Fig. 4). No COVID constraints		

Each unique combination of the PPCA scenario elements (three coalition accession thresholds, two interpretations of policy ambition and three COVID-19 recovery directions) constitutes one full PPCA scenario (for example 95%-likely power-exit policy uptake following a green COVID recovery, that is power-green-95p), for a total of 18 modelled scenarios. The 50p coalition and neutral recovery represent our default set of assumptions. The other scenarios are included for sensitivity analysis. We consider it similarly probable that a given nation's PPCA accession may signify either interpretation of policy ambition, so both are presented as default scenarios.

(Fig. 3d), so liquid-fuelled transport tapers just marginally and gas demand rises 9% (8%) as industry transitions toward gasification and electrification (Extended Data Fig. 5). China's disproportionate influence on VRE diffusion is evident, as VRE increases 13% in neutral but just 6% in brown, 99% (96%) of which comes after the OECD stage (~75% of coal phased out 2020–2030 is replaced by oil and gas).

Freeriders

The response of freeriding nations in demand-neutral-50p and demand-brown-50p follow similar temporal profiles, albeit at varying magnitudes (Fig. 3c,d). Freeriders also increase industry electrification and gasification (Extended Data Fig. 5a) but fuel it with coal (Fig. 3c). A knock-on coal-for-oil swap in freerider transport liquids is evident, particularly strong when China freerides in demand-brown-50p, but inverts after non-OECD adoption. Coal accounts for all carbon leakage into demand-brown-50p freeriders (7% rate), which is just 24% of global carbon leakage (29% rate). In demand-neutral-50p, freerider leakage rates are net-negative (−1% coal, −0.4% carbon), so the 20% global leakage rate occurs exclusively within the coalition.

Policy evaluation

The demand-neutral-50p scenario reduces global cumulative coal use by 10,300 EJ and CO_2 emissions by 790 Gt below NPi-neutral, leaving coal-exit and climate ambition gaps of 48% and 77.5%, respectively (Fig. 4a). Hence, probable PPCA self-propagation may reduce the effort required to achieve 1.5 °C by roughly one-quarter if members phase out coal economy-wide. Intracoalition fossils leakage prevention could save another 7% (177 $GtCO_2$). In demand-brown-50p, China's abstention leaves considerably wider gaps of 70.5% (coal) and 88.4% (CO_2).

Sensitivity analyses

The 95p and 5p coalitions embody the uncertainty inherent in approximating future political decisions. Demand-neutral scenarios leave residual coal-exit ambition gaps ranging from 95.5% to 15.4% (95p-5p) and climate gaps of 98.5–62.8% (Fig. 4a). Power-neutral scenarios exhibit uncertainty ranges of 101.4–98.2% (coal) and 100.6–98.9% (CO_2). Therefore, while demand-exit outcomes are highly sensitive to coalition size, the power-exit is robustly inconsequential.

Carbon leakage primarily emerges through coal markets in power-exit scenarios and interfuel substitutions in demand-exit simulations. Extraordinarily, we find that all power-95p scenarios exhibit leakage rates >100% (237% in power-neutral-95p). This occurs because the power-exit impedes e-mobility diffusion, locking in liquid-fuelled transport (Extended Data Fig. 4a). This feedback persists in power-neutral-5p but the leakage rate is just 56% because of the larger policy effect.

Comparatively, the demand-exit tempers leakage: 72% in demand-neutral-95p and 17% in demand-neutral-5p. Irrespective of policy, we find that larger coalitions elicit lower global carbon leakage

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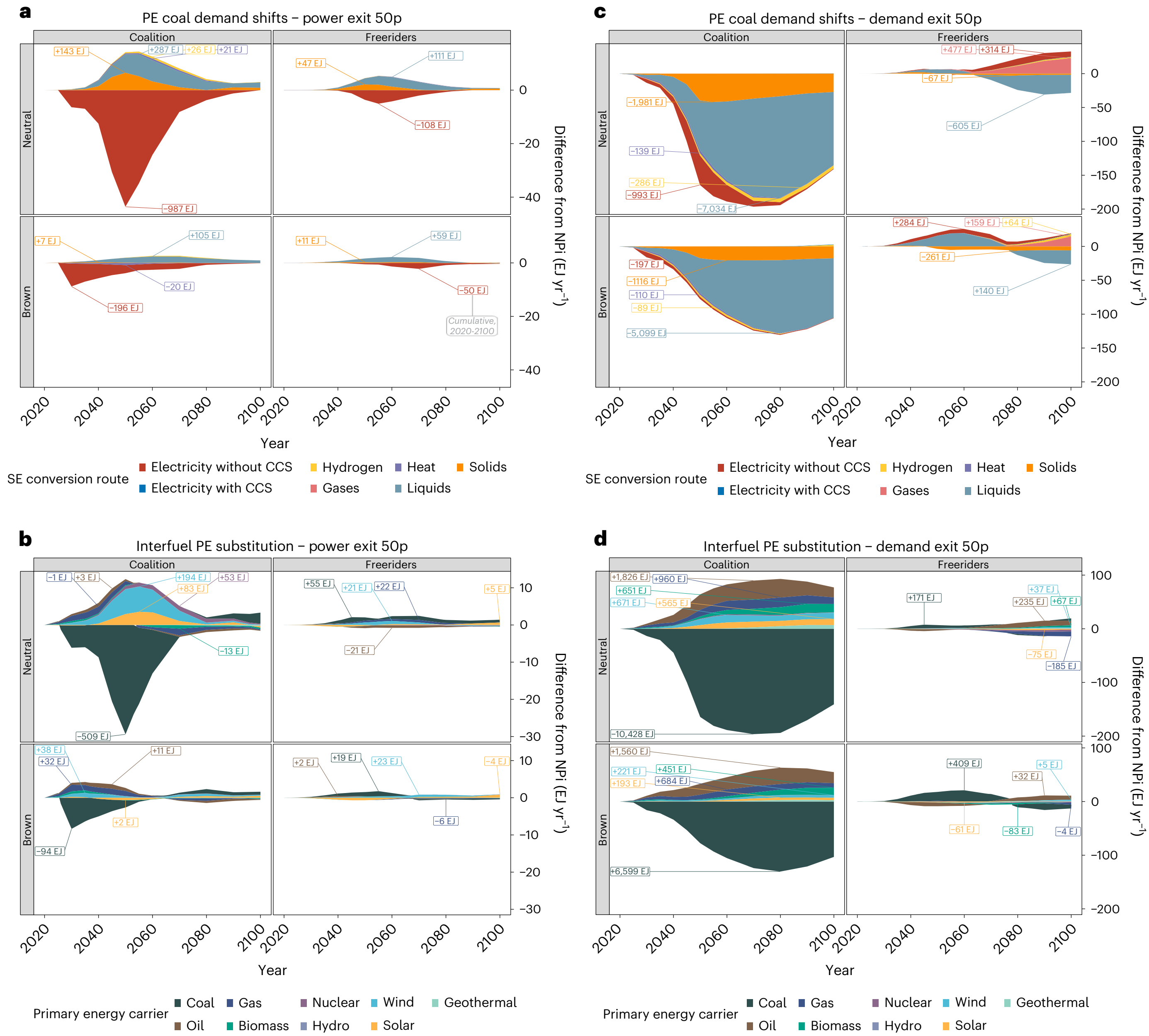

Fig. 3 | Annual PPCA-induced deviations from reference baseline. a–d, In probable power-exit (**a**,**b**) and demand-exit (**c**,**d**) scenarios for coal (**a** + **c**) or primary energy (PE; **b** + **d**). Labels denote cumulative differences this century. Columns distinguish between coalition members and freeriders in the COVID recovery direction represented by each row. Coal demand is given in primary energy values and categorized by secondary energy (SE) conversion route. Generally, negative areas in the 'Coalition' column reflect the intended policy effect, while all other differences indicate system feedbacks.

rates but higher intracoalition leakage volumes, dwarfing freerider leakage. These findings are all robust across COVID recovery scenarios (Supplementary Fig. 3).

The cumulative impact of power-exit on VRE ranges from +353 EJ (neutral-5p) to −53 EJ (neutral-95p), the latter another apparent consequence of the negative e-mobility feedback. Bioenergy and other low-carbon energy deployment experiences marginal upticks of 2–55 EJ (95p-5p). Under a demand-neutral regime, these second-order effects range from 0 to 2,080 EJ for VRE and 4 to 1,330 EJ for other low-carbon energies.

Our high-optimism green-5p scenarios elicit virtually global PPCA diffusion and demonstrate that the demand-exit has 38× the coal-exit potential (27× the CO_2 mitigation potential) as the power-exit. Power-green-5p even exacerbates the striking divergence (17× cumulative difference) in non-electric coal demand between NPi-green and 1.5 °C (Fig. 4b). Other urgent policy priorities include natural gas phase-downs and bioenergy support, given the abrupt bifurcation between their 1.5 °C and other trajectories (Fig. 4b). Moreover, demand-green-5p incentivizes an additional 1,510 EJ gas and 2,770 EJ oil (Supplementary Fig. 3f), avoidable with immediate and sustained investment in renewable industry and transport fuels.

COVID-19 recovery and path dependency

We find residual coal ambition gaps (95p-5p range) of 70.5% (96.5–24.5%) from demand-brown and 47.1% (94.4–14.3%) from demand-green and climate ambition gaps of 88.4% (99.2–67.3%) and 77.1% (98–62.3%), respectively. Greener investments at this critical juncture reduce immediate emissions and may also propel political coal-exit momentum. Coal-powered recoveries may appear attractive to current regimes but

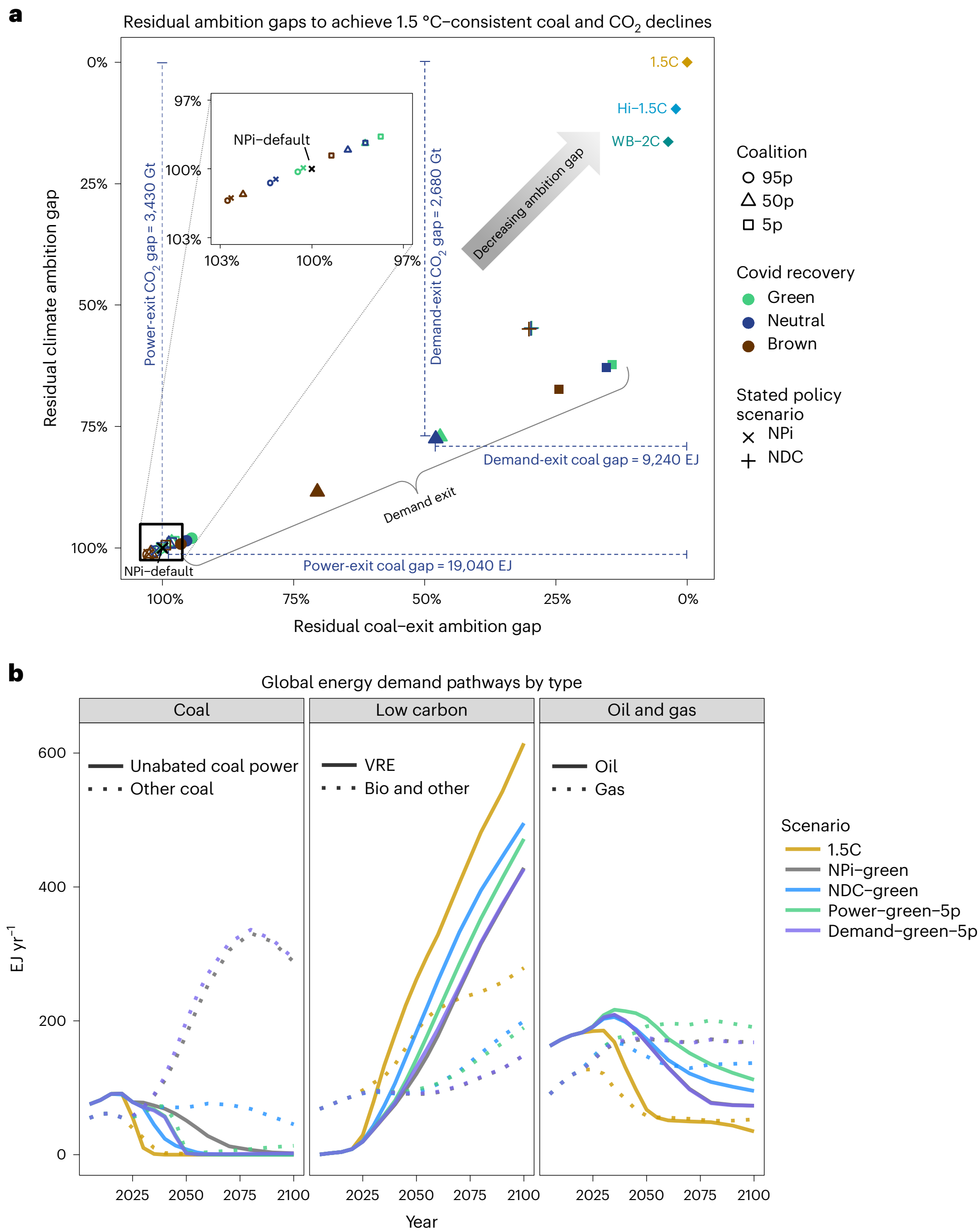

Fig. 4 | Evaluating PPCA scenario outcomes. a, Evaluated in terms of the cumulative coal and CO_2 emissions gaps they leave between current revealed-ambition (NPi-default) and 1.5 °C alignment. These residual ambition gaps are normalized (see inset for power-exit) but magnitudes are shown for the neutral-50p scenarios. **b**, Comparison of aggregate PE demand trajectories in power- and demand-green-5p scenarios—which are effectively conventional PEAs defining either policy's maximum potential—against the gold-standard CEA (1.5 °C) reveals substantial residual policy effort necessary in key energy sectors. 'Unabated coal power' trajectories are identical in power-green-5p and demand-green-5p and oil and gas pathways are identical in NPi-green and power-green-5p.

would impose substantial financial strain on those assets as they lose economic and/or political favour. Power-exit scenarios corroborate this sensitivity, however minimally (Fig. 4a).

Discussion

The integration of sociopolitical and techno-economic analyses is an emerging endeavour in climate mitigation research[7,26]. Thus far, attempts to merge empirical social sciences on energy transitions with energy-economy models[26,56] have not robustly improved the realism of mitigation pathways[5]. DPE confronts this challenge with the technocratic view that although policy decisions are best understood through high-resolution political economy analyses, they also correlate significantly with IAM variables on global, comparative scales. We build on the tradition of validating and improving model assumptions through empirical data[23,57–59] and complement literature bridging IAMs with established sociotechnical transition frameworks[4,37,60] or coupling fuzzy societal factors such as governance[61] or behaviour with climate system dynamics[62,63].

Pitfalls and potentials

The PPCA declaration cites ref. 64, an ex post ensemble analysis of coal-fired electricity in Paris-consistent CEA pathways of select IAMs and energy system models[64]. However, coal-fired electricity exits these scenarios amidst rapid economy-wide coal declines. The power-sector bias, evident throughout the coal-exit discourse[40,45,49], may be explained in part by data accessibility barriers. The only open-access, comprehensive, coal-asset-level datasets were power-plant-specific[65] until comparable data on mines and steel plants were published in 2021. We therefore surmise that the sector-exclusivity of PPCA was motivated by politics—for example, to encourage maximum participation—and undercontextualized scientific messaging.

The declaration's myopia is evidenced by the future coal demand profile in the NPi scenarios of REMIND; while electricity accounted for ~60% of 2015 coal use[66], it represents just 16% cumulatively from 2020 to 2100 (Fig. 4b). Moreover, the power-exit generally decreases freerider coal electricity while transport-sector and industrial coal use increase ubiquitously, as they do in other model baselines[67,68]. Although a recent review suggested that IAM scenarios are unrealistically coal-dependent, its analysis exhibited some power-sector bias and found that coal is phased out most readily by REMIND[40]. We therefore contend that freeriding by PPCA members' industry and transport sectors is a material risk, not a model artefact. The coalition-of-the-willing must confront this hazard without impeding power-sector decarbonization and end-use electrification, core tenets of cost-effective mitigation[69,70].

If the PPCA closes sectoral loopholes, the demand-exit scenarios illustrate its considerable uncertainty range and the ability of DPE to set reasonable expectations: demand-neutral-50p closes the coal-exit and emissions gaps by one-half and one-quarter, respectively. However, we acknowledge that COALogit cannot accurately estimate demand-exit feasibility since only power-exit pledges have been observed. Our analysis assumes perfect interchangeability to directly compare the two policies but a real-world trade-off between sectoral coverage and coalition growth is implied by the first-round NDCs: coal-power phases out by 2060 while non-electric coal persists through 2100 (Fig. 4b).

Nevertheless, the least-effective demand-exit (brown-95p) outperforms the most optimistic power-exit (green-5p). Default demand-exit-50p scenarios phase out 30× more coal on average than virtually global power-exit-5p scenarios. These outcomes indicate that the PPCA should prioritize sectoral over geographical coverage and that demand-exit feasibility must diffuse globally before 2050 to align aspirations with welfare-optimal Paris pathways[48] (Fig. 4a).

For each COVID recovery, COALogit derives near-identical power-exit and demand-exit coalitions, owing to its parsimonious dependence on REMIND-computed coal-power-shares and the demand-exit's comprisal of a power-exit. For both policies, greater OECD participation generally decreases non-OECD accession probabilities due to coal-power leakage (Supplementary Fig. 1b–d). Freerider coal-fired electricity falls in power-50p scenarios but coal-power-shares are largely unaffected because electrification declines across all sectors (Extended Data Fig. 5a). Consequently, assuming 'middle-of-the-road' socio-economic development and stagnant climate ambition, we find global PPCA accession ~2% probable.

Policy recommendations
These odds would improve if norms around sustainable growth or carbon pricing prevail instead[71,72]. Additionally, PPCA members can still galvanize Paris-aligned coal-exit momentum by immediately confronting freeriding sectors and ramping-up VRE, electrification and technological (and financial) transfers to freerider nations.

Recent literature highlights the importance of complementing demand-side antifossil initiatives with supply-side actions[73–75], for example, mining or export restrictions. This counteracts price depression and leakage, increasing phase-out policies' self-propagation potential. Given geographical variance in coal quality and trade, however, policy efficacy depends upon the specific adopters. Crucially, the largest anticipated coal consumers in 2045—China, India and ASEAN members (Fig. 2c)—can each sustain self-sufficient coal supplies.

However, their demand-side capacity is largely financed by the OECD[76], where fossil divestment campaigns are historically commonplace[75] and may induce decarbonization abroad. The G20 recently pledged to halt public finance for overseas coal plants, but complementary green finance must be affordable to truly disincentivize recipient nations and private capital from coal[77–79]. Although China, the pre-eminent coal financier[76], may insulate its domestic industry, its historical 22 yr plant lifetimes (Supplementary Appendix Table 1.1) and 2060 carbon neutrality pledge[80] breed cautious optimism.

Those coal-rich developing nations also exhibit the highest path-dependence of accession probability to near-term decisions. Most glaringly, China falls below the 50% threshold and Indonesia below 5% in brown scenarios. Additionally, we observe that several highly probable OECD coalition members install new coal plants in brown and neutral COVID recoveries. PPCA accession then forces a sudden exodus of unamortized capital from 2025 to 2030. Thus, to preserve the health of their economy[45], citizens[46], grid[81] and credibility, OECD governments must cancel all coal projects.

Future research
DPE presents a way forward for climate policy research at the intersection of techno-economic, sociopolitical and mitigation target feasibility. Subsequent efforts require systematic empirical analyses[82] to continuously identify and validate forecastable variables as contextual drivers of policy emergence and diffusion[23–25,35]. For COALogit, this may include new regressions against REMIND-endogenous descriptors of state capacity or predictors of demand-exit pledges if/when they arise. Importantly, DPE is not limited to discrete-choice and optimization models. Non-binary policies like carbon pricing may be fully endogenized as nonlinear functions in simulation models, for example. Ultimately, we envision compound DPE scenarios that coherently depict policy interactions in terms of efficacy[83,84] as well as sequencing and acceptability[85,86].

Parallel research must examine supplementary policy options that best augment PPCA growth and mitigation efficacy. Our PPCA scenarios constitute 'living' baselines that endogenize policy feedbacks of other real-world developments and policy candidates on coal-exit diffusion, enabling research to identify high-synergy, low-risk policy suites for willing-and-able nations to propel global energy transitions. Supply-side, financial and carbon pricing policies are prime candidates given their uptake frequency[75] and anticipated efficacy[74]. If Paris-aligned coal-exits grow increasingly improbable, cost-effective analyses must revisit expectations for oil and gas[39,41,48,87].

Online content
Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-022-01570-8.

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 https://doi.org/10.1038/s41558-022-01570-8

Methods

The present study introduces DPE, a conceptual framework for integrating techno-economic and sociopolitical disciplines, a widely recognized gap in the climate mitigation literature[4,5,7,56,60]. DPE asserts that policy decisions and their feedbacks with global energy system evolution can be prospectively modelled if empirical correlations are established between observed real-world policy and energy-economic variables. The methodology we detail below is specific to the present demonstration of DPE in the context of the PPCA and future studies may explore vastly different implementations depending on the empirical methods used.

REMIND–COALogit model coupling

Building on the logistic regression analysis in ref. 31, we designed a soft-link interface between a country-level, stochastic binary model of coal-exit policy adoption (COALogit; Supplementary Appendix III) and the global, forward-looking, deterministic IAM REMIND (Supplementary Appendix II; ref. 55 gives a full description). The coupling occurs in a sequential loop between them to simulate multistage, bottom-up legislative decisions and translate them to inter- and intra-regionally fragmented policies in long-horizon REMIND scenarios.

First, COALogit defines the current coal-exit ambition of each REMIND region (Supplementary Appendix Fig. 2.1) on the basis of observed PPCA pledges (Supplementary Table 1). Second, a subsequent REMIND run is constrained accordingly, effecting global energy transformations. Third, COALogit inputs data from this REMIND run to the logit model to determine future national PPCA accession probabilities, thereby endogenizing feedback effects of the PPCA on its own prospects. Fourth, COALogit assumes that all countries above an exogenously determined probability cutoff join the PPCA and updates regional coal-exit ambition appropriately. Finally, another REMIND run applies these constraints, which trigger endogenous energy system feedbacks such as international, intersectoral and interfuel leakage effects, as well as technological learning (Fig. 1). The REMIND–COALogit sequence (Extended Data Fig. 4) thereby cohesively depicts the interactions between economic and political coal-exit dynamics.

PPCA declaration. A limiting factor of modelling co-evolutionary transformation pathways is the paucity of historical climate policy observations upon which empirical models can be constructed. The PPCA provides a real-world basis for logit model calibration and precise policy timing in REMIND. The PPCA declaration, although non-binding, defines clear targets for its members: OECD and European Union (OECD henceforth) member nations are expected to observe a 2030 phase-out of unabated coal-fired electricity while all other countries (non-OECD henceforth) are afforded until 2050. For the purposes of this study, we assume that all PPCA signatories will comply with the prescribed deadlines. Countries are defined according to the ISO 3166-1 convention, listing 249 world nations.

Logit model. Supplementary Appendix III details the empirical relationship modelled in COALogit between a nation's likelihood of PPCA membership and the predictor variables, GDPpc and coal-power share, defined by equations (1) and (2).

$$p\,(Y=1)=\frac{e^{\beta_0+\beta_1 x+\beta_2 y}}{1+e^{\beta_0+\beta_1 x+\beta_2 y}} \qquad (1)$$

where $p(Y=1)$ is the probability of PPCA membership, β_i are fitted model parameters (Supplementary Appendix Table 3.1), x is the coal-power share and y is GDP per capita.

$$\ln\frac{p_{\hat{n}}\,(t)}{1-p_{\hat{n}}\,(t)}=\beta_0+\beta_1 x_{C,\hat{n}}\,(t)+\beta_2 y_{\hat{n}}\,(t) \qquad (2)$$

where: $\hat{n}$ is nation of analysis, $p_{\hat{n}}$ is national probability of coalition accession, t is time (refers to REMIND time-steps in our analyses), $x_{C,\hat{n}}$ is national coal-power share and $y_{\hat{n}}$ is national GDP per capita.

The parameters are fit against observed PPCA pledges, which delimits the political feasibility space of the PPCA (Supplementary Appendix Table 3.1). COALogit dynamizes this model by assuming that the empirical foundation persists over time, which appears reasonable thus far (Supplementary Appendix III).

Probabilistic coalitions. To operationalize accession probabilities into policy assumptions for deterministic REMIND scenarios, we partition countries into members and freeriders. We define thresholds within the feasibility space (Supplementary Appendix Table 3.3), represented as linear relationships in Fig. 2 between GDPpc and coal-power share, along which the probability of coalition accession is constant. Any country that reaches an accession probability above the threshold value before its PPCA-imposed phase-out deadline is considered an irreversible member of the coalition. The coal-exit policy is then exclusively applied to these nations in the subsequent (downstream) REMIND run.

To simulate coalition accession of OECD countries, we use COALogit to identify which OECD nations lie above each threshold in the 2025 REMIND time step, representing a 5 yr period ending in June 2027. Any prospective member is assumed to have decided by then whether they will observe the 2030 phase-out. Similarly, we define non-OECD coalition members by comparing non-OECD countries to the thresholds in the 2045 model period, July 2042 to June 2047.

Ideally, the coalition would be updated every year, or at least every 5 yr REMIND period, for DPE to depict the most realistic coal phase-out trajectories. However, such a rolling policy enforcement horizon would be highly resource-intensive and impractical for broad sensitivity analyses such as those we report. Future DPE implementations may explore reducing the IAM optimization horizon of each REMIND scenario to reduce the computational burden.

COALogit inputs and outputs. The implementation of REMIND–COALogit requires the downscaling of the relevant variables in equation (2), as derived by REMIND simulations, for all countries in future periods (Supplementary Table 4). For instance, the future development of coal use in REMIND regions must be disaggregated to the country level so that the COALogit model can derive the accession of individual nations to the PPCA coalition. The country-level results are later re-aggregated to the level of REMIND regions to define policy constraints for a downstream REMIND run.

COALogit performs three core functions: (1) reading in and downscaling REMIND results to the country level, (2) logit analysis to define coalition membership and (3) derivation of policy stringency coefficients (PSCs), which account for the distribution of future coal and energy demand between members and freeriders within individual REMIND regions to translate country-level coalitions into region-level policies (Extended Data Fig. 3; equation (6)).

First, COALogit intakes regional variables for total energy demand as well as coal-fired and total electricity generation from the upstream REMIND run, that is a preceding run in which the coalition was not fully defined (Extended Data Fig. 4). COALogit then downscales (equations (4) and (5)) and divides the variables to derive country-level coal-power shares.

Second, the logit model determines national accession probabilities for the specified time step using the national coal-power shares downscaled from the upstream REMIND run and GDPpc from SSP 2 (ref. 88). All countries above the assumed feasibility threshold are considered coalition members. Third, the cumulative coal-power shares of all countries (from the phase-out deadline to 2100) are calculated on the basis of the upstream REMIND run. This is set to zero for coalition members. PSCs are derived by aggregating the cumulative coal-power shares to the REMIND region-level and these are exported REMIND for use in the downstream run.

Power-exit scenario cascade. Each PPCA scenario requires a sequence of four REMIND runs with a COALogit run between each. Extended Data Fig. 4 illustrates this automated cascade and the Roman numerals used below refer to that figure. (I) The starting point of a PPCA scenario cascade is always an NPi reference case, to which historical developments (2005–2015) in all REMIND runs of the cascade are fixed. (II) COALogit regionally downscales the relevant NPi variables (Supplementary Table 3) to derive PSCs for current real-world PPCA members. (III) These PSCs are fed downstream to the 'Current PPCA' REMIND run, a conventional SPE of the PPCA (Table 1).

(IV) 'COALogit-2025' derives the 95p, 50p and 5p (henceforth, xp) OECD coalition scenarios (Fig. 2b) on the basis of accession probabilities calculated by equation (2) using historical data extrapolation (Supplementary Appendix I) and 2025 variables computed in Current PPCA (Supplementary Table 3). Conceptually, the near-term actions of today's PPCA may influence the energy landscape in freeriding OECD nations and thus their decision-making. COALogit-2025 returns PSCs for each OECD coalition scenario, which (V) are fed downstream for the 'OECD-xp' REMIND runs to enforce the 2030 phase-out policy.

(VI) Each OECD-xp run calls a unique COALogit-2045 instance, which forms the corresponding non-OECD-xp coalition (Fig. 2c,d) using 2045 variables from OECD-xp (Supplementary Table 3) and assigns PSCs accordingly. (VII) Finally, the 'non-OECD-xp' REMIND runs encapsulate all the information accrued throughout the cascade. These are fixed to OECD-xp through 2030, preventing non-OECD members from prematurely anticipating the policy while also affording them sufficient lead-time for adherence. Both the OECD and non-OECD phase-outs are enforced during this final run's 2035–2100 optimization horizon. The non-OECD-xp REMIND runs are the full DPE–PPCA scenarios analysed in Figs. 3 and 4.

Demand-exit cascade. Additionally, we consider an alternate interpretation of PPCA accession: a commitment by national governments to phase all unabated coal consumption out of the economy in accordance with the PPCA's timeline. This reflects the assumption that PPCA members truly represent a coalition-of-the-willing or are at least predisposed to accept further responsibilities. This demand-exit policy interpretation imposes the PPCA phase-out timeline on all coal-consuming technologies in all economic sectors except the iron and steel industry, which is permitted a 10 yr grace period. This is intended to represent techno-institutional inertia, given that steelmaking is considered a particularly difficult industrial process to decarbonize[67] and that high-grade met-coal is a substantially higher-value commodity than is thermal coal.

(I) The same starting point (NPi) and sequence progression applies to demand-exit PPCA scenarios but the coal phase-out constraints and the variables exchanged between REMIND and COALogit (Supplementary Table 3) differ. (II) COALogit-2015 provides (III) Current PPCA with six PSCs—three for the OECD phase-out and three for the non-OECD phase-out. (IV) COALogit-2025 generates three PSCs for each (V) OECD-xp run and (VI) COALogit-2045 xp feeds three more PSCs to its corresponding (VII) non-OECD-xp run. The relevant calculations are detailed below.

Technical implementation

This section details the procedures, calculations and assumptions involved in the REMIND–COALogit interface. Each subsection presents the general logic and formulae that pertain to the indicated steps of Extended Data Fig. 4. Supplementary Table 3 details the sources and flow of variables exchanged along the cascade.

OECD national coal-power shares derivation (IV). In the 2025 COALogit instance, country-level coal-fired power generation is calculated on the basis of the coal-power capacities extrapolated from Global Coal Plant Tracker (GCPT) data[65] (Supplementary Appendix I). These are multiplied by the national 2025 utilization rates, which are in turn extrapolated from 2015 data. Countries with zero coal capacity in 2015 are assigned their REMIND region mean utilization rate. Per the default exogenous assumption used in REMIND, equation (3) describes how all countries linearly converge to a utilization rate of 50% by the 2035 period, persisting until 2100.

$$\mu_{\hat{n}}(t) = \mu_{\hat{n}}(t_0) + \frac{0.5-\mu_{\hat{n}}(t_0)}{t_c-t_o}(t-t_0) \quad \text{for } t_0 < t < t_c \tag{3}$$

where: $\mu_{\hat{n}}$ is the national utilization rate, t_0 is 2015 and t_c is 2035 (time step when μ becomes constant).

Some regions in REMIND are individual countries (India, Japan and the United States). For these countries, total electricity generation in all periods is taken directly from the upstream run. Other REMIND regions are aggregates of three to 54 nations, hence projected electricity generation must be downscaled. Disaggregation weights for total power generation are assigned to each region by assuming that base-period per capita electricity demand remains constant in each of its nations (Supplementary Table 4). To prevent negative weights, countries with low base-year electrification and a declining population are instead assumed to keep their total electricity generation constant at base-year levels. National coal-power shares in 2025 are thus calculated as the ratio of extrapolated bottom-up coal-power generation values and disaggregated top-down total electricity production figures.

Non-OECD national coal-power shares derivation (VI). To extrapolate national coal-power shares from multinational REMIND regions in the 2045 instance of COALogit, we use a different downscaling routine, grounded in the assumption that the relative difference between the coal-power share of a region and those of its member nations remains constant. First, national coal-power shares in 2030 are downscaled from the upstream REMIND run (OECD-xp, Extended Data Fig. 4) by assuming its percentage above or below its region's coal-power share remains unchanged from 2025. This is represented by equation (4).

$$x_{\hat{n}}(t) = \begin{cases} x_{\hat{n}}(t-\Delta t) + \frac{x_{\hat{n}}(t-\Delta t)-x_R(t-\Delta t)}{1-x_R(t-\Delta t)} \times (1-x_R(t)), & \text{if } x_R(t) \geq x_R(t-\Delta t) \\ x_{\hat{n}}(t-\Delta t) - \frac{x_R(t-\Delta t)-x_{\hat{n}}(t-\Delta t)}{x_R(t-\Delta t)} \times x_R(t), & \text{if } x_R(t) < x_R(t-\Delta t) \end{cases} \quad \text{for } t \geq 2030 \tag{4}$$

where:

$t-\Delta t$ is the previous period analysed (Δt varies between 5 and 15 yr) and R is the REMIND region containing nation $\hat{n}$.

Country-level coal-power generation in 2030 is then calculated by multiplying total national electricity generation by coal-power share. However, OECD coalition members, as defined in the 2025 COALogit instance, must have zero coal electricity generation. Their newly derived coal electricity values are thus counterfactual and must be redistributed to other nations in the region. Equation (5) describes this.

$$\widetilde{\text{seel}}_{C,\hat{n}}(t) = \begin{cases} 0, & \text{if } \hat{n} \in M_R \\ \widehat{\text{seel}}_{C,\hat{n}}(t) + \frac{\widehat{\text{seel}}_{G,\hat{n}}(t)}{\sum_{n \in F_R} \widehat{\text{seel}}_{G,n}(t)} \times \sum_{n \in M_R} \widehat{\text{seel}}_{C,n}(t), & \text{if } \hat{n} \in F_R \end{cases} \quad \text{for } t \geq 2030 \tag{5}$$

where: $\widetilde{\text{seel}}_{C,\hat{n}}$ is the national coal electricity after accounting for OECD phase-out, $\widehat{\text{seel}}_{C,\hat{n}}$ is the counterfactual national coal electricity downscaled from upstream REMIND run, $\widehat{\text{seel}}_{G,\hat{n}}$ is the total national electric-

 https://doi.org/10.1038/s41558-022-01570-8

ity generation downscaled from upstream REMIND run and n is each nation within region R, M_R is the OECD coalition members in region R and F_R is the freeriding nations in region R.

Finally, with the OECD phase-out reflected in the national coal-power generation values, coal-power shares are recalculated for 2030. National coal-power shares in 2045 can then be derived through equation (4) using 2030 as the previous period and these values are used in equation (2) to derive non-OECD coalition accession probabilities. Nations above the xp threshold of the scenario must enact the power-exit in the downstream REMIND run.

Power-exit policy stringency coefficients (IV and VI). Because several REMIND regions contain both coalition members and freeriders, COALogit translates its national output into regional policy constraints via PSCs. Member-rich regions are assigned highly stringent PSCs, while freerider-dominant regions adopt less stringent policies. Member-only regions must fully exit coal-fired electricity (PSC = 0) and regions containing only freeriders are unconstrained (PSC = 1, that is 100% of electricity can be coal-fired). COALogit-2025 defines PSCs for the OECD phase-out from 2030 to 2100 and COALogit-2045 for the non-OECD phase-out from 2050 to 2100. These two coefficients can vary greatly in a region containing both OECD and non-OECD states.

PSCs in power-exit scenarios denote the maximum cumulative share of coal permitted in the electricity generation of each region. This is defined in equation (6) as the freeriders' coal-power generation of a region divided by the region's total electricity generation in the upstream run. As this would constrict those freeriders to their reference coal-power demand, thereby preventing leakage, we include a term permitting them to increase coal-fired electricity a maximum of 50% in response to PPCA phase-outs.

$$\mathrm{PSC}_{R,\alpha} = \frac{\sum_{t=t_\alpha}^{2100} \sum_{n\in F_R} \widehat{\mathrm{seel}}_{C,n}(t)}{\sum_{t=t_\alpha}^{2100} \sum_{n\in R} \widehat{\mathrm{seel}}_{G,n}(t)} \times L \qquad (6)$$

$$\text{for } t_\alpha = \begin{cases} 2030, & \text{if } \alpha = \mathrm{OECD} \\ 2050, & \text{if } \alpha = \mathrm{non-OECD} \end{cases}$$

where $\mathrm{PSC}_{R,\alpha}$ is the policy stringency coefficient for region R in the current accession stage α and L, the intraregional coal leakage allowance, is 1.5.

Criteria for policy enforcement. Similarly, if the coalition members of a region are greatly outweighed by its freeriders, COALogit sets PSC to 0. Coalition members must fulfil three criteria for their region to enforce a power-exit. They must: (1) constitute at least 20% of the upstream coal-power generation of their region and (2) total PE demand and (3) not be the sole coalition member in a multinational region. These conditions ensure that the emerging economies of a region are not artificially prevented from capitalizing on PPCA-induced coal price depression simply because the wealthy few accede (for example, South Korea in 'Other Asia').

Power-exit implementation in REMIND (V and VII). We model the power-exit in REMIND by restricting the share of total electricity production from coal-fired power plants without CCS. The sum of electricity generated by REMIND unabated coal plants (Supplementary Appendix II gives technology types) from the policy start year until 2100 in each region is constrained to a PSC-defined fraction of the total regional electricity generated in that timespan. Equation (7) describes this constraint, unique to power-exit scenarios.

$$\sum_{t=t_\alpha}^{2100} \check{\mathrm{seel}}_{R,U}(t) \le \mathrm{PSC}_{R,\alpha}\left(\sum_{t=t_\alpha}^{2100} \check{\mathrm{seel}}_{R,G}(t)\right) \qquad (7)$$

where: $\check{\mathrm{seel}}_{R,U}$ is the unabated coal-fired electricity generation in downstream run and $\check{\mathrm{seel}}_{R,G}$ is the electricity generation in downstream (relative to PSC derivation) run.

Note that non-OECD-xp REMIND runs include both the OECD and non-OECD constraints. Coal-power generation from 2050 to 2100 is ultimately bounded by the more stringent of the two but a region is theoretically free to consume its entire 2030–2100 allowance within the 2030–2050 timespan.

Demand-exit policy stringency coefficients (IV and VI). Demand-exit policies are implemented through a three-step process. First, a PSC is derived to limit the share of total regional CO_2 emissions that can come from non-solid coal consumption from 2030 (2050) until 2100 in the OECD (non-OECD). Second, a separate PSC constrains the CO_2 from coal solids used for non-metallurgical purposes, for example cement production, as a share of overall regional CO_2 over the same horizons. Third, another PSC limits CO_2 emissions from coal-based metallurgy, applied from 2040 (2060) to 2100. Equations (8)–(10) describe this procedure. Demand-exit PSCs are derived on the basis of the emissions from each coal demand vector rather than consumption because REMIND v.2.1 directly calculates the emissions from each fuel type in each industrial subsector (cement, steel, chemicals and process heat) using baseline energy demands and marginal abatement cost curves. Relative emissions are equivalent to relative consumption because REMIND assumes identical emissions factors for all coal uses.

$$\mathrm{PSC}_{R,\alpha_c} = \frac{\sum_{t=t_{\alpha_c}}^{2100} \sum_{n\in F_R}\left(\widehat{\mathrm{emi}}_{n,\bar{c}}(t) - \widehat{\mathrm{emi}}_{n,\bar{s}}(t)\right)}{\sum_{t=t_{\alpha_c}}^{2100} \widehat{\mathrm{emi}}_{R,E}(t)} \times L \qquad (8)$$

$$\mathrm{PSC}_{R,\alpha_s} = \frac{\sum_{t=t_{\alpha_s}}^{2100} \sum_{n\in F_R}\left(\widehat{\mathrm{emi}}_{n,\bar{s}}(t) - \widehat{\mathrm{emi}}_{n,m}(t)\right)}{\sum_{t=t_{\alpha_s}}^{2100} \widehat{\mathrm{emi}}_{R,E}(t)} \times L \qquad (9)$$

$$\mathrm{PSC}_{R,\alpha_m} = \frac{\sum_{t=t_{\alpha_m}}^{2100} \sum_{n\in F_R} \widehat{\mathrm{emi}}_{n,m}(t)}{\sum_{t=t_{\alpha_m}}^{2100} \widehat{\mathrm{emi}}_{R,E}(t)} \times L \qquad (10)$$

$$\text{if} \quad \alpha = \begin{cases} \mathrm{OECD},\ \text{then } t_{\alpha_c}, & t_{\alpha_s} = 2030,\ t_{\alpha_m} = 2040 \\ \mathrm{non-OECD},\ \text{then } t_{\alpha_c}, & t_{\alpha_s} = 2050,\ t_{\alpha_m} = 2060 \end{cases}$$

where: $\widehat{\mathrm{emi}}_n$ is the CO_2 emissions of each nation in R, downscaled from the upstream run, E is all energy end-use activities, c is non-solids coal end-uses, $\bar{c}$ is all coal end-uses, s is non-metallurgical coal solids end-uses, $\bar{s}$ is coal solids end-uses and m is met-coal end-uses (that is, iron and steel manufacturing).

Analogous policy enforcement criteria as defined for the power-exit apply to each of the demand-exit PSCs individually, for example $\mathrm{PSC}_m = 1$ unless the region's coalition members account for 20% of its total emissions from met-coal. If they do, the met-coal emissions of that region are constrained but its non-solids coal emissions may not be if coalition members emitted <20% of total regional coal-based CO_2.

Demand-exit policy implementation (V and VII). The three PSCs enter REMIND in a series of corresponding equations that enforce the demand-exit policy. Equation (11) illustrates how the non-solids coal and non-metallurgical coal solids elements of the policy are implemented by controlling different sets of technologies, just like the power-exit. Equation (12) shows the additional assumption used to isolate the emissions from met-coal, namely that the share of coal in a region's solid energy consumption is uniform across all sectors.

https://doi.org/10.1038/s41558-022-01570-8

$$\sum_{t=t_{\alpha_j}}^{2100} \underset{R,j}{\check{\text{emi}}}(t) \le \text{PSC}_{R,\alpha_j}\left(\sum_{t=t_{\alpha_j}}^{2100} \underset{R,E}{\check{\text{emi}}}(t)\right) \tag{11}$$

$$\sum_{t=t_{\alpha_m}}^{2100}\left(\underset{R,m}{\check{\text{emi}}}(t) \times \frac{\underset{R,\bar{S}}{\check{\text{FE}}}(t)}{\underset{R,S}{\check{\text{FE}}}(t)}\right) \le \text{PSC}_{R,\alpha_m}\left(\sum_{t=t_{\alpha_m}}^{2100} \underset{R,E}{\check{\text{emi}}}(t)\right) \tag{12}$$

where: $j = \{c, s\}$, $\underset{R}{\check{\text{emi}}}$ is the regional CO_2 emissions variable in downstream run, $\underset{R}{\check{\text{FE}}}$ is the regional final energy production variable in downstream run and S is all solid final energy production.

COVID-19 recovery programs

The third dimension of our analysis (Table 2) considers the near-term uncertainties associated with the COVID-19 shock[89]. We assess the path-dependencies[90–94] of PPCA dynamics and outcomes to different near-term trajectories of coal-power capacity. These are derived by first calculating detailed national-level historical statistics using plant-level data and then applying stylized global assumptions (Supplementary Appendix Table 1.3) to extrapolate potential future trends (Extended Data Fig. 1).

We name these outlooks green, neutral and brown COVID recoveries, in ascending order of the global coal-power generation in 2025. The neutral recovery assumes that the COVID crisis has no effect on the average lifespans of coal plants nor the historical completion rates of projects in each phase of the development pipeline. The green and brown recoveries, meanwhile, are designed to capture the 'reasonable' range of COVID-induced changes to those statistics (Supplementary Appendix I).

Despite their fast-approaching PPCA deadline, our neutral and brown extrapolations expect several OECD states to continue increasing coal capacity (Korea and Japan even in the green recovery). Under default REMIND assumptions, early coal plant retirement is generally limited to 9% of a total fleet of a region each year (45% per 5 yr time step). A power-exit by 2030 was thus mathematically infeasible in several regions, leading us to relax this constraint to 20% (that is, a 100% power-exit is possible within 5 yr even if all plants are under 40 years old).

Unlike the other two dimensions, these exogenous constraints are independent of the PPCA and also apply to the NPi and NDC scenarios. Hence, each of the three NPi-COVID baselines (NPi-green, NPi-neutral and NPi-brown) initiates its own two scenario cascades, one for each policy interpretation (Extended Data Fig. 4) and all runs within these two cascades are fixed to the same 2025 coal-power generation level. Importantly, the COVID-19 dimension can have direct impacts on the energy system as well as feed-forward effects on the growth of the coalition, indirectly affecting scenario outcomes.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data and analysis scripts that support the findings of this study are publicly available on Zenodo at https://doi.org/10.5281/zenodo.7335236.

Code availability

The source code of the REMIND–COALogit model version used in this study are available on Zenodo at https://doi.org/10.5281/zenodo.7335042. Source code for REMIND input data processing functions are openly available on GitHub at https://github.com/pik-piam/mrremind.

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Acknowledgements

The research leading to the results reported in this study was supported by the PEGASOS project (01LA1826C; S.B. and N.B.), made possible by funding from the German Federal Ministry of Education and Research (BMBF), and the MANIFEST project (950408; J.J.), funded by the European Commission's Horizon 2020 ERC Starting Grant programme. We thank L. Merfort, V. Vinichenko, A. Malik and M. Pehl for correspondence and specific recommendations of data or code that enabled the implementation of certain elements of our study.

Author contributions

S.B. and N.B. conceived of the research questions, while J.J. and S.B. conceptualized the methodology. All authors contributed to the literature review. S.B. led the implementation, analysis and manuscript writing with contributions from all authors. J.J. conceived of Figs. 1 and 2. N.B. conceived of Table 1. S.B. conceived of all other display items.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41558-022-01570-8.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41558-022-01570-8.

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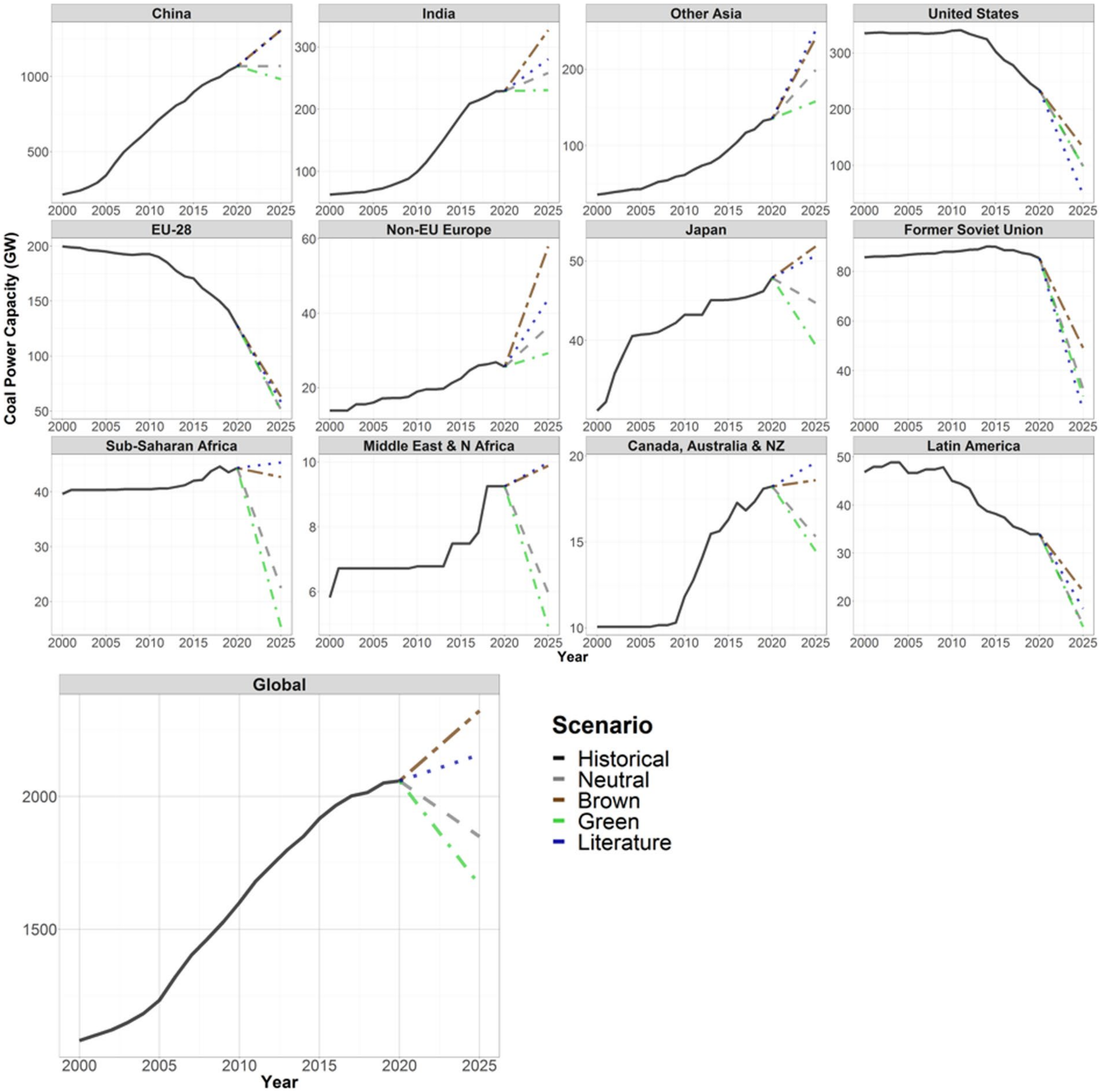
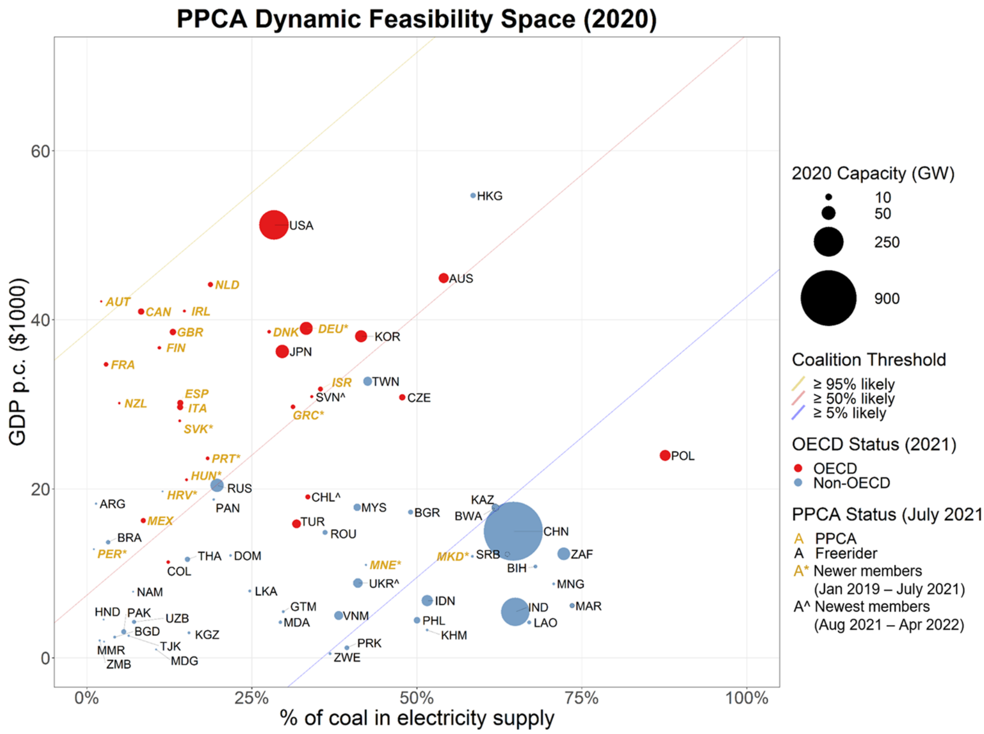
Peer review information *Nature Climate Change* thanks Mark Roelfsema and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

 https://doi.org/10.1038/s41558-022-01570-8



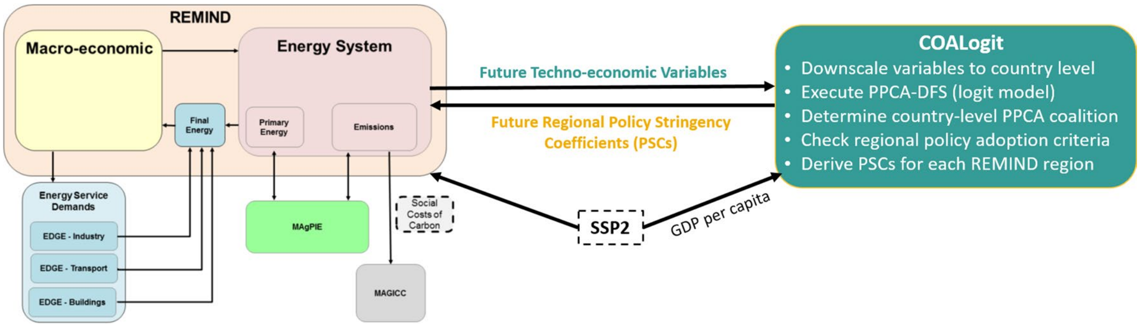
Extended Data Fig. 1 | Historical coal power capacity in GW from 2000–2020 and near-term extrapolations with varied assumptions. aggregated to REMIND regions (Supplementary Fig. A3.1) and globally. The 'Literature' scenario corresponds to global assumptions of 40-year lifetimes and 100% project completion, as is often used in prior studies on 'committed emissions.'[44] See Supplementary Table A1.5 for exact GW values per region.

https://doi.org/10.1038/s41558-022-01570-8



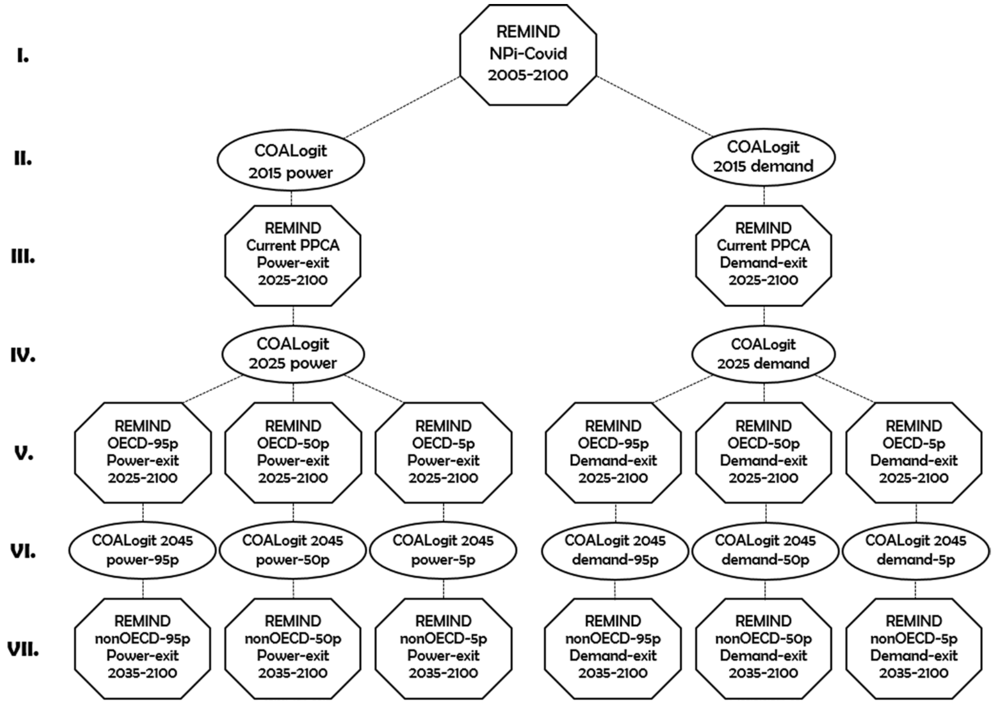
Extended Data Fig. 2 | The approximated PPCA-DFS in 2020. which better illustrates the logit model's ability to predict PPCA accession than the 2015 snapshot in Fig. 2a. REMIND source data licensing agreements unfortunately prevent us from using more recent data at the moment, so COALogit parameters are estimated using 2015 data. Coal-power-shares are derived for this figure from historical coal capacities, extrapolated utilization rates, and downscaled electricity generation from REMIND.

https://doi.org/10.1038/s41558-022-01570-8



Extended Data Fig. 3 | Depiction of the REMIND–COALogit framework. Supplementary Table 3 lists all the specific variables passed from REMIND to COALogit, which vary by scenario. Policy stringency coefficients (PSCs) translate country-level coalitions into the fraction of each REMIND region's coal demand (electricity or total) that the PPCA phases out. Their derivation is also scenario-dependent, as shown in Eqs. (1)-(2) and (5)-(11). The REMIND schematic (from Baumstark et al. [55]) includes some pre-existing interfaces for context and illustration of model structure. The coupling routines vary from iterative co-optimization (REMIND-MAgPIE) to ex post calculations (MAGICC), but none are identical to the REMIND–COALogit soft-link.

 https://doi.org/10.1038/s41558-022-01570-8



Extended Data Fig. 4 | REMIND–COALogit cascade for modelling multistage PPCA accession. shown for six PPCA scenarios. Each Roman numeral corresponds to a distinct REMIND or COALogit run in the sequence, and numerals used throughout the Methods refer to this figure. Each REMIND run is a global Nash equilibrium solution in which regional welfare is intertemporally optimized across the time horizon shown (prior periods are fixed to the upstream run). The year in each COALogit oval indicates the REMIND period from which input data is received. This cascade is repeated for each COVID recovery, giving a total of 18 PPCA scenarios.

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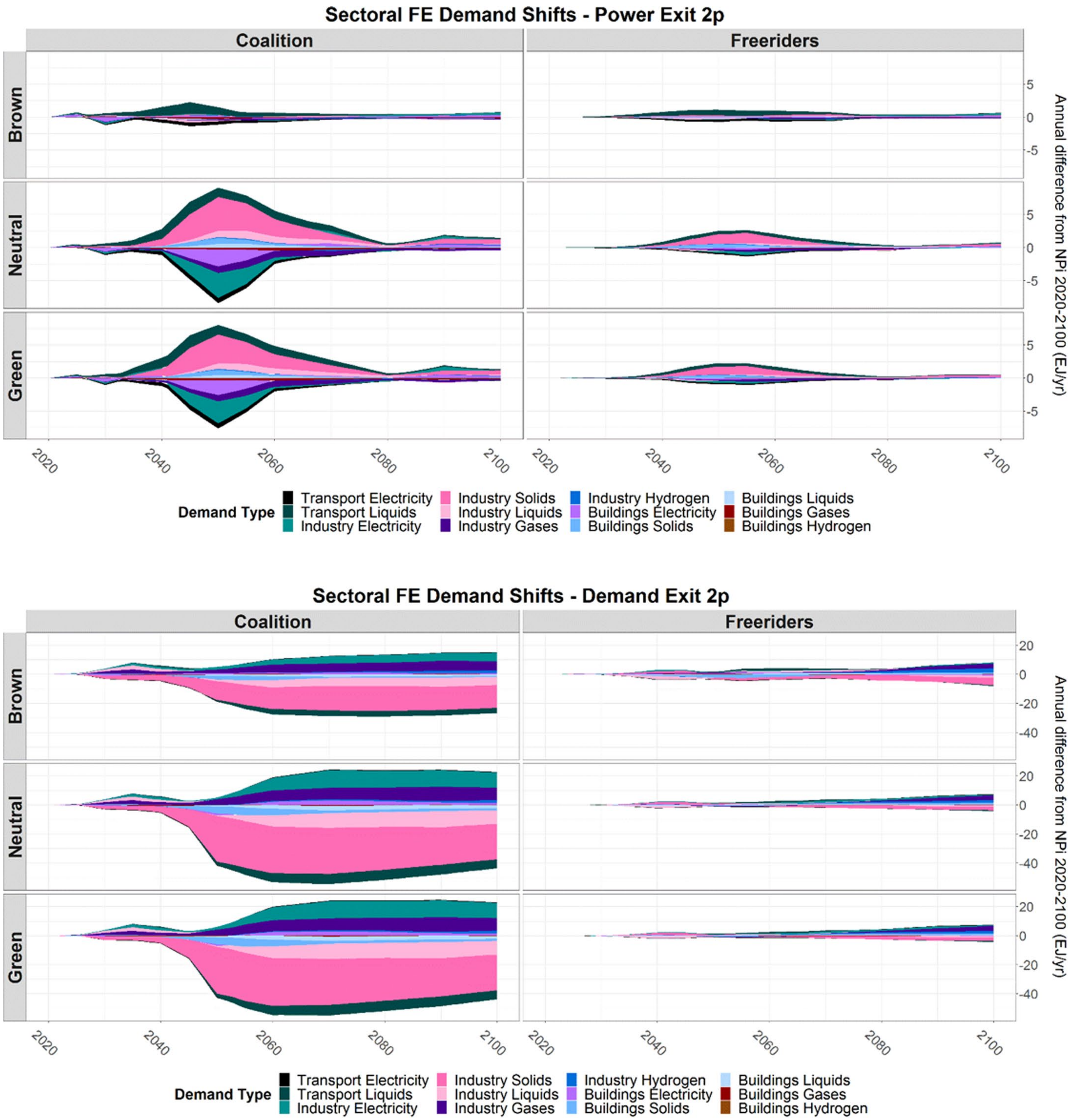

Extended Data Fig. 5 | Impacts of the *power-exit* (a) and *demand-exit* (b) PPCA scenarios on final energy (FE) consumption in each sector. Not shown are gas- and hydrogen-based mobility, and heat used in industry and buildings.

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Last updated by author(s): Nov 18, 2022

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used for data collection
Data analysis	All code used and developed for this study is or will be open source. Source data was processed with the R package mrremind, version 0.66.2 (https://github.com/pik-piam/mrremind) for use in our custom version of the REMIND model (https://github.com/stephenbi/remind/tree/PPCA_final/), based on the release version 2.3.1 (https://github.com/remindmodel/remind/tree/v2.1.3). The COALogit model can be found within our custom REMIND repository (https://github.com/stephenbi/remind/blob/PPCA_final/scripts/input/COALogit_PPCA.R). Some prominent third-party R packages are also used, including dplyr, stats, and ggplot2.

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- A list of figures that have associated raw data
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The data that support the findings of this study are publicly available on Zenodo with the identifier 10.5281/zenodo.5977793. Additional data is available from the author upon request.

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Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The study quantifies the probabilistic expansion of the Powering Past Coal Alliance (PPCA) using a logistic regression model defined by Jewell et al. (2019) coupled to the integrated assessment model REMIND, which simultaneously enables a long-term analysis of the PPCA's energy system and climate impacts.
Research sample	The sample used to refit the logistic regression model were the 41 current PPCA members and the 62 non-participating nations which derived at least 1% of their electricity from coal. The source data for national coal-fired electricity production in 2015 is the IEA World Energy Balances 2017, and per-capita GDP data was taken from the Institute for Health Metrics and Evaluation (IHME). These data were chosen because they are taken as input by REMIND, but they are not identical to the original logistic regression analysis of Jewell et al.
Sampling strategy	All countries with either PPCA membership or >1% electricity generated from coal were sampled for logit model parametrization.
Data collection	Data taken from various sources described in the Methods and Supplementary Information.
Timing	All data used in the parametrization of the logit model are for the year 2015.
Data exclusions	Kosovo was excluded from our analyses because it is not recognized by the ISO 3166 country code standard.
Non-participation	N/A
Randomization	N/A

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n/a	Involved in the study	
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☒	☐	Human research participants
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging