Coal Exit Policy Must Confront Loopholes and Laggards for Political Momentum to Matter for Paris Targets

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Coal Exit Policy Must Confront Loopholes and Laggards for Political Momentum to Matter for Paris Targets

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Abstract

The global phase-out of coal by mid-century is considered crucial to achieving the Paris Agreement and keeping warming well-below 2°C above pre-industrial levels. Since the Powering Past Coal Alliance's (PPCA) inception at COP23, political ambitions to accelerate coal's decline 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), the first evidence-based approach for emulating real-world policymaking. Given empirical relationships established between energy-economic developments and PPCA membership, we endogenise national policy decision-making into the integrated assessment model REMIND via iterative, multi-stage feedback loops with a political feasibility model. DPE finds the PPCA ~5% likely to diffuse globally – indicative of baseline coal exit ambition – and exposes severe, unconventional risks of current power-sector-specific action. Furthermore, PPCA evolution exhibits path-dependence to Covid-19 recovery investments, illustrating DPE's utility for exploring policy synergies.

Introduction

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 pathways to achieve the climate targets[2,3], the political feasibility of these scenarios is under scrutiny[4–7]. Socio-political barriers are well-acknowledged, typically analysed through exogenously-determined 'second-best' scenarios, such as delayed action[8], regionally-differentiated ambition[9], or technological skepticism[10]. However, these still presume global policy coordination, which appears infeasible in a bottom-up international regime without credible enforcement mechanisms[11,12].

Whereas CEA explores the political ambition needed to achieve stated goals, stated policy evaluation (SPE) illustrates the consequences of maintaining current ambition levels, e.g. already-implemented national policies (NPi) or nationally-determined contributions (NDCs) to Paris. SPE scenarios are often used as reference baselines for CEA and policy evaluation analyses (PEA), which assess subsequent mitigation options for their potential contribution to specified targets (Table 1). Conspicuously, for all the endogenous techno-economic dynamics represented in IAMs[13], SPE and PEA rely on exogenous assumptions to prescribe policies top-down across disparate societies. To portray realistic expectations for baseline ambition and subsequent policy options, models should instead emulate the bottom-up nature of climate politics[14,15]. Two methodological innovations are necessary to achieve this: (i) to objectively and dynamically quantify policy feasibility[6] and diffusivity[16], and (ii) to harness bidirectional feedbacks between national policy adoption and the global energy economy[7].

Here, we introduce dynamic policy evaluation (DPE), a novel IAM approach (Table 1) which fulfills both requirements to endogenise bottom-up policy coordination. Given that IAMs derive long-term energy system investment patterns consistent with empirical data and anticipated socioeconomic trends, it follows that observed policy developments can be coherently extrapolated in parallel. Recent empirical research has begun to codify causal links between national techno-economic contexts and real-world political decisions[17–19], and vice-versa[20]. DPE *merges*[7] this knowledge with SPE. To wit, SPE captures the global energy system impacts of an emerging policy initiative in the variables computed, which can be input to empirical models that then systematically define policy stringencies across model regions and periods for a subsequent scenario (Methods; Figure M2). This iterative feedback loop mimics the co-evolution of energy economics and energy politics; each government's behavior can be influenced by the actions of any other nation(s) or perturbations to the system.

IAM Approach	Research Question	Coal Phase-Out Insight	Feasibility Focus
Cost-Effectiveness Analysis (CEA)	*What policy actions and ambition levels are* <u>*required*</u> *to achieve cost-optimal pathways toward an environmental goal (e.g. Paris climate targets)?*	Coal is often phased out by 2050 in cost-efficient, Paris-compliant, benchmark scenarios[21,22].	Endogenous assessment of a target's techno-economic feasibility given assumptions on future technology and socioeconomic developments that may include political feasibility constraints.
Stated Policy Evaluation (SPE)	*What are the long-term outcomes if* <u>*revealed*</u> *or* <u>*stated*</u> *ambition essentially remains static over time?*	Current PPCA members abate 2.5 $GtCO_2$ of emissions from coal-fired electricity[18].	Assessment of current policies or pledges assumed to be politically feasible but also to remain static. Often used as baseline reference scenarios.
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^{o}C Paris climate target[23].	Assessment of long-term impacts of hypothetical policy options with endogenous technological feasibility and exogenous prescription of political feasibility (or global policy adoption).
Dynamic Policy Evaluation (DPE)	*Given diverse and fluid national contexts, how does the* <u>*implied*</u> *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?	Concurrent endogenous assessment of a policy's techno-economic feasibility via IAM and political feasibility via empirical analysis of IAM scenario data. This inter-disciplinary coupling captures reciprocal feedbacks between policy adoption and the energy system, improving realism of future policy uptake and thus emissions.

Table 1. Approaches to IAM scenario analysis compared. Dynamic policy evaluation merges the divide between energy-economy models (e.g. IAMs), which excel in depicting long-term techno-economic feasibility, and social science research, which excels at understanding today's technology and policy landscape. DPE endogenises feedbacks between the two analytical approaches to embed socio-political dynamics into IAM scenarios, improving conventional SPE representations of baseline policy ambition and opening new doors for research on politically feasible mitigation strategies. The present study demonstrates DPE on the coal phase-out agenda.

CEA-derived mitigation strategies and international negotiations frequently prioritize the phase-out of coal[21,22,24,25], owing to its low economic value, high emissions factor, readier substitutes, and longer-lived capital relative to other fossil fuels[26–29]. The aggregate desirability of abandoning coal is further underscored by PEA demonstrations of the health and environmental benefits[23]. The socio-political feasibility, meanwhile, remains underexplored[18,30,31]. As some nations continue to commission coal-fired power plants[19,32–34] (Table 2), others have formed the Powering Past Coal Alliance (PPCA), an opt-in initiative aspiring to eradicate "unabated coal-fired electricity" by 2030 in the OECD and EU, and by 2050 in developing and emerging economies[35].

Although the 41 current national PPCA members[i] comprise just 5.1% of global coal-fired electricity, this constitutes a doubling since Jewell et al. (2019). Despite grave uncertainty, SPE and PEA can essentially only depict all-or-nothing outcomes for the coal phase-out agenda (Table 1). Using DPE, we fill this exigent research gap and address the following research questions. Under standard baseline assumptions, which countries can be reasonably expected to accede, and what constitutes a plausible range of outcomes? Can the PPCA's sector-specific policy foster Paris-consistent coal declines, or is economy-wide coverage necessary? What are the relative effects of carbon leakage and renewable technology spillovers on PPCA evolution? Finally, how path-dependent is PPCA growth and efficacy to near-term coal demand uncertainties after Covid-19[36]?

World Region	Operating Capacity (GW)	Mean Plant Age (yrs)	Mean Lifespan (yrs)	Capacity Pipeline (GW)	Project Completion Rates	Implied Emissions ($GtCO_2$)
Canada, AUS, NZ	34.4	33.1	40.2	5.2	35.5%	1.96
China	1028.4	11.2	22.2	285.6	54.8%	78.25
EU-27 + UK	141.5	32.8	42.0	1.8	43.2%	8.26
Former Soviet Union	85.8	42.8	51.2	5.6	47.4%	4.57
India	225.7	12.3	38.9	102.7	35.8%	34.73
Japan	47.2	22.3	36.9	9.8	71.0%	5.68
Latin America	17.5	18.1	31.6	5.2	40.1%	2.19
MENA	9.2	21.3	36.9	19.9	43.2%	1.06
Non-EU Europe	26.4	22.2	48.0	29.5	41.8%	5.93
Other Asian States	129.2	11.7	35.0	154.9	58.8%	25.57
Sub-Saharan Africa	44.1	31.2	48.0	34.9	39.7%	2.21
USA	248.8	40.5	48.9	0.0	1.4%	13.89
World	**2058.1**	**18.5**	**31.1**	**655.1**	**50.1%**	**184.3**

Table 2. Bottom-up coal power capacity statistics aggregated to REMIND's 12 world-region level, including the operating capacity in 2020, the capacity-weighted mean age of operating plants, the historical capacity-weighted mean lifespan, currently planned capacity, and the completion rate of pipeline projects from 2014-2020. The final column calculates the implied total emissions from operating and planned coal plants if these historical values are held constant in the future (*neutral* Covid recovery scenario). See Table A3 for implied emissions of other recovery scenarios, and Table A2 for planned capacity and completion rates of each project phase.

We define an outcome as socio-politically feasible if there are actors who have the capacity to realise it in a given context[37]. Thus, a national energy and climate policy is feasible if it aligns with state imperatives and if the state has sufficient capacity to overcome vested interests[6]. For the coal phase-out arena, Jewell et al. (2019) defined a dynamic feasibility space[6] (DFS) in terms of national likelihoods of joining the PPCA. Specifically, the study analysed a pool of 2,036 regression models, permuting eleven independent variables seeking to explain PPCA membership, and established that high per-capita GDP and low reliance on coal for electricity supply (coal-power-share) have particularly strong explanatory power (Figure 2a)[18]. In a first attempt to quantify future policy feasibility, we use the IAM REMIND[13] to provide scenario data to the DFS via the novel COALogit model, which employs spatial downscaling routines and probabilistic thresholds, or 'socio-political tipping points'[38–40], within the PPCA-DFS to iteratively define country-level, evidence-based scenarios of PPCA growth for REMIND analysis (Figure 2; see Methods).

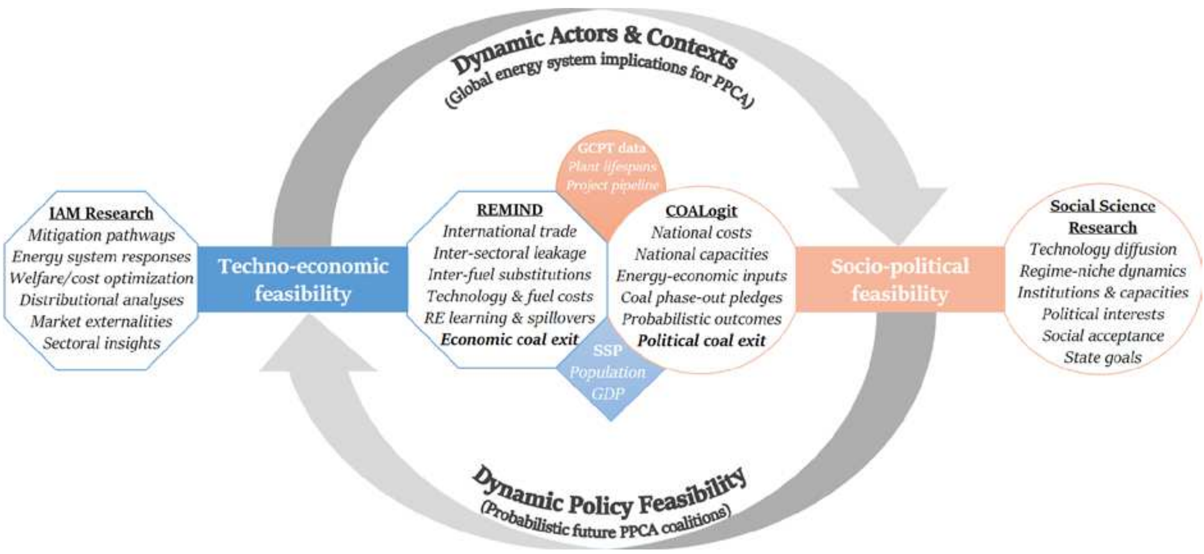
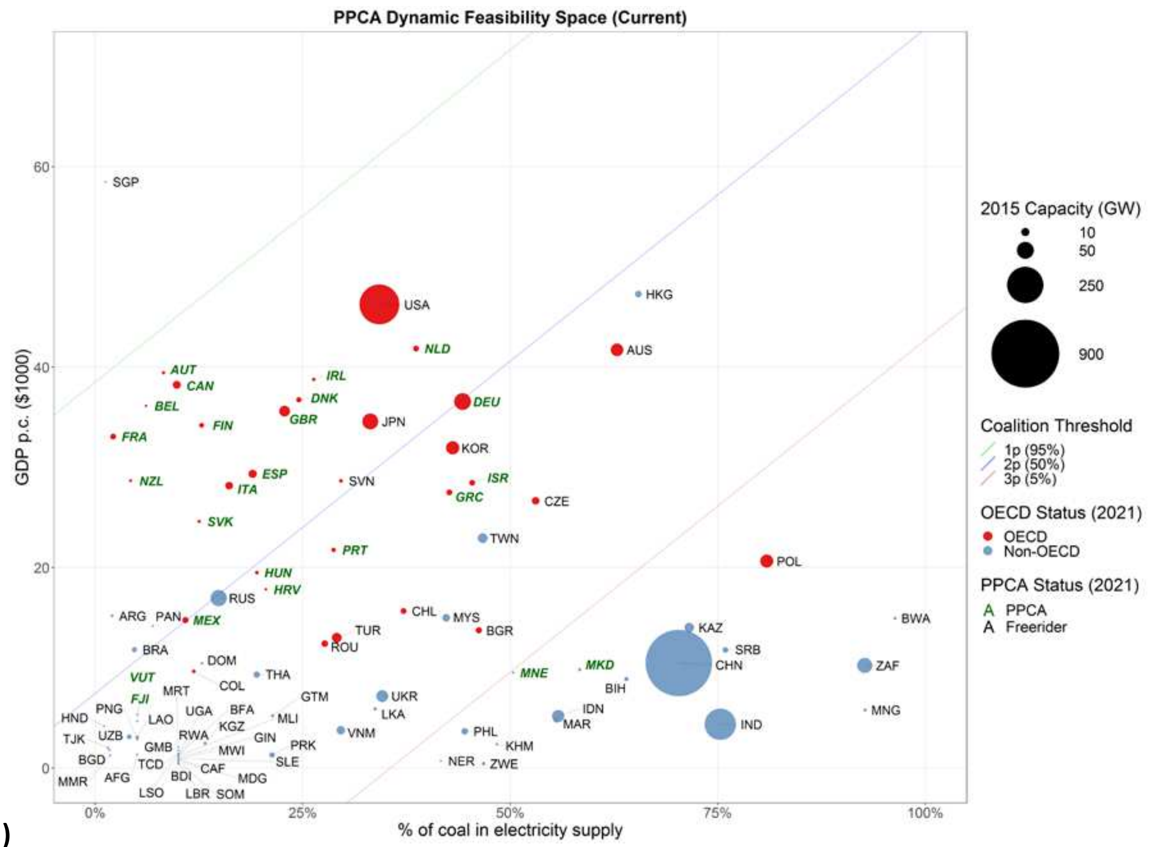
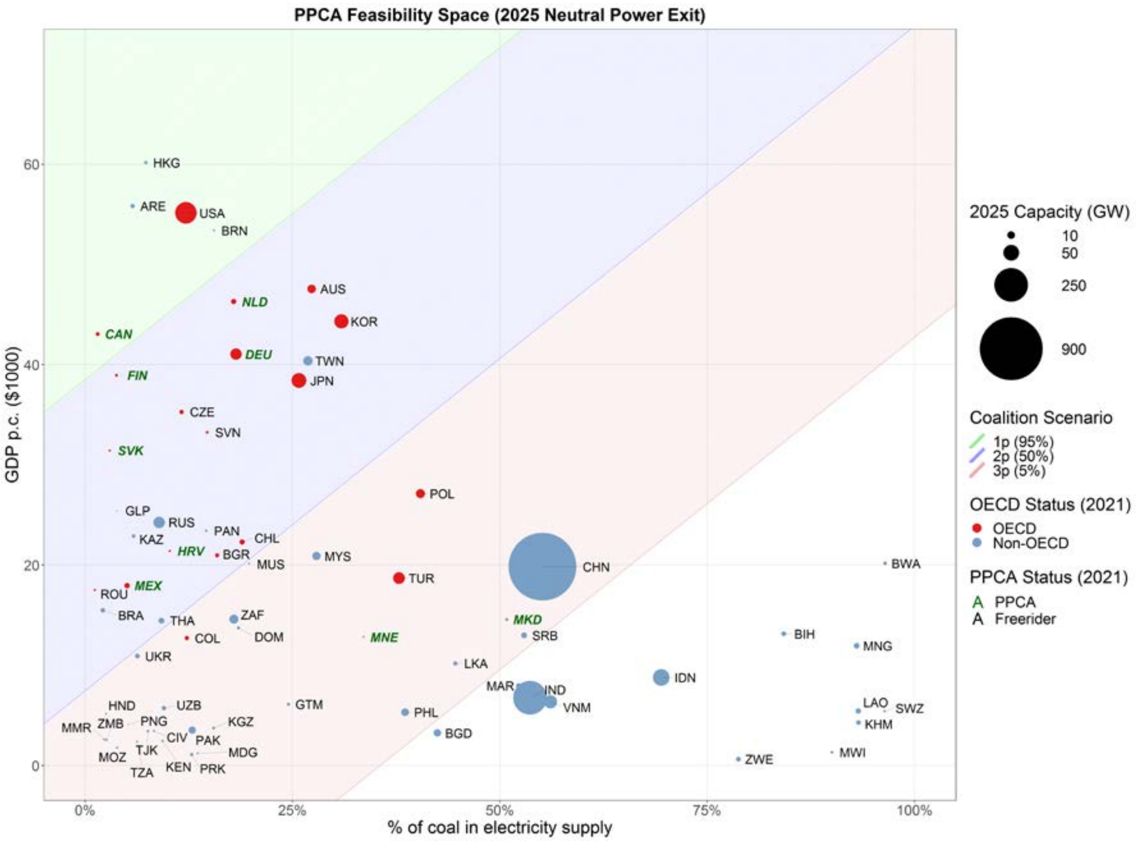


Figure 1. Dynamic Policy Evaluation depicted as a cyclical, iterative interface between techno-economic and socio-political analyses, both in the present study (inner circle and parentheses) and in the broader context of integrating IAMs and social sciences (outer circle). Policy feedbacks in this study begin with the impacts of currently legislated coal exits on national energy sectors, regional energy systems, and the global energy market, i.e. dynamic actors and contexts, via REMIND-endogenous effects (inner blue hexagon). REMIND feeds future per-capita GDP and coal-power-shares to COALogit, which infers national probabilities of PPCA accession. These political prospects are translated to coalition scenarios and policy stringency coefficients (Methods) which inform regionally-differentiated policy uptake in REMIND. Staged accession is simulated by repeating the cycle in different model time-steps.

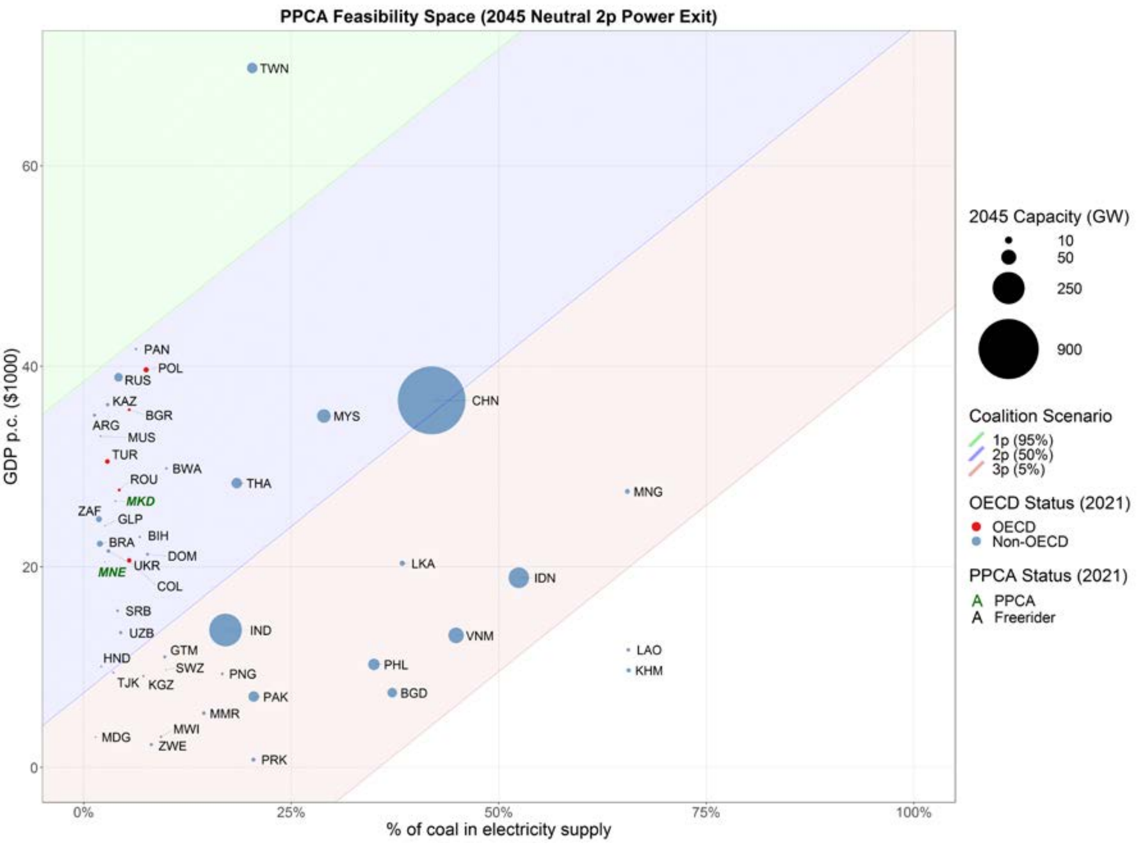


a)



PPCA Feasibility Space (2025 Neutral Power Exit)
GDP p.c. ($1000)
% of coal in electricity supply
0%
25%
50%
75%
100%
0
20
40
60
HKG
ARE
USA
BRN
AUS
NLD
KOR
CAN
DEU
TWN
FIN
JPN
CZE
SVN
SVK
POL
GLP
RUS
PAN
KAZ
CHL
HRV
BGR
MUS
MYS
CHN
BWA
ROU
MEX
TUR
BRA
ZAF
THA
MKD
COL
DOM
MNE
SRB
BIH
UKR
MNG
LKA
IDN
MAR
IND
VNM
HND
UZB
GTM
PHL
LAO
SWZ
MMR
ZMB
PNG
KGZ
KHM
CIV
PAK
BGD
MOZ
TJK
MDG
MWI
ZWE
TZA
KEN
PRK
2025 Capacity (GW)
10
50
250
900
Coalition Scenario
1p (95%)
2p (50%)
3p (5%)
OECD Status (2021)
OECD
Non-OECD
PPCA Status (2021)
A PPCA
A Freerider

b)



PPCA Feasibility Space (2045 Neutral 2p Power Exit)
GDP p.c. ($1000)
% of coal in electricity supply
0%
25%
50%
75%
100%
0
20
40
60
TWN
PAN
POL
RUS
KAZ
BGR
CHN
ARG
MYS
MUS
TUR
BWA
ROU
THA
MNG
MKD
ZAF
GLP
BIH
BRA
DOM
LKA
MNE
UKR
IDN
COL
SRB
UZB
IND
VNM
GTM
LAO
HND
SWZ
PHL
PNG
KHM
TJK
KGZ
PAK
BGD
MMR
MWI
MDG
ZWE
PRK
2045 Capacity (GW)
10
50
250
900
Coalition Scenario
1p (95%)
2p (50%)
3p (5%)
OECD Status (2021)
OECD
Non-OECD
PPCA Status (2021)
A PPCA
A Freerider

c)

d)

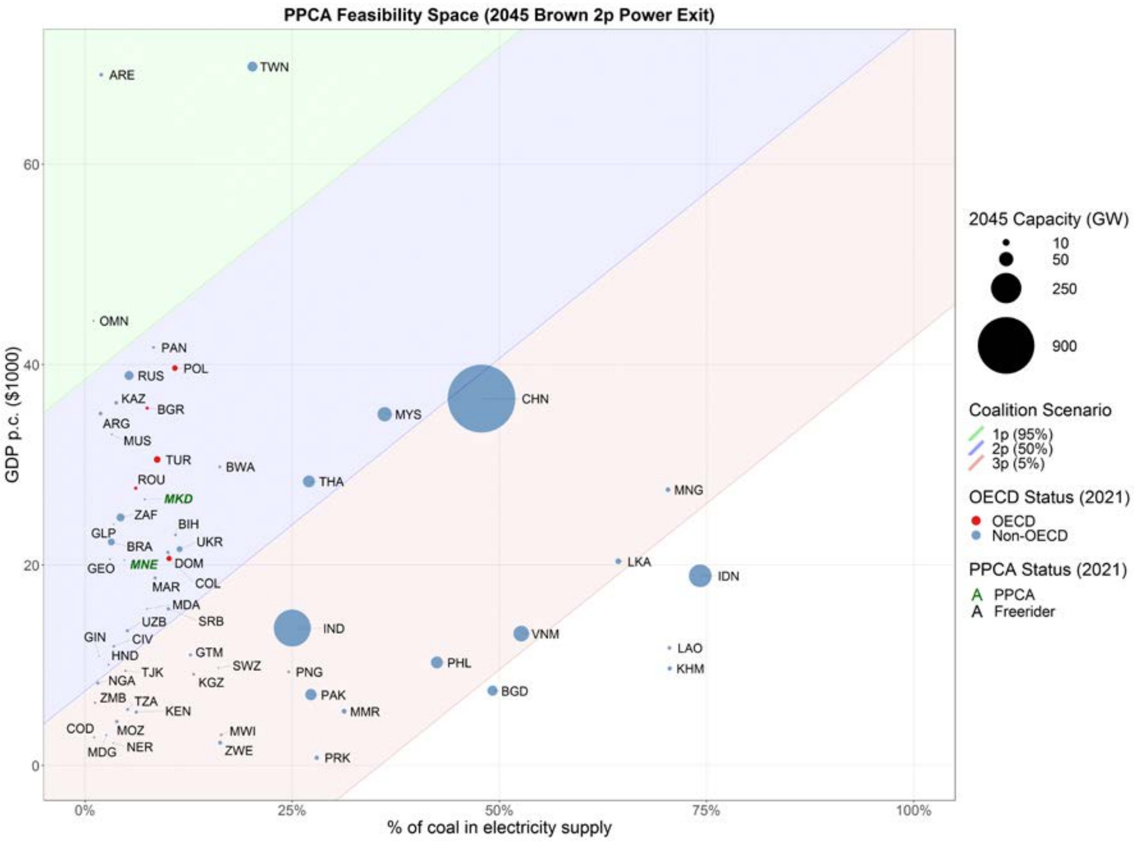


Figure 2. Dynamic feasibility of PPCA adoption in each country according to COALogit. Logistic regression of Alliance membership based on GDP per capita (indicator of state capacity) and coal-power-share (proxy for coal phase-out policy cost) in 2015 (a), 2025 (b) and 2045 (c & d), depicting all nations with >1% coal-power-share in the respective year. Bubble size indicates the operating coal capacity at that time, while 'PPCA Status' and 'OECD Status' reflect membership as of July 2021. The shaded areas show the probabilistic coalition scenarios: *proven (1p)*, *proven + probable (2p)*, and *proven + probable + possible (3p)*. Panels (b) and (c) represent the *neutral* Covid recovery – (c) follows directly from a 2030 *power-exit* by *OECD-2p* coalition members in (b) – while (d) illustrates the *brown* recovery, following from Figure SF1a.

Results

Scenario Implementation

To address these questions, we model 18 scenarios investigating three dimensions: coalition expansion, policy ambition, and Covid-19 recovery (Table 3). The REMIND-COALogit model-coupling framework mimics the PPCA's staged accession through an iterative cascade (Figure M4) which dynamically fragments policy stringency across model regions. We first analyse the energy system impacts of our 'median-estimate' *probable-neutral* scenarios alongside the analogous *probable-brown* scenarios, selected for the divergence in China's behavior (Figure 2c+d):

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

Thereafter, we analyse sensitivities across each dimension using efficacy indices for coal phase-out and climate mitigation which compare scenarios on unit scales, where 0 represents reference (NPi) coal consumption or CO_2 emissions and 1 corresponds to 1.5°C levels.

	IAM Mode	Analysis Dimension	Scenario Name	Scenario Definition
PPCA Scenario Elements	DPE	**Coalition Expansion** *(endogenous)*	*1p (proven)*	Real-world PPCA members (Table SF1) and nations assigned ≥95% probability of coalition accession by COALogit
			2p (probable)	1p plus nations above 50% coalition threshold
			3p (possible)	2p plus nations above 5% coalition threshold
	PEA	**Policy Ambition** *(exogenous)*	*Power-exit*	Unabated coal-fired electricity phase-out by 2030 in OECD+EU coalition members and 2050 in non-OECD+EU coalition members (verbatim PPCA declaration)
			Demand-exit	Unabated coal consumption phase-out along same timeline, except metallurgical coal is permitted a ten-year delay (2040 and 2060 deadlines) to reflect steel decarbonisation inertia and China's 2060 carbon neutrality pledge[41].
		Covid-19 Recovery *(exogenous)*	*Neutral (N)*	Covid-19 recovery plans re-confirm national historical tendencies in terms of project completion rates and mean plant lifespans in the coal power sector until 2025.
			Green (G)	Completion rates fall 50% and all shelved pre-construction projects cancelled, but plant lifespans unaffected.
			Brown (B)	Project cancellation rates decline 50%, and plants operate 5 years longer than historical national average.
External Scenarios	SPE	**Reference Scenario**	*NPi(-covid)*	Currently-implemented national policies, a revealed-ambition scenario serving as our baseline. We model four variations: *NPi-N, NPi-B,* and *NPi-G*, which correspond to each Covid recovery scenario, and *NPi-default*, without Covid constraints.
		Benchmark Scenarios	*NDC(-covid)*	Stated-ambition scenario assuming full compliance with the first-round 'nationally-determined contributions' to the Paris Agreement. We model three Covid-dependent variations (*NDC-N, NDC-B, NDC-G*).
	CEA		*WB-2C*	'Well-below 2°C', a scenario with >67% likelihood of limiting global mean temperature rise to <2°C above pre-industrial levels throughout the century. Without Covid constraints.
			Hi-1.5C	'Higher 1.5°C', a 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.
			1.5C	Scenario with >67% probability of achieving 1.5°C and a 50% chance of temporary overshoot by <0.1°C. Along with *NPi-default*, used to define efficacy indices (Figure 4). No Covid constraints.

Table 3. Definition of each scenario within each dimension of analysis, including reference and benchmarks. The 18 total DPE-PPCA scenarios cover every unique combination of the three 'PPCA scenario elements'. The *2p* coalition and *neutral* recovery represent our default set of assumptions, while the other scenarios are included for sensitivity analysis. We consider the two policy options (or a mixture thereof) to be similarly probable, so both are presented in detail as 'median-estimate' scenarios.

Power-Exit

OECD+EU *2p-N* Accession by 2025

Following a *neutral* Covid-19 recovery, operating coal power capacity in 2025 declines 10% from 2020 to 1850GW globally (Appendix I), corresponding to a 0.8EJ/yr reduction in coal-fired power generation. The resulting trends in national coal-power-shares and the general upward movement of per-capita GDP along the 'Middle-of-the-Road' SSP2[42] development trajectory lead 45 of 48 OECD+EU nations[ii] to exceed a 50% accession probability by 2025 (Figure 2b). COALogit assigns these nations to the *2p-N* coalition, and the *power-2p-N* REMIND scenario applies the *power-exit* policy to them in 2030.

Non-OECD+EU *2p-N* Accession by 2045

Using results from these intermediate REMIND scenarios (Table M2), COALogit assesses the propensity of non-OECD+EU countries to adopt a 2050 power-exit based on their per-capita GDP and coal-power-shares in 2045. We find that 137 of 201 non-OECD nations cross the *2p-neutral* threshold, so the full *power-2p-N* coalition comprises 182 members representing 82% of 2020 coal power generation, of which 70% was in non-OECD members.

2p-B Accession

The *brown* recovery, meanwhile, increases coal-fired capacity by 13% (to 2320GW) and generation by 0.8EJ/yr globally from 2020-2025. Coal-power-shares thus deviate from the *neutral* recovery, but per-capita GDP develops identically. This leads Chile and China to abstain from accession (Figure 2d), so the *power-2p-B* scenario consists of 44 OECD and 136 non-OECD members, representing 36% of 2020 coal-fired electricity, 70% of which was generated by OECD nations.

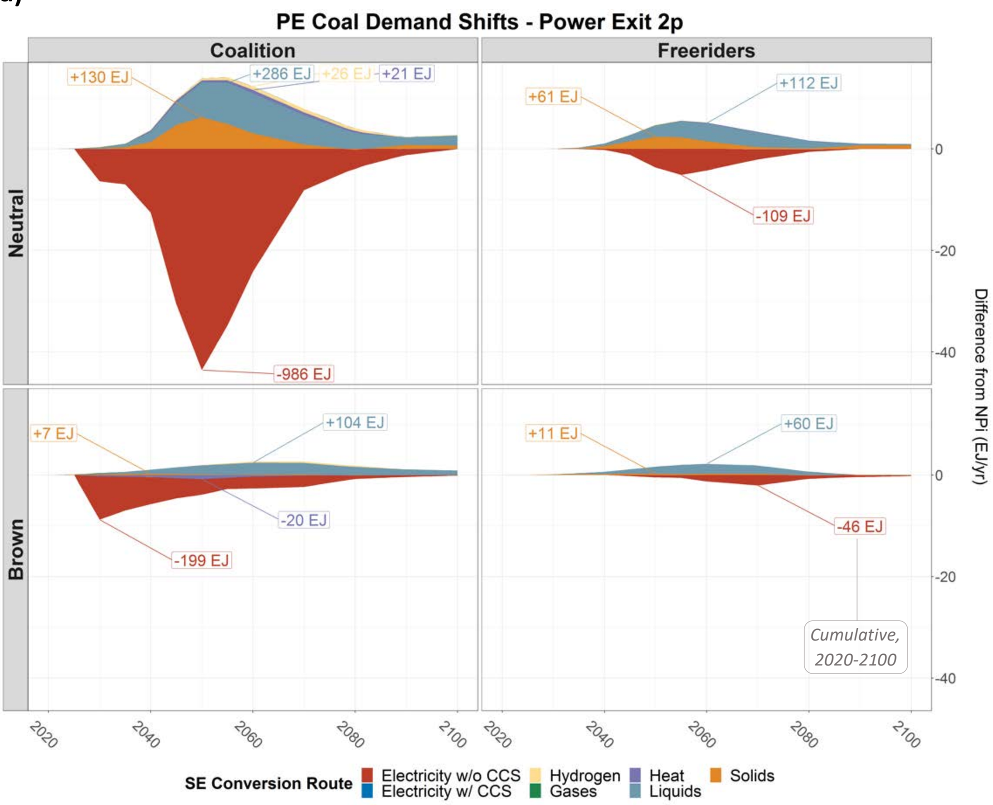
Coal Market Response

The *power-2p-N* coalition reduces their cumulative 2020-2100 unabated coal-fired electricity by 38% compared to *NPi-neutral* (*NPi-N*) (Figure 3a). Depression of global coal market price reaches 8% by 2050, leading to a 54% global coal leakage rate – i.e. each joule of coal phased-out incentivises 0.54J of coal use in another sector or country. Meanwhile, *power-2p-B* coalition members reduce their reference coal electricity 24% – viz. China's abstention decreases the magnitude of the first-order effect by 80% – while coal leakage rises to 63% globally. Extra-coalition coal power demand counterintuitively declines in both scenarios, complemented by increased coal-to-liquids (CtL) and solids consumption. In either case, coalition members contribute 80% of the global coal leakage, vastly exceeding the conventional free-rider problem.

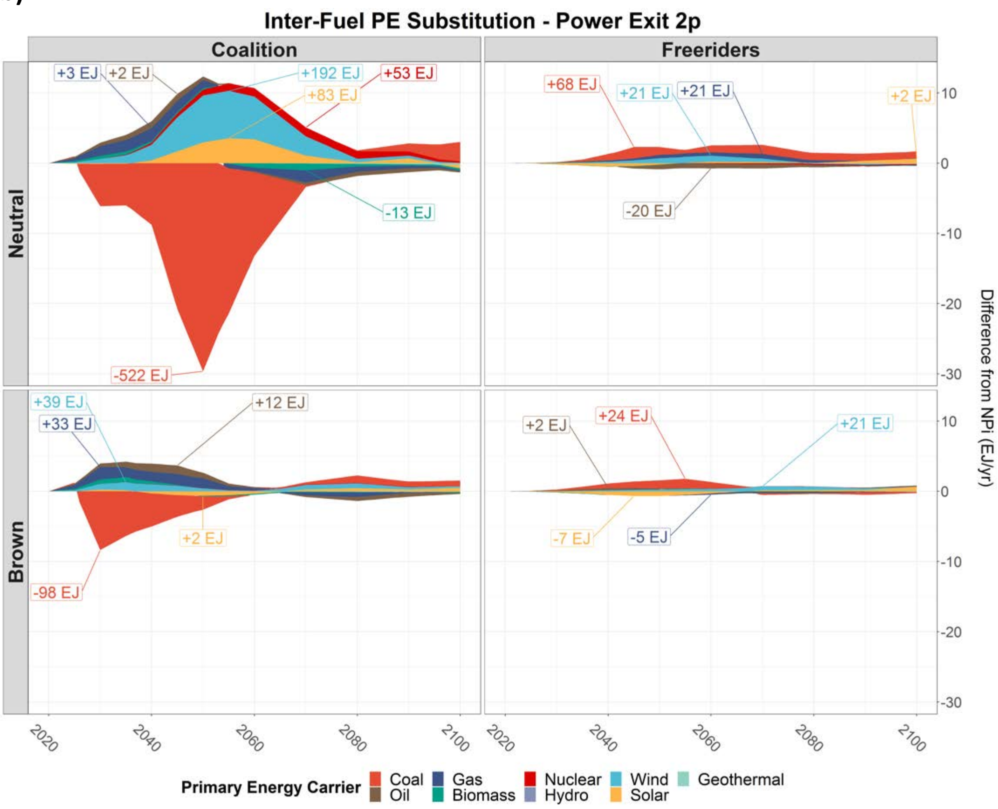
Energy System Response

Figure 3b illustrates the overall primary energy (PE) demand impacts of these *power-2p* scenarios. Oil and gas (O&G) account for two-thirds of the fuel switching during the OECD stage (2020-2035; see Figure M4) of *power-2p-N*. After the non-OECD phase-out commences in 2035, VRE dominates 93% of the energy system response. The latter phenomenon is not evident in the *power-2p-B* coalition, illustrating China's importance for VRE penetration and learning-by-doing spillovers. The benefits remain within the coalition, however, as VRE diffusion into free-riders increases minimally (<0.5%) in either scenario. A global scale-back of end-use electrification across all sectors (Figure SF3b), dually disincentivised by higher power system capital costs and cheaper coal-based solids and liquids, is an apparent limiting factor of additional VRE deployment. Globally, we calculate carbon leakage rates of 54% in *power-2p-N* and 76% in *power-2p-B*, over 85% of which occurs intra-coalition in both cases.

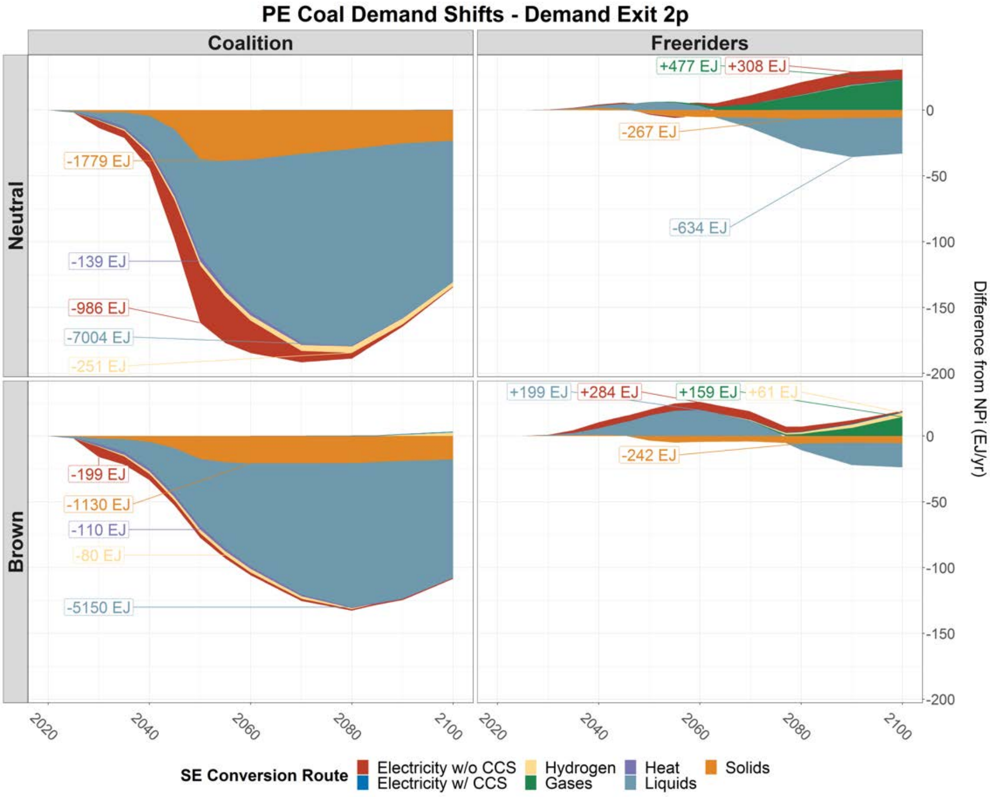
a)


PE Coal Demand Shifts - Power Exit 2p
Coalition
Freeriders
Neutral
Brown
+130 EJ
+286 EJ
+26 EJ
+21 EJ
-986 EJ
+61 EJ
+112 EJ
-109 EJ
+7 EJ
+104 EJ
-20 EJ
-199 EJ
+11 EJ
+60 EJ
-46 EJ
Cumulative, 2020-2100
0
-20
-40
Difference from NPi (EJ/yr)
2020
2040
2060
2080
2100
SE Conversion Route
Electricity w/o CCS
Electricity w/ CCS
Hydrogen
Gases
Heat
Liquids
Solids

b)


Inter-Fuel PE Substitution - Power Exit 2p
Coalition
Freeriders
Neutral
Brown
+3 EJ
+2 EJ
+192 EJ
+53 EJ
+83 EJ
-13 EJ
-522 EJ
+68 EJ
+21 EJ
+21 EJ
+2 EJ
-20 EJ
+39 EJ
+33 EJ
+12 EJ
+2 EJ
-98 EJ
+2 EJ
+24 EJ
+21 EJ
-7 EJ
-5 EJ
10
0
-10
-20
-30
Difference from NPi (EJ/yr)
2020
2040
2060
2080
2100
Primary Energy Carrier
Coal
Oil
Gas
Biomass
Nuclear
Hydro
Wind
Solar
Geothermal

c)



d)

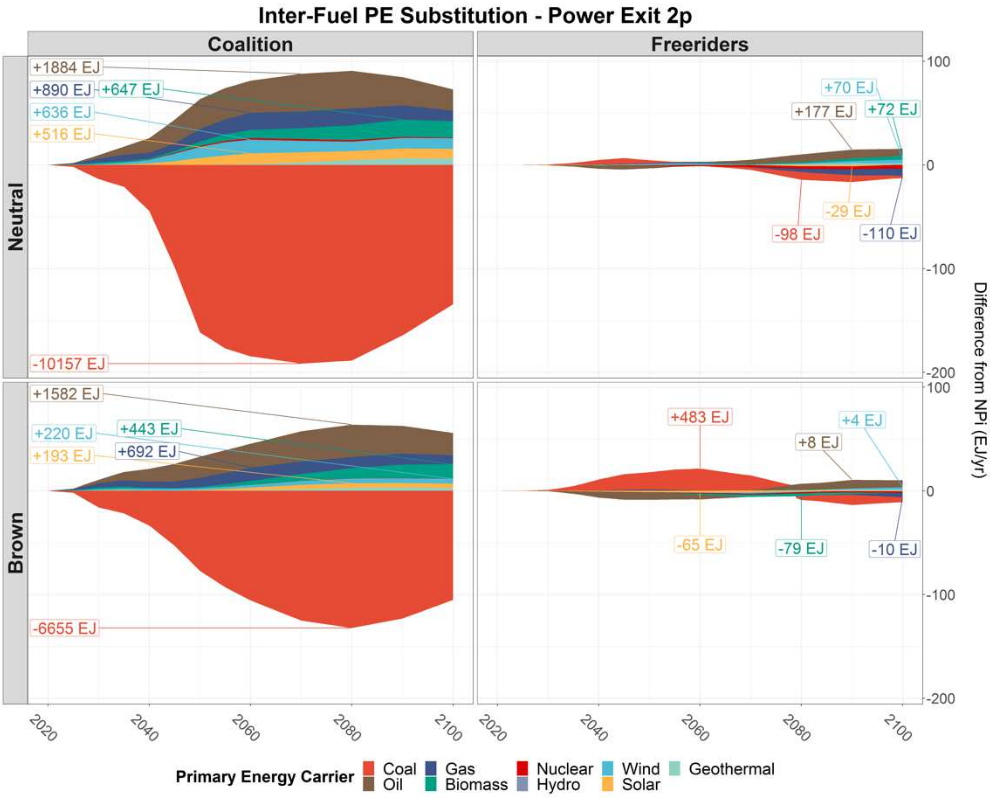


Figure 3. Annual differences in coal (a + c) or primary energy (b + d) demand from NPi in probable *power-exit* (a-b) and *demand-exit* (c-d) scenarios, with the cumulative differences denoted by labels. Columns distinguish between coalition members and free-riders in the Covid recovery scenario represented by each row. Coal demand is given in primary energy (PE) values and categorised 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.

Power-exit Policy Evaluation

At the global level, the *power-2p-N* policy-coalition scenario reduces coal use by 450EJ compared to *NPi-N*. Indexed to *NPi-default*, this achieves just 1.2% of the cost-efficient coal phase-out derived in the 1.5°C scenario. Thus, the median-estimate *power-exit* scores just .01 on the coal-exit efficacy index (Figure 4). The climate mitigation efficacy is even lower, scoring .01 (saving 6GtCO_2). Still, these are considerably better outcomes than *power-2p-B*, which underperform *NPi-default* on both indices (-.02 and -.01, respectively), implying that a global brown recovery from the Covid-19 recession may outweigh the PPCA's long-term coal and emissions reduction prospects. In any event, the verbatim *power-exit* contributes negligibly toward Paris-consistent abatement, assuming weak strengthening of global carbon pricing and non-electric sector regulations.

Demand-Exit

Coalition Expansion

For the *demand-exit*, COALogit returns a *2p-neutral* coalition scenario identical to *power-2p-N*. These 182 members comprise 81% of global coal demand in 2020, 25% of which was from OECD frontrunners. The *demand-2p-brown* coalition contains just one fewer member than *power-2p-B* (Serbia), totaling 179 nations which comprise 32% of 2020 coal demand. OECD members represent a 60% share.

Alliance Members

From 2020-2100, both *demand-2p-N* and *demand-2p-B* coalition members phase-out over three-quarters of their respective NPi coal consumption. CtL accounts for 68% of this decline in *2p-neutral* (77% in *2p-brown*) and solids for 18% (17%), while unabated electricity only constitutes 10% (3%) (Figure 3c). Intra-coalition oil demand surges 25% in both scenarios due to an oil-for-CtL swap in transport (Figure 3d), and gas demand increases 9% (8%), as industry's coal transition is divided between gasification and electrification (Figure SF4e). Cumulative VRE deployment increases 12% in *2p-N* members but just 4% in *2p-B*, 99% (96%) of which occurs post-2035 as the OECD again substitutes their phased-out coal primarily with O&G (~75%). Biomass deployment rises ~15% in either scenario, suggesting China is particularly important for VRE penetration.

Free-riders

The response of free-riding nations in *demand-2p-N* and *demand-2p-B* follow similar temporal profiles, albeit with high variance in magnitudes (Figure 3c+d). Free-riders also increase industry electrification and gasification (Figure SF4e), but fuel it with coal (Figure 3c). A knock-on coal-for-oil swap in extra-coalition transport liquids is evident following the OECD phase-out – much stronger when China freerides in the *brown* recovery – but inverts after non-OECD adoption. Coal drives the entirety of extra-coalition carbon leakage in *demand-2p-B* (7% rate), which is just 24% of global carbon leakage (30% rate). In *demand-2p-N*, free-rider leakage rates are slightly net-negative (-1% coal, -0.4% carbon), so intra-coalition emissions are the sole driver of the 18% global carbon leakage rate.

Demand-exit Policy Evaluation

Globally, the *demand-2p-N* scenario results in a coal phase-out of 10,300EJ from 2020-2100 compared to *NPi-N*. Isolated from other policies, this 50%-probable Alliance leads to a cumulative 3040GtCO_2 globally, saving 790Gt compared to *NPi-N*. Hence, moderate growth of a *demand-exit* coalition leads to efficacy indices of .52 for coal phase-out and .22 for mitigation. China's abstention is highly detrimental, as *demand-2p-B* scores .29 and .12, respectively. In both cases, the adverse effect of O&G leakage is evidenced by the ~250% spread between coal and emissions abatement efficacies.

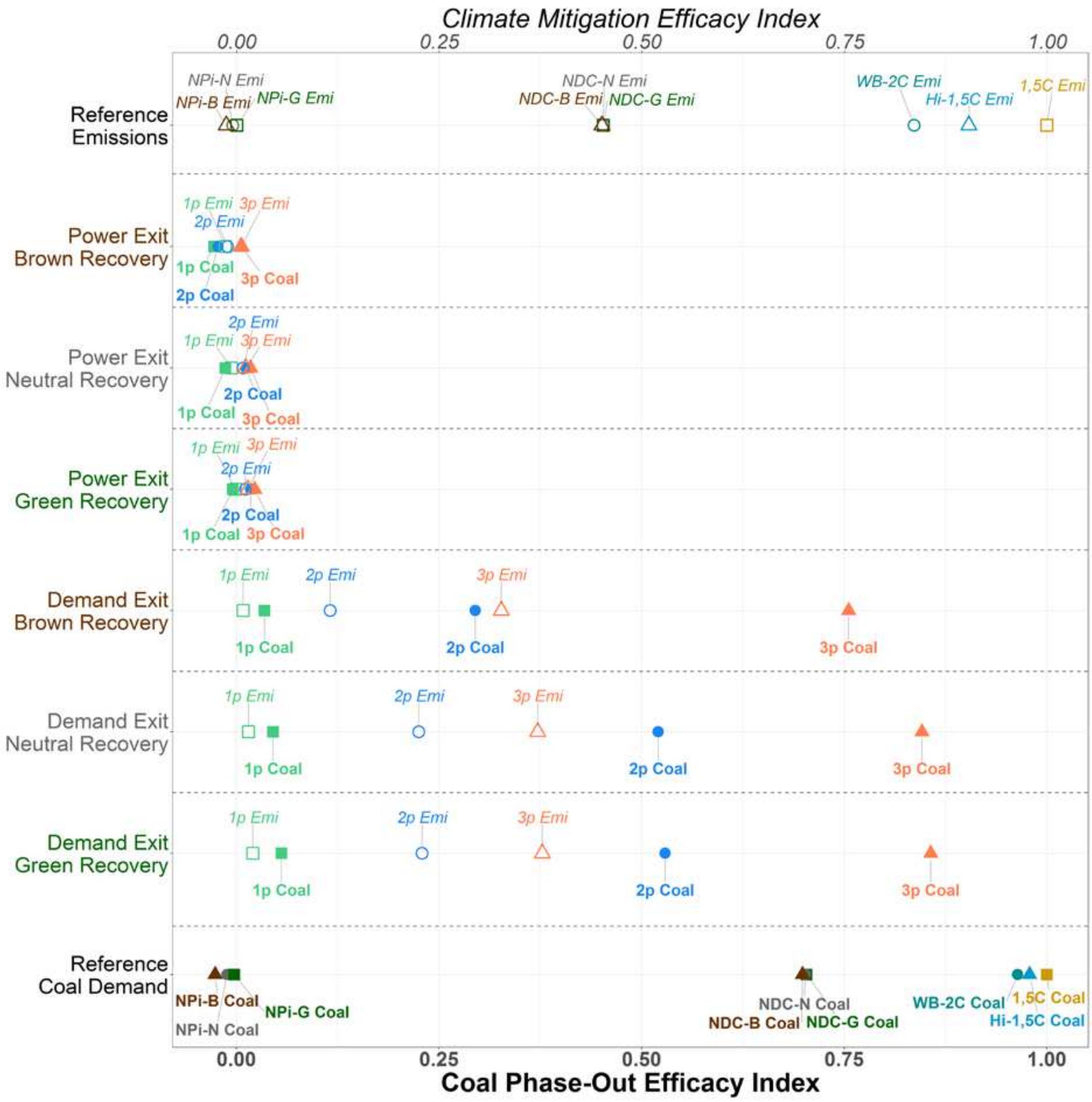


Figure 4. **Compilation of all 18 scenarios, assessed for their efficacy relative to 1.5°C pathways** in terms of coal phase-out (indicated by the lower x-axis, solid points, and bold font) and CO_2 emissions reductions (upper x-axis, hollow points, italic font). Each scenario is scored on an index between 0 and 1, where 0 represents the NPi reference scenario (without Covid considerations) and 1 corresponds to 1.5°C. For each row, the 2p points can be considered the DPE median estimate, and the range between 1p and 3p indicates the uncertainty range.

Sensitivity Analyses

Coalition Growth

Efficacy Indices

The 95%-probable *1p* and 5%-probable *3p* coalition scenarios embody the considerable uncertainty inherent to estimating future political decisions. For the *demand-neutral* case, the *1p-3p* range of coal phase-out efficacy is .05–.85, and .02–.37 for emissions mitigation (Figure 4). *Power-neutral* scenarios have an uncertainty range of -.01–.02 for coal and -.01–.01 for emissions. Therefore, while the *demand-exit* is highly sensitive to coalition size, the *power-exit* is robustly inconsequential.

Carbon Leakage

Carbon leakage primarily emerges through coal markets in *power-exit* scenarios and through inter-fuel substitutions in *demand-exit* simulations. We find p*ower-1p* scenarios to be extraordinary cases which exhibit >100% leakage rates (237% in *power-1p-N*). Figure SF4a suggests that the *power-exit* retards electro-mobility learning, leading to lock-ins of inefficient CtL and oil. This (small-magnitude) feedback is robust to coalition size but becomes overshadowed by other responses, resulting in a 56% carbon leakage rate in *power-3p-N*.

Comparatively, the *demand-exit* tempers leakage: 72% in *demand-1p-N* and 17% in *demand-3p-N.* Irrespective of policy choice, we find that global carbon leakage rates decrease as the coalition grows, and intra-coalition leakage dwarfs extra-coalition leakage with sufficiently large policy uptake (all 2p and 3p). These findings are all robust across Covid recovery scenarios.

Low-Carbon Substitution

The impact of the *power-exit* on VRE ranges from -3EJ in *1p-N* to 348EJ in *3p-N*. The decline in *1p* VRE penetration is another consequence of the negative electro-mobility feedback. Bioenergy and other low-carbon energy (Bio&LCE) deployment experiences marginal upticks of 2-55EJ (*1p-3p*). Under a *demand-exit-neutral* regime, these second-order effects range from 112-2070EJ for VRE and 63-1320EJ for Bio&LCE.

Sectoral Ambition

We demonstrate that the *demand-exit* policy is 38x as effective at phasing out coal and 27x as potent at CO_2 abatement as the *power-exit* in our most optimistic scenarios – *green* Covid recovery with virtually global participation (*3p*). Figure 5 compares the PE trajectories of *demand-3p-G* and *power-3p-G* against *NPi-green, NDC-green*, and 1.5°C to visualise their aggregate effects and illuminate the remaining transformations necessary. The most glaring divergence between *NPi-G* and 1.5°C pathways is the 17-fold difference in non-electric coal consumption, which the *power-exit* further exacerbates.

Figure 5 suggests that natural gas restrictions and bioenergy support are the most urgent priorities after coal, given the sharp, immediate bifurcation between their 1.5°C trajectories and all other pathways. Moreover, *demand-3p-G* incentivises an additional 780EJ gas and 2100EJ oil (Figure SF2), which can be avoided with immediate and sustained investment in renewable industry and transport fuels.

Covid-19 Recovery and Path Dependency

Our three data-driven scenarios of post-Covid infrastructure (Appendix I) span a range of 1670GW-2320GW of coal power capacity in 2025[iii]. DPE demonstrates the path-dependence of PPCA expansion to these near-term uncertainties. Most notably, China accedes in *neutral-2p* (1070GW national 2025 capacity) and *green-2p* (980GW) scenarios but abstains in *brown*-2p (1310GW). Figure 3 illustrates the dynamic impacts of China's decision while Figure 4 shows the disparities in long-term prospects.

We report coal efficacy indices *(1p-3p* range*)* of .29 (.03–.76) for *demand-brown* and .53 (.06–.86) for *demand-green*, and mitigation efficacy scores of .12 (.01–.33) and .23 (.02–.38), respectively. *Power-exit* scenarios exhibit minimal overall sensitivity all analysis dimensions, meanwhile, with coal efficacy scores ranging between -.03 (*brown-1p*) and .02 (*green-3p*), and mitigation efficacies between -.01 and .01. Nevertheless, these results suggests a robust negative correlation between near-term coal power capacity and long-term PPCA efficacy. Greener public investment and regulatory decisions at this critical juncture not only reduce immediate emissions but also have legacy effects that facilitate future feasibility of coal phase-out policies. Myopic brown recovery packages, meanwhile, would impose substantial strain upon future generations to mobilise the necessary transition.

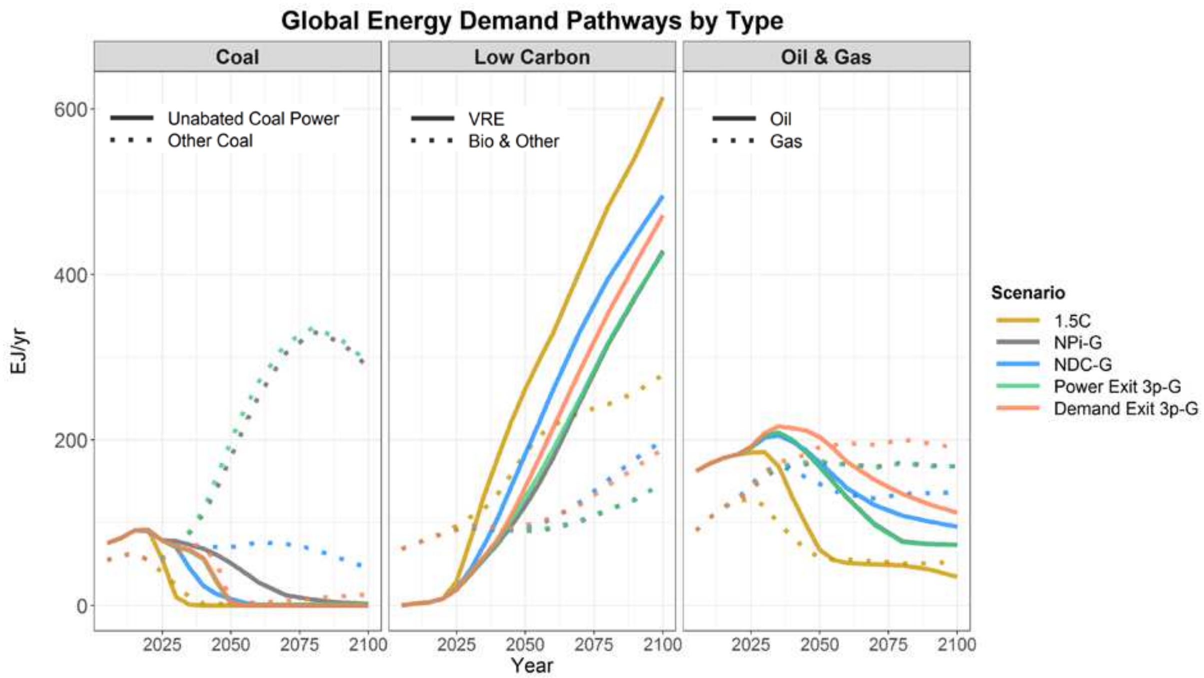


Figure 5. **Maximum potential impact of power- and demand-exit policies on global PE demand trajectories** from 2005-2100, in comparison with key benchmark scenarios. The green Covid recovery (-G) results in the most CO_2 and coal abatement in NPi, NDC, and demand-exit scenarios. Although the power-exit is found, against expectations, to be most effective after a brown recovery, its membership rate is highest in the *3p-G* coalition scenario, which captures 99.9% of 2020 coal consumption in both policy scenarios. The *power-3p-G* and *demand-3p-G* scenarios are thus akin to conventional policy evaluation analyses which assess global policy potential.

Discussion

Interdisciplinary Linkage

The integration of socio-political and techno-economic analyses is an emerging endeavor in climate mitigation research[4,7]. Thus far, attempts to *merge* empirical social science research on energy transitions with energy-economy models[43,44] have not robustly improved the realism of mitigation pathways[5]. Our work confronts this challenge by focusing on political dynamics on a global, relative scale, and by narrowing our independent variable pool to IAM-native techno-economic factors, effectively building on a tradition of validating and improving model assumptions through empirical data[16,45–47]. We concede that behavioral, institutional, and cultural factors may hold greater predictive potential, but these fuzzier variables have not yet been prospectively quantified.

The Powerless Power-exit

The PPCA's *power-exit* declaration cites Rocha et al., an ex-post ensemble analysis of coal-fired electricity in Paris-consistent CEA pathways of select IAMs and energy system models (ESMs)[48]. However, coal power phases out in these scenarios amidst rapid coal and emissions declines economy-wide. The power-sector bias, evident throughout the coal phase-out discourse[24,29,32], may be explained in part by data accessibility barriers. The only open-access, comprehensive, coal-asset-level datasets[iv] were power-plant-specific[49] until comparable data on mines[v] and steel plants[vi] were published in 2021. We therefore surmise that the PPCA's sector-exclusivity was motivated by politics – e.g. to encourage maximum participation – and by under-contextualised scientific messaging.

The inadequacy and myopia of the verbatim PPCA is evidenced by the future coal demand profile in REMIND's NPi scenarios; while electricity accounted for ~60% of 2015 coal use[50], it represents just 16% cumulatively from 2020-2100 (Figure 5). Moreover, the *power-exit* generally decreases free-rider coal electricity while CtL and industrial coal use universally increase. Other model baselines robustly corroborate coal demand growth in industry[51] and transport[52]. A recent review suggested that model scenarios are often overly-dependent on coal, but some power sector bias was evident and it found that coal phases-out most readily in REMIND's CEA simulations[24]. The present study does not dispute the urgency of power sector decarbonisation, as electrification is vital to myriad mitigation strategies[53], but it provides grounds for the *coal*ition-of-the-willing to explicitly cover non-electric sectors.

The Demanding Demand-exit

We acknowledge that COALogit cannot accurately estimate *demand-exit* feasibility since *power-exit* PPCA pledges form our empirical basis. Our analysis assumes perfect interchangeability to directly compare the two policy options, but a real-world trade-off is anticipated between policy ambition and coalition growth. Stated political ambition, as insinuated by the first-round NDCs, supports this theory. Relative to 1.5°C-consistent levels, the NDC scenario leaves 10x as much residual non-electric coal use as unabated coal power, which is phased-out faster than any PPCA scenario modeled here (Figure 5).

Nevertheless, the least effective *demand-exit(-1p-B)* outperforms the most optimistic *power-exit(-3p-G)*, and our median-estimate *demand-exit-2p* coalitions effect 30x more coal phase-out on average than the virtually-global *power-exit-3p* scenarios. These outcomes strongly indicate that the PPCA should prioritise sectoral coverage over coalition expansion. Still, expanding the policy to new countries is ultimately essential, and a *demand-exit* along currently proposed timelines is ultimately insufficient, as even the most optimistic *demand-3p-green* cannot replicate the coal use pathways of our least-optimistic Paris-compliant benchmark, well-below 2°C (Figure 4)[vii].

The Policy Feedback Loop

The evolving coalitions derived by COALogit are largely insensitive to policy choice, i.e. for a given Covid recovery, *power-exit* and *demand-exit* coalitions are nearly indistinguishable. This is an artefact of COALogit's parsimonious dependence on coal-power-shares and the fact that the *power-exit* is simply a subdivision of the *demand-exit*. Generally, we observe an inverse relationship between OECD coalition size and non-OECD accession probabilities due to extra-coalition leakage of coal electricity, best illustrated by Figure SF1b-d.

Although *demand-2p* scenarios trigger net-negative extra-coalition coal leakage, free-rider coal power consumption actually increases, discouraging their accession. *Power-2p* scenarios are also unique, in that extra-coalition coal-fired electricity decreases. However, the root cause is a hindrance of end-use electrification globally, notably exacerbating liquid-fueled transport, the most notoriously challenging end-use to decarbonise across IAM scenarios[54]. Hence, PPCA members must counteract the negative feedbacks provoked by their demand-side efforts and mobilise self-perpetuating policy uptake by ramping up electrification, VRE, and knowledge transfer to maximise technological spillovers.

A Supplementary Supply-exit

Furthermore, recent literature highlights the importance of complementing demand-side policies with supply-side action[55–57], e.g. through mining or export restrictions. This counteracts price depression and leakage, increasing the potential for self-propagation. Given bilateral trade partnerships and spatial variance in coal quality, however, policy efficacy depends upon the specific adopters.

Crucially, the largest anticipated coal consumers in 2045 – China, India, and ASEAN members (Figure 2c) – can each sustain a self-sufficient coal supply. However, finance for their coal infrastructure largely flows from the OECD[58], where divestment campaigns are historically commonplace[57]. Granted, Chinese banks are the world's largest overall coal financiers[58] and may insulate the domestic industry from foreign politics, but OECD legislatures can conceivably induce coal declines through cross-border financial mechanisms, e.g. debt-for-nature swaps[59]. China's historical 22-year mean plant lifetime (Table 2) and its 2060 carbon neutrality pledge[41] breed cautious optimism.

Averting the Next Crisis

These coal-rich nations also exhibit the highest path-dependence of accession probability to near-term investment decisions. Most glaringly, China falls below the *2p* threshold[viii] and Indonesia below *3p* probability in *brown* recovery scenarios. Additionally, we observe that numerous highly-probable coalition members within the OECD continue to commission coal power plants in *brown* and *neutral* Covid recoveries[ix]. PPCA accession then forces a sudden mass exodus of unamortised capital – a 100% rate of early retirement[x] from 2025-2030. Thus, to protect the health of their economy[29], power grid[60], citizenry[23], and global-leader status, OECD governments must cancel their entire coal pipelines[61].

Future Research

DPE presents a way forward for inter-disciplinary climate policy research seeking to understand the intersection of techno-economic, socio-political, and climate target feasibility. To enable similarly evidence-based simulations of policy uptake in future studies, empirical research must identify robust correlations between revealed ambition, viz. domestic legislation, and energy-economic variables computed endogenously by forward-looking models. As the remaining window to respect the 1.5°C target dwindles[2], we invite the data science community to contribute their expertise in large-scale regression exercises[16,62]. As more DFS models are derived, they can be merged with IAMs as nested or sequential feedback loops to portray a cohesive, inter-reactive landscape of baseline climate ambition.

Furthermore, parallel research needs to examine supplementary policy options for frontrunners ('early entry points'[63]) that best augment global mitigation efficacy. We offer our median-estimate scenarios as 'living' baselines upon which subsequent DPE and PEA studies can be performed. By capturing the global policy interactions that other real-world developments and policy candidates can have with the PPCA and each other, researchers can identify high-synergy, low-risk policy suites for willing-and-able nations to facilitate energy transitions in less capable economies. Supply-side fossil fuel regulations and carbon pricing are prime candidates given their uptake frequency[57] and anticipated efficacy[56]. Finally, future work should strive to fully endogenise policy formation and feedback, with maximal temporal resolution, into IAM optimization routines.

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Methods

The foundational question of dynamic policy evaluation (DPE) concerns the coevolution of domestic energy politics with global energy systems. We emulate this interdependency in the context of the coal phase-out by coupling REMIND, a multi-regional, forward-looking, deterministic global energy systems model, with COALogit, a country-level, empirical, probabilistic coalition-forming logistic regression model. The soft-linkage enables simulation of bottom-up policy adoption with staged accession and inter- and intra-regionally-fragmented ambition in long-term energy-economy scenarios. A detailed model description is available in Baumstark et al. (2021)[1].

Based on national coalition accession, COALogit informs coal phase-out adoption and stringency in each REMIND region (Figure M1) in a given period, effecting global energy sector transformations in that REMIND scenario. Policy feedback effects on future policy uptake are quasi-endogenised by iterating the REMIND-COALogit sequence (Figure M4) in successive periods. In the context of coal phase-out policies, REMIND captures feedbacks through its representation of international, inter-sectoral, and inter-fuel leakage effects, as well as changes in technological learning (Figure 1).

REMIND-COALogit integration (Figure M2) is made possible by the latter's reliance on energy-economic variables – GDP and the share of coal in electricity generation (coal-power-share) – computed endogenously by the former. Generally, a limiting factor of modeling co-evolutionary transformation pathways is the dearth of historical climate policy observations upon which empirical models can be constructed. The PPCA provides a real-world policy basis which enables logit model calibration and precise policy timing in REMIND. The REMIND-COALogit model and DPE are described in detail below.

REMIND Model

REMIND is a global, multi-regional energy-economy general equilibrium model linking a Ramsey-type macroeconomic growth model with a bottom-up technologically-detailed energy system model[1] which accounts for greenhouse gas (GHG) emissions from all human activities, including land use and forestry (Figure M2). The model is implemented in GAMS and solved by CONOPT. The model configuration in this study considers twelve world regions (Figure M1) and solves for interdependent regional and global equilibria. Regions individually optimize intertemporal welfare by allocating economic output to capital investments, consumption, energy system costs, and inter-regional trade of energy resources and composite goods. However, these solutions are contingent upon global market prices, which are adjusted between each iteration of the Nash solution algorithm until an international economic equilibrium is found, i.e. all trade markets are balanced in all periods of the model horizon 2005-2150 (5-year periods until 2060, 10-year until 2110, 20-year until 2150; henceforth, any mention of years refer to these time-steps unless otherwise specified).

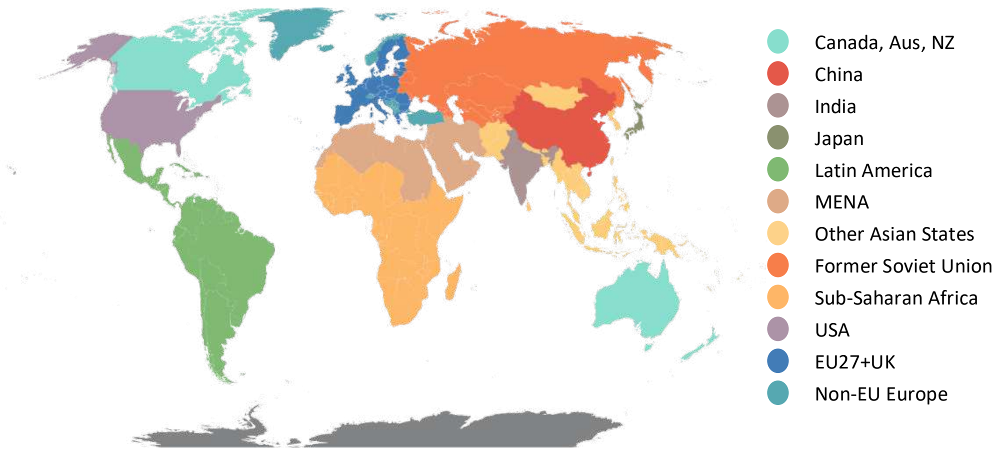


Figure M1. REMIND world regions in the default 12-region configuration used in this study.

Coal Demand Representation

Final energy is demanded by REMIND regions as a factor of production in accordance with macroeconomic assumptions (e.g. GDP and population) given by the Shared Socioeconomic Pathway (SSP) convention[2]. To satisfy final energy needs, regions demand coal based on cost competition with other energy carriers and the existing energy capital stock[1]. Coal primary energy (PE) can be converted into electricity, solid energy, liquids, gases, heat, and hydrogen through various transformation technologies with disparate conversion efficiencies. In the electricity sector, coal power plants are categorized into pulverized coal (PC), coal-fired combined heat and power (CCHP), and integrated gasification combined-cycle (IGCC) technologies. Additionally, carbon capture and storage (CCS) is possible for PC (PCC) and IGCC (IGCCC) plants, as well as oxy-fuel combustion (PCO). Other secondary energy conversion routes are only represented by a single technology, e.g. coal-to-hydrogen or coal-to-liquids (CtL) via Fischer-Tropsch, which are the only other processes with CCS available.

Coal Supply Representation

Regions are endowed with coal deposits graded by extraction costs, which increase within each grade as reserves are depleted according to a cumulative extraction cost curve[3]. In the original formulation, these parametric curves are grade-specific and time-dependent – viz. costs decline with fossil fuel sector investment and the associated technological change – but for typical REMIND simulations, resource extraction dynamics are simplified using an emulator. The representation used in the present study is parametrized in accordance with the complex model's behavior given SSP2 assumptions[4]. Coal grades are not differentiated by physical properties, i.e. metallurgical coal (met-coal) is indistinct from high-cost thermal coal at the PE level. Emissions accounting has greater sectoral granularity, e.g. the emissions from steel or cement manufacturing are derived based on the assumption that each subsector in each region maintains its historical mix of final energy carriers.

Fossil extraction is also subject to short-term decline and increase rates between time-steps, representative of geophysical, infrastructural, and institutional inertia[4]. Extracted resources not consumed within the producing region are exported to the world market, a global pool of quantities with price vectors that reflect the aggregate supply and demand and are adjusted between iterations until a Walrasian equilibrium is achieved[1]. Thus, a phase-out of demand in one region increases the supply available for other regions in the near-term, as the equilibrium solution requires the surplus in each resource market to fall below a negligible threshold in each period, but also shifts the long-run equilibrium price downward.

Policy Representation and Analysis

Policy Evaluation

In policy evaluation mode, climate and energy policies can be prescribed to REMIND with uniform or differentiated stringency across regions, periods, sectors, etc., to analyse the energy, climate and economic impacts. Any comprehensive or piecemeal combination of carbon pricing instruments, technology- or fuel-specific taxes or subsidies, or activity-specific constraints or incentives can be implemented through a variety of levers. DPE and SPE are subcategories of PEA, as policies and their stringencies are prescribed – albeit objectively and grounded in real-world developments – rather than endogenously derived by the model. DPE then relies on the assumption that strong empirical models of policy feasibility remain valid over time to endogenise the fragmentation and staggering of policy prescription as a function of prospective variables computed by REMIND.

In the present analysis, the reductions of total CO_2 emissions and coal use in various SPE and DPE scenarios are compared with the optimal and necessary levels derived by CEA benchmark scenarios. Coal phase-out policies and their timing, as defined by the PPCA, are implemented by constraining secondary energy (SE) production in *power-exit* scenarios and emissions variables in *demand-exit* scenarios. Each region is permitted up to a certain share of its total cumulative SE electricity production or CO_2 emissions that can come from coal during each PPCA phase-out stage (i.e. 2030-2050 when only OECD nations are constrained, and 2050-2100 when all coalition members must implement the policy). The share is defined by COALogit and reflects the specific countries which adopt the policy within each REMIND region. We constrain cumulative rather than annual variables to afford the model flexibility as to the speed of phase-outs and the timing of leakage.

Cost-effectiveness analysis

CEA scenarios begin with a known environmental goal, viz. a climate stabilization target, and translate it to a model constraint. Most typically in REMIND, the Paris temperature targets are converted into cumulative carbon budgets which must be satisfied by the welfare-optimal solution[5]. This can be achieved through any mitigation strategy, and the model has full flexibility as to when, where and how to abate, barring any additional exogenous constraints. Cost effectiveness implies that marginal abatement costs are equalised across time, countries, and sectors[6]. The CEA scenarios in this study are implemented by assigning each region a starting carbon price level and date, then allowing the prices to endogenously converge over time up to the level of marginal abatement cost to adhere to the remaining budget. By default, inter-regional emissions permit trading is enabled.

Reference and Benchmark scenarios

The baseline reference for our analyses imposes only currently implemented national policies (NPi) on the energy system, such as the European Union's emissions trading scheme (EU ETS) and various technology-specific efficiency mandates, energy consumption taxes, and minimum share requirements, e.g. the EU Energy and Climate package for 2030[xi]. To emulate weak yet dynamic climate policy ambition[7], carbon prices begin at zero in non-EU regions and increase gradually to reach a global convergence point of \$12.50 per ton of CO_2 in 2100. The PPCA-DPE scenarios described below implement the coal exit policies on top of this weak policy backdrop, hence free-riders follow the same modest carbon price trajectory and technological policies as the reference case. For purposes of comparison, we also compute a scenario that implements the NDCs via the conventional PEA mode, as well as three scenarios with carbon budgets imposed in the conventional CEA mode.

These budgets are standardized to values reported in the IPCC's Special Report on Global Warming of 1.5°C[8]. The 1.5°C scenario imposes a cumulative 2011-2100 carbon budget of 900 $GtCO_2$, corresponding to a 67% probability of staying below 1.5°C in 2100 and a 50% likelihood of remaining below 1.5°C in the time-step of peak emissions (2045). The Hi-1.5C scenario limits emissions to 1100 $GtCO_2$ and leads to a 50% likelihood of global mean temperature below 1.5°C in 2100 but allows a small overshoot such that the peak period temperature may slightly exceed 1.6°C. The well-below 2°C (WB-2C) scenario constrains REMIND to 1350 $GtCO_2$ and implies a >67% probability of remaining below 2°C throughout the century.

Interactions between policies and energy system

The REMIND model endogenously represents important feedback mechanisms which can be induced by coal phase-out policies. The feedback mechanisms relevant to the present study are those where the coal phase-out policies lead to changes in coal use in unregulated countries or sectors and therefore have an impact on emissions or change a country's decision with regards to coalition accession. For one, decreased coal demand elicits downward price pressure in coal markets and greater cost-competitiveness of coal-fueled technologies, provoking carbon leakage effects through international trade of coal, a well-studied consequence of freeriding[9]. The present study deems this extra-coalition coal leakage, and furthermore examines intra-coalition coal leakage, referring to increased coal-based emissions from unregulated sectors of coalition members in response to piecemeal policy adoption. A heavy emphasis is placed on shifts of coal into non-electric applications, which we deem inter-sectoral coal leakage. Both intra- and extra-coalition coal leakage undermine the effectiveness of coal phase-out policies, and the latter also reduces the likelihood with which free-riders ultimately accede.

Technological learning – particularly of solar photovoltaics (costs decline 20.7% per doubling of cumulative capacity), wind turbines (10.8%), electric vehicles (10%), and grid storage (10%) – mediates two additional feedback mechanisms. First, there is a potential positive technological spill-over effect. Coal phase-outs in PPCA countries can trigger increased domestic renewable energy deployment to substitute the short-fall of coal-fired electricity, accelerating learning-by-doing effects of renewable alternatives. This lowers costs globally, promoting diffusion into non-member countries and potentially displacing coal in their power sectors.

Second, there is a potential negative spillover effect. Coal phase-outs may cause electricity prices to increase in some regions due to restrained electricity supply. This can discourage end-use electrification and, consequently, retard technological learning of burgeoning technologies such as electric vehicles. This negative feedback may, in turn, decelerate learning-by-doing in renewable energy generation and storage technologies, improving the prospects for fossil-fueled technologies. Depending on the relative strength of positive and negative spillover effects, global coal use can increase or decrease, thus affecting the effectiveness of phase-out policies. Furthermore, DPE completes the policy feedback loop by capturing the effect of these endogenous system responses on the propensity of free-riders to adopt the policy.

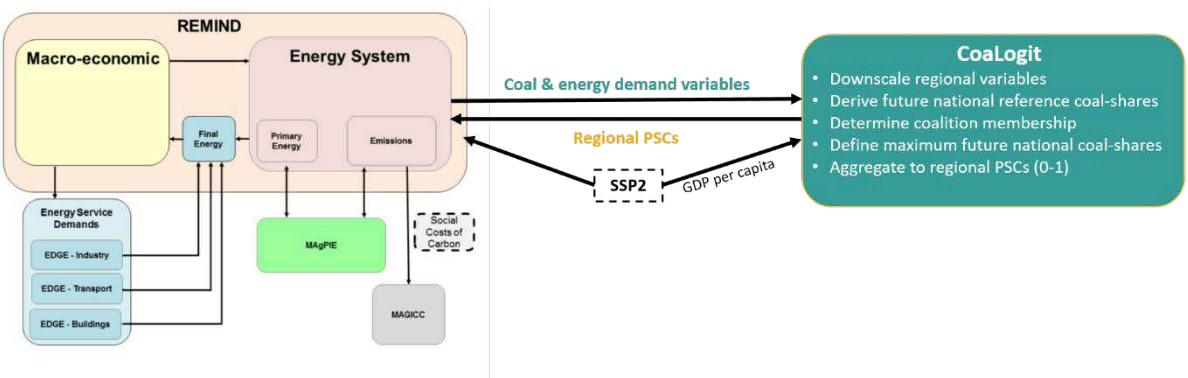


Figure M2. Depiction of the REMIND-COALogit coupled-model framework with a brief description of COALogit functions, inputs, and outputs. Table M4 lists all the specific variables passed from REMIND to COALogit, which vary by scenario. PSC derivation is also scenario-dependent, as shown in equations 1-2 and 5-11. The REMIND schematic (from Baumstark et al.[1]) 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.

COALogit Model

Determinants of PPCA Feasibility

Jewell et al. (2019) performed a multi-variate statistical analysis to investigate the significance of eleven independent variables from prior coal phase-out literature in explaining national accession to the PPCA[10]. The study reported a best-fit parsimonious logistic regression explaining current PPCA membership with (low) domestic coal-power-shares, a proxy for policy cost, and (high) Functioning of Government Index (FoG) scores, indicative of a state's relative institutional capacity[10]. The overall best-fit model described three additional factors[xii], including a positive correlation to GDP per capita (GDPpc), which had high covariance with FoG[xiii]. The authors thus deemed GDPpc, which is, like coal-power-shares, prospectively quantifiable via accepted methods[2], highly suitable for our dynamisation of their findings. This dynamic feasibility space (DFS) of the PPCA represents the core of COALogit.

Coalition Accession Probabilities

The logit model is trained by providing the *glm* function of the *stats* R package[11] with real-world PPCA adoption among countries with at least a 1% coal-power-share in 2015 as the observed outcome variable and their GDPpc and coal-power-shares in 2015 as the independent variables. Eq. (1) defines the empirical relationship modeled between a nation's likelihood of PPCA membership and the predictor variables.

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

where:
$p(Y=1)$ = *probability of PPCA membership,*
β_i = *fitted model parameters (Table M1),*
x = *coal-power-share,*
y = *GDP per capita.*

Parameter	Estimate	Std. error	Z-score	p-value	95% CI
β_0	-0.896	0.390	-2.298	0.021577	[-1.660; -0.132]
β_1	-5.747	1.726	-3.329	0.000872	[-9.131; -2.363]
β_2	0.095	0.022	4.257	$2.08e^{-5}$	[0.051; 0.138]

Table M1. Estimates and uncertainty ranges of the logit model coefficients corresponding to Equation (1). β_1 and β_2 describe the linear correlation of the log-odds of PPCA accession to coal-power-share and GDPpc, respectively, while β_0 is the intercept, i.e. H_0. The 103 observations (2015 data) used for model calibration are shown in Table SF1, along with the predicted accession probabilities of those countries.

Table M1 reports the estimates of the parameters – which are of the expected sign and significant in comparison to the null model H_0 – that describe the proportionality between each independent variable and the log-odds (logit) of any nation becoming a member. The calibrated model, represented by Eq. (2), is then used to infer the probability of each of the 249 ISO 3166-1 countries joining the coalition in a given period.

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

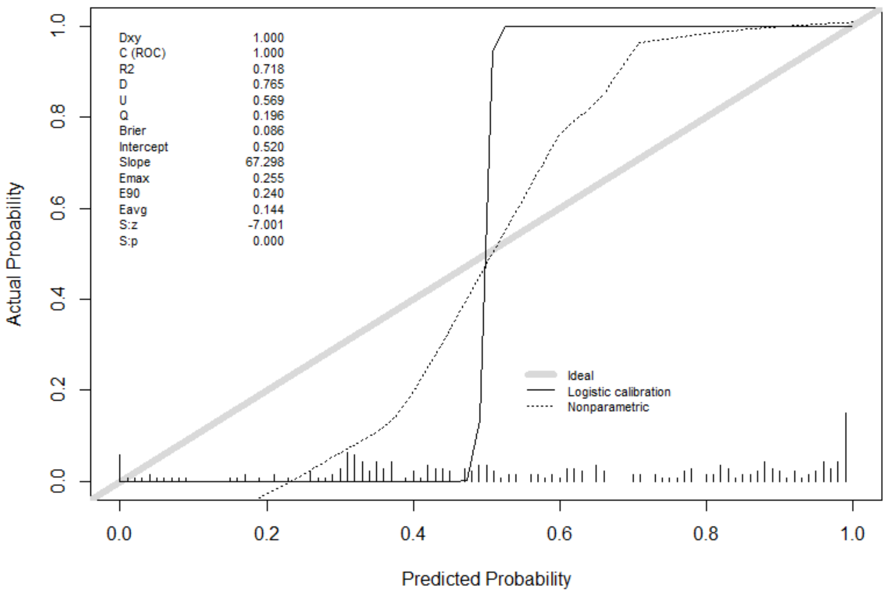
where:
$\hat{n}$ = *nation of analysis,*
$p_{\hat{n}}$ = *national probability of coalition accession,*
t = *time (refers to REMIND time-steps in our analyses),*
$x_{C,\hat{n}}$ = *national coal-power-share,*
$y_{\hat{n}}$ = *national GDP per capita.*

In order to preserve consistency with REMIND v2.1[1], the present study does not use identical historical databases[12–14] as those used in Jewell et al. (2019). The data vintage is also one year prior to the original model's, and eleven more countries have acceded to the PPCA since the previous study (Table SF1). Nonetheless, we find a statistically significant, well-fitting[xiv] and accurately predictive relationship between dependent and independent variables, suggesting that the model is reasonably robust. Table

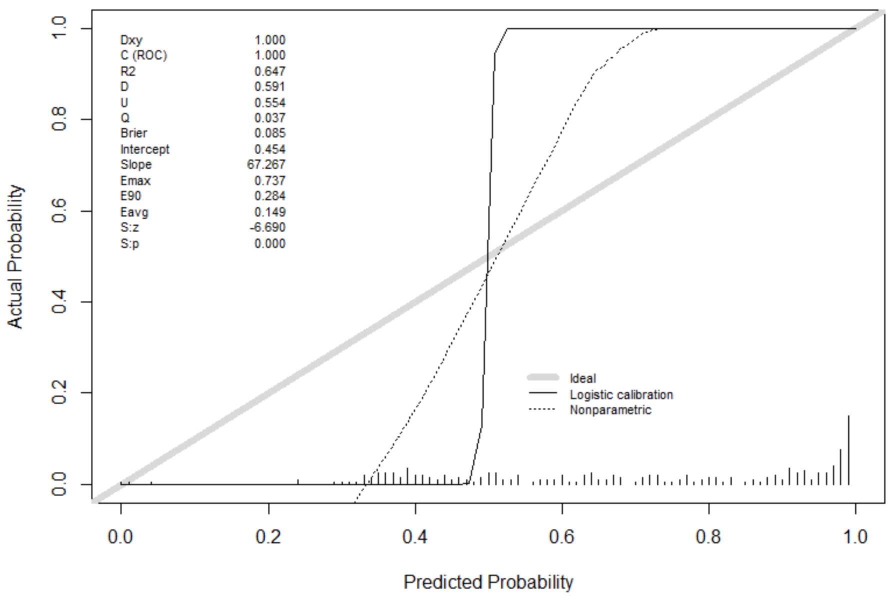
M2 displays several measures of model performance, and Figure M3 shows the logistic calibration curves and various fit metrics describing the predictive performance in future periods.

Model Performance Metric	Value
p-value	$4.45e^{-9}$
Pseudo R^2 (adj. McFadden)	0.271
Residual standard error	0.980
Log Loss	0.466
Predictive accuracy (bootstrap AUC)	87.71% (SE=3.72%)

Table M2. Statistical metrics describing the logit model's significance, goodness-of-fit, and prediction quality.



a)



b)

Figure M3. Logistic calibration curve for the validation of predicted national accession probabilities in 2025 (a) and 2045 (b). Generated using the *val.prob()* function of the *rms* R-package[16]. Dxy = Somers' D, R2 = Nagelkerke-Cox-Snell-Maddala-Magee pseudo-R^2 index, D = discrimination index, U = unreliability index, Q = quality index, Emax/90/avg = maximum/0.9 quantile/average absolute difference in predicted and loess-calibrated probabilities, S:z = Spiegelhalter's Z-score for calibration accuracy, S:p = two-tailed p-value for S:z. Both (a) and (b) are specific to the *neutral* Covid recovery.

Coalition Scenarios

In this study, we translate this output into operational assumptions for REMIND policy scenarios by defining probability thresholds of coalition accession. The three thresholds, as defined in Table M3, are represented as linear relationships in Figure 2 between GDPpc and coal-power-share, along which the probability of coalition accession is constant. In a given scenario, the postulated threshold can be interpreted as a socio-political 'tipping point'[17–19]. That is, any country which reaches a sufficiently high GDPpc and sufficiently low coal-power-share – and thus an accession probability above the threshold value – before the 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 (or 'downstream') REMIND scenario.

Coalition Threshold	Probability	Slope	Intercept
1p	95%	60.6	40.5
2p	50%	60.6	9.4
3p	5%	60.6	-21.6

Table M3. Definition of the linear relationships between GDPpc and coal-power-share at the coalition threshold probabilities. These lines, as seen in Figure 2, have the general form $y = mx + b$, where y is GDPpc and x is coal-power-share.

Coalition membership in this study only implies that a country imposes a national coal phase-out policy along the lines prescribed by the PPCA. Membership is not subject to a monitoring and sanctioning mechanism, hence there are no issues with compliance and enforcement. Furthermore, the coalition is not a club because membership does not provide exclusive access to a club good from which non-members are excluded.

REMIND-COALogit Model Coupling

PPCA Declaration

Here, we define the soft-link created between REMIND and COALogit to model the PPCA coal phase-out with the DPE approach. The PPCA declaration, though non-binding, defines clear targets for its members: OECD and EU (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, despite e.g. Germany's domestic plans for a delayed phase-out by 2033-2038.

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 five-year 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 scenarios by comparing non-OECD countries to the thresholds in the 2045 model period, 6/2042–6/2047. Table M4 details how the logit model receives its country-level independent variables in either case.

COALogit inputs and outputs

The implementation of REMIND-COALogit requires the downscaling of the relevant variables in Eq. (2), as derived by REMIND simulations, for all countries in future periods. Downscaling here means that, 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 in order to define constraints that are used in a subsequent, downstream REMIND run.

Consequently, COALogit performs three core functions: (i) reading in REMIND results and downscaling them to the national level, (ii) logit analysis to define coalition membership scenarios, and (iii) derivation of regional *policy stringency coefficients* (PSCs) that are used as constraints in REMIND (Figure M2). First, COALogit intakes regional variables for total energy demand as well as coal-fired and total electricity generation from the 'upstream' REMIND scenario, i.e. a preceding counterfactual scenario in which the coalition was either only partially formed or not yet modeled (Figure M4). COALogit then downscales and divides the variables to derive country-level coal-power-shares.

Second, the logit model determines coalition scenarios for the specified time-step using the derived national coal-power-shares and GDPpc from the SSP2 projections[14]. Third, the cumulative coal-power-shares from the PPCA-defined phase-out year until 2100 are calculated for all countries and set to zero in coalition members. PSCs are derived by aggregating the cumulative coal-power-shares to the regional level, and these are exported to a REMIND-readable file for use in the downstream scenario. Figure M4 illustrates the sequential iterations between REMIND and COALogit required to model each DPE-PPCA scenario.

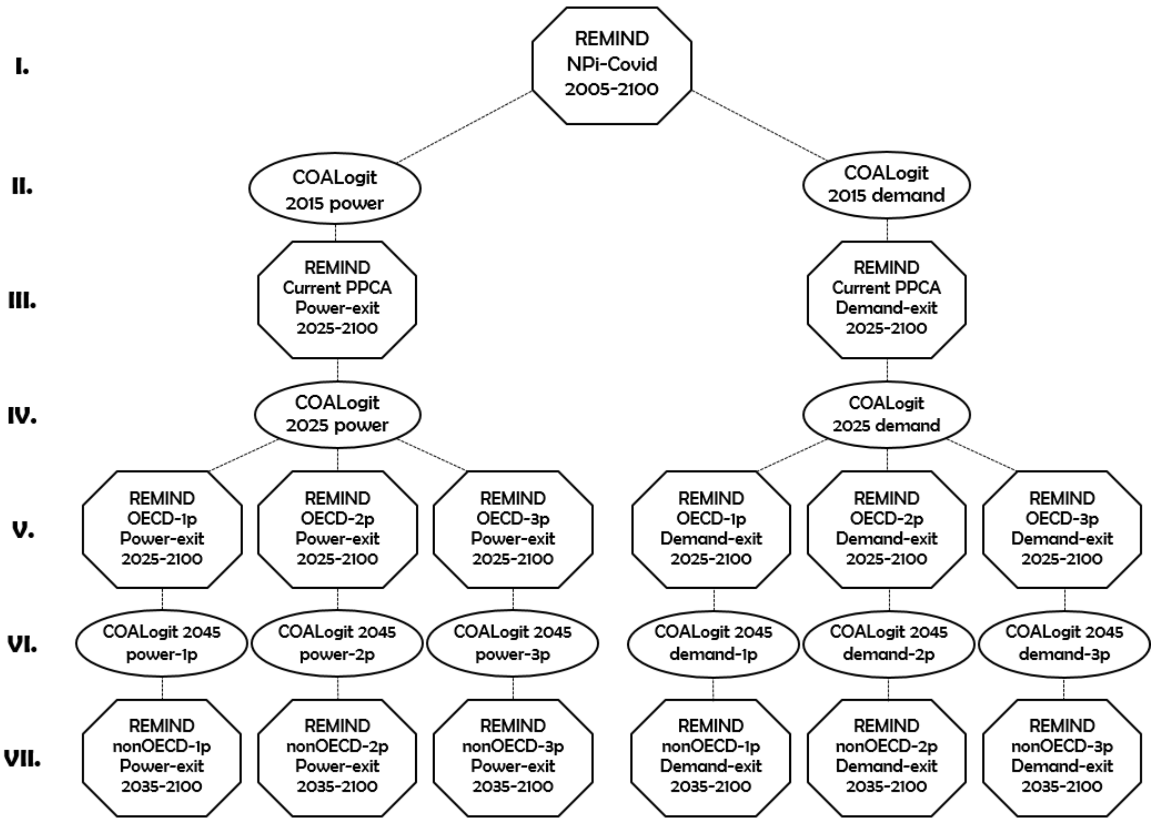


Figure M4. Flow chart of simulations with REMIND-COALogit. Each instance of the automated REMIND-COALogit DPE cascade flows along a dotted line from the NPi scenario (upstream) to one of six possible downstream PPCA scenarios. The Roman numerals here correspond to each step in the sequence, and numerals are used throughout the text refer back to this figure. The year displayed in each instance of COALogit indicates the time-step in which the logit analysis is performed to determine the policy-adopting coalition in the downstream REMIND scenario. The range of years shown in each REMIND run denotes the optimization horizon for that scenario (all prior periods are fixed to the upstream scenario). This simulation cascade is run for each Covid recovery scenario, giving a total of 18 DPE-PPCA scenarios.

Power-exit scenario cascade

A single PPCA scenario consists of four REMIND runs with a COALogit run between each, all executed in an automated sequence (Figure M4). (I.) The starting point of a PPCA scenario cascade is always an NPi reference case. (II.) COALogit regionally downscales the relevant NPi variables (Table M4) to derive the PSCs for current real-world OECD and non-OECD PPCA members, respectively. (III.) These PSCs are read into the downstream 'Current PPCA' REMIND scenario, which is the SPE scenario of the PPCA (see Table 1). Historical developments (2005-2020) in all scenarios of the cascade are fixed to NPi. The optimization horizon then begins in the 2025 time-step for 'Current-PPCA' and 'OECD-*xp*' – where '*xp*' is a placeholder for the *1p*, *2p*, and *3p* coalition scenarios – and in the 2035 period for 'nonOECD-*xp*'.

(IV.) 'COALogit 2025' derives 1p, 2p, and 3p OECD coalition scenarios (Figure 2b) based on accession probabilities calculated by Eq. (2) using historical data extrapolation and 2025 variables computed by the 'Current PPCA' simulation (now the upstream scenario). Logically, the near-term actions of the current PPCA may influence the energy landscape in freeriding OECD nations and increase or decrease their probabilities of acceding. Likewise, analysis of non-OECD countries is forestalled because the actions of the OECD coalitions may, in turn, affect their decisions in the following two decades. 'COALogit 2025' then returns OECD PSCs for each coalition scenario. (V.) These are fed downstream to the 'OECD-*xp*' REMIND scenarios, which enforce the 2030 phase-out policy.

(VI.) Each 'OECD-*xp*' scenario calls a separate instance of 'COALogit 2045', such that each coalition scenario represents a unique and consistent degree of optimism, e.g. the 50%-probable OECD-*2p* can only lead to nonOECD-*2p* and not the 5%-probable nonOECD-*3p*. Each of these non-OECD coalitions is formed by logit analysis of 2045 'OECD-*xp*' variables (Table M4) and assigned a PSC accordingly. (VII.) The 'nonOECD-*xp*' scenarios are fixed to 'OECD-*xp'* through 2030, preventing premature anticipation of the policy by the newly-defined non-OECD members but also affording them sufficient lead-time for adherence. Both the OECD and non-OECD phase-outs are enforced during this final scenario's 2035-2100 optimization horizon. The 'nonOECD-*xp*' REMIND runs are therefore complete DPE-PPCA scenarios containing all the information accrued throughout the cascade.

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 *coal*ition-of-the-willing, or are at least predisposed to accept further responsibilities. This *demand-exit* policy scenario extends the PPCA phase-out timeline to all coal-consuming technologies in all economic sectors except the iron and steel industry, which is permitted a 10-year grace period. This is intended to represent techno-institutional inertia, given that steelmaking is considered a particularly difficult industrial process to decarbonize[20], and that high-grade metallurgical coal is a significantly higher-value commodity than thermal coal. Hence, the *demand-exit* scenario with only current coalition membership (i.e. 'Current-PPCA') is a hypothetical PEA rather than a SPE.

(I.) The same starting point (NPi) and sequence progression applies to *demand-exit* policy scenarios, but the coal phase-out constraints and the variables exchanged between REMIND and COALogit (Table M4) 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'* scenario, and (VI.) 'COALogit 2045 *xp*' feeds three more PSCs to its corresponding (VII.) 'nonOECD-*xp'* scenario. The relevant calculations performed throughout both the *power*- and *demand-exit* cascades are detailed below.

REMIND-COALogit Interface

This section provides a full technical account of the procedures and assumptions, and the rationales for each, involved in our coupling routine. Each subsection presents the general logic and formulae as they pertain to particular steps of the flow chart in Figure M4, and Table M4 details the sourcing and flow of information exchanged along the cascade.

OECD national coal-power-shares derivation (IV.)

In the 2025 COALogit instance, country-level coal-fired power generation is calculated based on the coal power capacities extrapolated from GCPT data[13] (Appendix I). These are multiplied by the national 2025 utilization rates, which are in turn extrapolated from historical data[12] such that all countries[xv] linearly converge to a long-term assumption of 50% utilization by the 2035 period. Eq. (3) describes the linear extrapolation starting from 2015, the base period of our analyses.

$$(3) \quad \mu_{\hat{n}}(t) = \mu_{\hat{n}}(t_0) + \frac{0.5 - \mu_{\hat{n}}(t_0)}{2035 - t_o}\,(t - t_0)$$

$$for\ t_0 < t < 2035$$

where:

$\mu_{\hat{n}}$ *= national utilization rate,*

$t_0 = 2015.$

Some regions in REMIND are equal to countries (India, Japan, and the USA). For these countries, total electricity generation in all periods is taken directly from the upstream scenario. Other REMIND regions are aggregates of 3 to 54 nations, hence projected electricity generation must be downscaled. Disaggregation weights for total power generation are assigned to each nation according to the ratio of its base-period electricity generation[12] adjusted for population change[14] to the region's, generally assuming constant per-capita electricity demand in the future[xvi]. 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 employ a different downscaling routine, grounded in the assumption that the relative difference between a region's coal-power-share and those of its member nations remains constant. First, national coal-power-shares in 2030 are downscaled from the upstream REMIND scenario (*OECD-xp*, see Figure M4) by assuming its percentage above or below its region's coal-power-share remains unchanged from 2025. This is represented by Eq. (4).

$$(4)\ \ x_{\hat{n}}(t) = \begin{cases} x_{\hat{n}}(t-\Delta t) + \dfrac{x_{\hat{n}}(t-\Delta t) - x_R(t-\Delta t)}{1 - x_R(t-\Delta t)} \cdot \big(1 - x_R(t)\big)\,, & if\ x_R(t) \geq x_R(t-\Delta t) \\ x_{\hat{n}}(t-\Delta t) - \dfrac{x_R(t-\Delta t) - x_{\hat{n}}(t-\Delta t)}{x_R(t-\Delta t)} \cdot x_R(t)\,, & if\ x_R(t) < x_R(t-\Delta t) \end{cases}$$

$$for\ \ t \geq 2030$$

where:

$t - \Delta t$ *= previous period analysed (*Δt *varies between 5 and 15 years),*

R *= 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 just-derived coal electricity values are thus counterfactual and must be redistributed to other nations in the region. Eq. (5) describes this process.

$$(5)\ \ \widetilde{seel}_{C,\hat{n}}(t) = \begin{cases} 0, & if\ \ \hat{n} \in M_R \\ \widehat{seel}_{C,\hat{n}}(t) + \dfrac{\widehat{seel}_{G,\hat{n}}(t)}{\sum_{n \in F_R} \widehat{seel}_{G,n}(t)} \cdot \displaystyle\sum_{n \in M_R} \widehat{seel}_{C,n}(t)\,, & if\ \ \hat{n} \in F_R \end{cases}$$

$$for\ \ t \geq 2030$$

where:

$\widetilde{seel}_{C,\hat{n}}$ *= national coal electricity after accounting for OECD phase-out,*

$\widehat{seel}_{C,\hat{n}}$ *= counterfactual national coal electricity downscaled from upstream REMIND scenario,*

$\widehat{seel}_{G,\hat{n}}$ = *total national electricity generation downscaled from upstream REMIND scenario,*

n = each nation within region R,

M_R *= OECD coalition members in region R,*

F_R *= 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 Eq. (4) using 2030 as the previous period, and these values are used in Eq. (2) to derive non-OECD coalition accession probabilities.

Power-exit Policy Stringency Coefficients (IV. & VI.)

The need for PSCs is also to address the spatial mismatch between REMIND and COALogit. Not only are multinational REMIND regions often divided between coalition members and free-riders, but some contain both OECD and non-OECD countries, so policy adoption is likely staggered and non-uniform within a single region. These coefficients encode the country-level granularity of coalition membership as a maximum share of electricity generation which can come from unabated coal power plants in each region from (i) 2030-2100 for the OECD coal exit and (ii) 2050-2100 for the non-OECD PPCA target in the downstream REMIND scenario.

Policy enforcement within REMIND – and thus PSC derivation by COALogit – is conditional upon the coalition members' proportion of the region's future coal power demand and energy market in the counterfactual upstream REMIND scenario. Hence, Eq. (4) is repeated for all time-steps between 2030 and 2100 to derive counterfactual national coal power generation, and total PE must be downscaled to the national level for the same periods. An analogous principle is used in the PE disaggregation procedure as in the electricity downscaling routine, except weights are anchored by base-year PE consumption rather than electricity production.

The specific conditions upon which policy enforcement depends are that a region must contain at least two coalition members in the current accession stage, and these acceding nations must comprise over 20% of each of the region's cumulative PE and coal-fired electricity demand from the phase-out date until 2100 in the upstream scenario. These conditions are based on cumulative values to properly weight the expected future significance of emerging economies.

For the multinational regions that meet these criteria, PSCs are formulated by dividing the free-riders' counterfactual coal power generation by the region's total electricity generation in the upstream REMIND scenario. Eq. (6) shows how PSCs are derived for regions that meet the criteria but still contain free-riders. To enable leakage into the region's freeriding contingent during the downstream REMIND simulation, we include a multiplier which exogenously permits these free-riders to generate 50% more coal-fired electricity than they did in the upstream scenario.

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

$$for\ \ t_\alpha = \begin{cases} 2030, & if\ \alpha = OECD \\ 2050, & if\ \alpha = nonOECD \end{cases}$$

where:
$PSC_{R,\alpha}$ *= policy stringency coefficient for region R in the current accession stage α,*
L = intra-regional coal leakage allowance = 1.5.

Meanwhile, in regions consisting primarily of free-riding countries, and thus do not fulfill the minimum membership criteria, the potential for coal leakage is unbounded; they are assigned a PSC of one, i.e. 100% of their electricity generation in the subsequent REMIND scenario can be coal-fired in theory. On the other hand, if all countries in a region enter the coalition, then the region is assigned a PSC of zero, signaling a full-fledged phase-out in the downstream REMIND scenario. Only this phase-out case and the unconstrained case may apply to single-nation regions. Any region which consists solely of OECD-PPCA nations is assigned a PSC of 0 in both the OECD and non-OECD phases, while a region whose member states all accede during the non-OECD stage are assigned $PSC_{OECD} = 1$ and $PSC_{nonOECD} = 0$.

Power-exit policy implementation (V. & VII.)

We model the verbatim PPCA declaration (i.e. *power-exit* policy) in REMIND by restricting the share of total electricity production from coal-fired power plants without CCS. The sum of electricity generated by REMIND's unabated PC, IGCC, and CCHP plants 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.

$$(7) \sum_{t=t_\alpha}^{2100} \overset{\smile}{seel}_{R,U}(t) \leq PSC_{R,\alpha} \left(\sum_{t=t_\alpha}^{2100} \overset{\smile}{seel}_{R,G}(t) \right)$$

where:
$\overset{\smile}{seel}_{R,U}$ *= unabated coal-fired electricity generation in downstream scenario,*
$\overset{\smile}{seel}_{R,G}$ *= electricity generation in downstream (relative to PSC derivation) scenario.*

Note that REMIND scenarios which model the non-OECD phase-out include both the OECD and non-OECD constraints on regions with nonzero PSCs for both stages. Coal power generation from 2050-2100 is ultimately bounded by the more stringent of the two, but a region is theoretically free to deplete its entire 2030-2100 allowance within the 2030-2050 timespan.

Demand-exit PSCs (IV. & VI.)

The *demand-exit* policies are implemented for qualifying regions (based on analogous criteria to *power-exit* enforcement) through a three-step process. First, the share of total CO_2 that can be emitted by non-solid coal conversion technologies are assigned a PSC by COALogit from 2030 (2050) through 2100 in the OECD (non-OECD). Second, CO_2 emissions from coal solids used for non-metallurgical purposes, e.g. cement production, are restricted by a separate PSC over the same periods. Third, CO_2 emissions from coal-based metallurgy are assigned a third PSC, applicable from 2040 (2060) to 2100.

First, the relevant numerators are downscaled by the same technique as introduced by Eqs. (4)-(5); simply replace *seel* with the *emi* variables of interest (Tables M4+5). Next, total regional CO_2 emissions from the upstream REMIND scenario are downscaled according to the same disaggregation weights as used for PE downscaling. The PSCs are derived according to Eqs. (8)-(10) for qualifying regions.

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

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

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

$$if\ \alpha = \begin{cases} OECD, & then\ t_{\alpha_c}, t_{\alpha_s} = 2030, t_{\alpha_m} = 2040 \\ nonOECD, & then\ t_{\alpha_c}, t_{\alpha_s} = 2050, t_{\alpha_m} = 2060 \end{cases}$$

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

The criteria for PSC derivation apply to each of the *demand-exit* PSCs individually, and regions that do not satisfy the condition(s) are assigned PSC(s) of zero. This implies that there may be scenarios in which, for example, a region's met-coal emissions are constrained (i.e. $PSC_{R,\alpha_m} > 0$) but its non-solids coal emissions are not (i.e. $PSC_{R,\alpha_c} = 0$), because its members constitute over 20% of the region's steel production but under 20% of the overall coal consumption. Regions that exclusively contain coalition members are assigned ε for all three PSCs, meanwhile.

Demand-exit policy implementation (V. & VII.)

The PSCs enter REMIND in a series of corresponding equations that enforce the *demand-exit* policy. Eq. (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*. Eq. (12) shows the additional assumption used to isolate the emissions from metallurgical coal, namely that the share of coal in a region's solid energy consumption is uniform across all sectors.

$$(11) \sum_{t=t_{\alpha_j}}^{2100} \widetilde{emi}_{R,j}(t) \leq PSC_{R,\alpha_j} \left(\sum_{t=t_{\alpha_j}}^{2100} \widetilde{emi}_{R,E}(t) \right)$$

$$(12) \sum_{t=t_{\alpha_m}}^{2100} \left(\widetilde{emi}_{R,m}(t) \cdot \frac{\widetilde{FE}_{R,\bar{s}}(t)}{\widetilde{FE}_{R,S}(t)} \right) \leq PSC_{R,\alpha_m} \left(\sum_{t=t_{\alpha_m}}^{2100} \widetilde{emi}_{R,E}(t) \right)$$

where:
$j = \{c, s\}$,
$\widetilde{emi}_R$ = *regional CO_2 emissions variable in downstream scenario,*
$\widetilde{FE}_R$ = *regional final energy production variable in downstream scenario,*
S = *all solid final energy production.*

		COALogit Instance		
	COALogit Input *(usage)*	**Current/2015 (II.)**	**OECD/2025 (IV.)**	**Non-OECD/2045 (VI.)**
All Scenarios	**GDP per capita** *(logit)*	2015 data, Institute for Health Metrics and Evaluation (IHME)[21]	2025 SSP2 projections[14]	2045 SSP2 projections
	Coal-fired power generation *(logit)*	2015 data, IEA[12]	Extrapolated data from 2021 GCPT[13] (capacity) & 2015 IEA (utilization rates)	2045 **OECD-PPCA-xp** variable, downscaled by routine (a)
	Total electricity generation *(logit)*	2015 data, IEA	2025 **Current-PPCA** variable, downscaled by (b)	2045 **OECD-PPCA-xp** variable, downscaled by (b)
	Population *(weighting)*	2020-2100 SSP2 projections	2020-2100 SSP2 projections	2020-2100 SSP2 projections
	Total PE demand *(weighting)*	2015 data, IEA	2015 data, IEA	2015 data, IEA
	Total PE demand *(PSC condition)*	2030-2100 **NPi** variable, downscaled by (c)	2030-2100 **Current-PPCA** variable, downscaled by (c)	2050-2100 **OECD-PPCA-xp** variable, downscaled by (c)
Power-exit	**Coal-fired power generation** *(PSC)*	2030-2100 **NPi** variable, downscaled by (d)	2030-2100 **Current-PPCA** variable, downscaled by (d)	2050-2100 **OECD-PPCA-xp** variable, downscaled by (d)
	Total electricity generation *(PSC)*	2030-2100 **NPi** variable, downscaled by (b)	2030-2100 **Current-PPCA** variable, downscaled by (b)	2050-2100 **OECD-PPCA-xp** variable, downscaled by (b)
Demand-exit	**Total CO_2 emissions** *(PSC)*	2030-2100 **NPi** variable, downscaled by (c)	2030-2100 **Current-PPCA** variable, downscaled by (c)	2050-2100 **OECD-PPCA-xp** variable, downscaled by (c)
	Coal CO_2 emissions *(PSC)*	2030-2100 **NPi** variable, downscaled by (e)	2030-2100 **Current-PPCA** variable, downscaled by (e)	2050-2100 **OECD-PPCA-xp** variable, downscaled by (e)
	Coal solids CO_2 emissions *(PSC)*	2030-2100 **NPi** variable, downscaled by (f)	2030-2100 **Current-PPCA** variable, downscaled by (f)	2050-2100 **OECD-PPCA-xp** variable, downscaled by (f)
	Met-coal CO_2 emissions *(PSC)*	2040-2100 **NPi** variable, downscaled by (g)	2040-2100 **Current-PPCA** variable, downscaled by (g)	2060-2100 **OECD-PPCA-xp** variable, downscaled by (g)

Table M4. Delineation of input variables to each COALogit instance and their sources. Roman numerals refer to Figure M4. Bold text indicates the upstream REMIND scenario which computed the variable. The '*xp*' in OECD-PPCA-*xp* is a placeholder for the coalition scenarios 1p, 2p, and 3p, which each initiate a unique COALogit run. See Table M5 for the definition of downscaling routines (a)-(g).

	Downscaling routine description
(a)	Eqs. (4)-(5) – i.e. assume all countries' coal-power-shares remain a constant % above or below regional level from 2025 forward, then account for the OECD coal phase-out.
(b)	Assume per-capita electricity generation remains constant at historical levels[iii].
(c)	Assume per-capita PE demand remains constant at historical levels[xvii].
(d)	Eq. (4) only – i.e. counterfactual coal power generation, indicative of reference demand.
(e)	Eqs. (4)-(5), except [$seel_C := emi_c$]; [$seel_G := emi_E$]; and $x = \frac{emi_C}{emi_E}$
(f)	Eqs. (4)-(5), except [$seel_C := emi_s$]; [$seel_G := emi_E$]; and $x = \frac{emi_S}{emi_E}$
(g)	Eqs. (4)-(5), except [$seel_C := emi_m$]; [$seel_G := emi_E$]; and $x = \frac{emi_m}{emi_E}$

Table M5. Delineation of all downscaling routines required for the REMIND-COALogit coupling interface. The lettered rows correspond to the letters in Table M4.

Covid-19 recovery programs

The final dimension of our scenario analysis considers the near-term uncertainties associated with the Covid-19 shock[22]. This interruption of electricity demand and project construction cycles is an opportune moment for governments to reassess power sector investment options, and to wield their power as a financier, underwriter, and/or regulator. These decisions have wide-ranging near- and long-term consequences, including severe respiratory health implications[23] which may be of greater sociopolitical relevance than before the pandemic. We assess the potential path-dependencies[24–26] 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 (Table A1) to extrapolate future trend scenarios (Figure A1).

We name these scenarios *green (G)*, *neutral (N)*, and *brown (B)* 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' – not the maximum – range of Covid-induced changes to those statistics.

Unlike the other two dimensions, these stylized exogenous constraints are independent of the PPCA and thus also apply to the reference NPi and NDC scenarios. Hence, each of the three *NPi-Covid* baselines (*NPi-G, NPi-N,* and *NPi-B*) initiates its own two scenario cascades, one for each policy interpretation (Figure M4), and all scenarios 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.

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[i] The participating subnational governments and private sector organisations are not considered in our study.
[ii] Countries are defined according to the ISO 3166-1 convention (249 total).
[iii] For reference, we estimate 2160GW when extrapolating with globally-uniform 40-year lifespans and 100% project completion as assumed in prior literature (see Figure A1)[27].
[iv] Global Energy Monitor. Global Coal Public Finance Tracker July 2020. *EndCoal.org.*
[v] Global Energy Monitor. Global Coal Mine Tracker January 2021. *EndCoal.org*.
[vi] Global Energy Monitor. Global Steel Plant Tracker January 2021. *EndCoal.org*.
[vii] This may well be an artefact of REMIND-COALogit's low temporal resolution, as more 'reasonable' pathways could be modeled by allowing coalition accession and policy enactment along a rolling horizon, i.e. in each REMIND period, which would be highly resource-intensive. Future DPE implementations may explore reducing the IAM optimisation horizon in each iteration to enable this.
[viii] China did not breach the 2p coalition in any scenario until after COALogit was re-calibrated to account for the accession of Spain, Croatia, Albania, North Macedonia, and Montenegro in July 2021, illustrating the dynamism of the DFS, i.e. the sensitivity of COALogit to relatively minor developments.
[ix] Japan and South Korea in the *green* recovery as well.
[x] Under default REMIND assumptions, early retirement is limited to 9% p.a. (45% per 5-year time-step). Several regions were thus mathematically infeasible without removing this constraint.

[xi] As of its status in 2018, viz. we do not model here the 2021 'Fit for 55' proposal by the EU Commission.
[xii] Along with GDPpc, the other two were coal production per capita and the share of coal in total final energy consumption. The latter was found to have high covariance with coal-power-share (~0.6 correlation factor).
[xiii] Likelihood-ratio test results showed a correlation factor of ~0.8 between GDPpc (on a purchasing power parity basis) and FOG, the highest found for any two variables.
[xiv] An adjusted McFadden pseudo-R^2 value between 0.2 and 0.4 is considered an excellent fit[15].
[xv] Countries with zero coal power capacity in the base year are assigned their REMIND region's aggregate utilization rate.
[xvi] Special cases of countries with low base-year electrification and a declining population are instead assumed to keep their total electricity generation constant at base-year levels. This prevents negative weights.
[xvii] Special cases of countries with low base-year PE and a declining population are instead assumed to keep their total PE constant at base-year levels.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- NCCappendixDPEPPCA.pdf
- NCCsupplementDPEPPCA.pdf