# Dynamic Evaluation of Policy Feasibility, Feedbacks and the Ambitions of COALitions

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**Article**

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## Abstract

The Paris Agreement prioritised international bottom-up climate negotiations. Meanwhile, research has asserted the coal exit as a prerequisite for Paris-consistent pathways. The Powering Past Coal Alliance (PPCA), an opt-in initiative toward phasing-out coal-fired electricity by mid-century, embodies both paradigms but currently encompasses just 5% of global coal demand. To assess its long-term prospects against Paris-consistent pathways, we couple the energy-economy model REMIND to an empirical coalition accession model and demonstrate a novel scenario analysis technique, Dynamic Policy Evaluation (DPE). Capturing co-evolutionary feedbacks between policy uptake and global energy markets, we simulate nationally-and-temporally-fragmented PPCA accession and analyse its sensitivity to coalition growth, sectoral ambition, and Covid-19-related uncertainty. Surprisingly, we find that virtually-global PPCA participation achieves <3% of 1.5oC-consistent coal declines, as non-electric consumption remains unregulated. In contrast, our median-estimate scenario (82% accession) assuming economy-wide coverage achieves ~53% efficacy (virtually-global: ~85%), suggesting that the PPCA should prioritise policy ambition over coalition expansion.


## Main Text

Under the Paris Agreement, 175 nations agreed to common-but-differentiated responsibilities toward limiting global warming to 1.5-2$^{o}$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 illustrates the political ambition required, stated policy evaluation (SPE) explores the consequences of current ambition levels. Examples include nationally-implemented policies (NPi) and nationally-determined contributions (NDCs) to Paris, useful reference scenarios for CEA or policy evaluation analyses (PEA), which assess subsequent mitigation policies for their potential efficacy toward specified goals, such as emissions or temperature targets (Table 1). In the bottom-up world of climate action[13,14], however, defining reasonable expectations for a given policy requires objective evaluation of its acceptability and diffusivity[15], implying the need to systematically and dynamically[6] quantify political feasibility, including feedback effects between the socioeconomic and energy systems and the political realm.

| IAM Approach | Research Question | Coal Phase-Out Insight | Feasibility Focus |
|---|---|---|---|
| **Cost-Effectiveness Analysis (CEA)** | *What actions characterize economically optimal mitigation pathways to achieve an environmental goal (e.g. Paris targets)?* | Coal is often phased out by 2050 in cost-efficient, Paris-compliant, benchmark scenarios[16,17]. | 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 of the current policy landscape or stated ambitions?* | 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. Useful as a baseline or benchmark scenario. |
| **Policy Evaluation Analysis (PEA)** | *What could a given policy accomplish towards a goal if adopted globally or in a predetermined coalition?* | A rapid global coal exit by 2050 can account for half the emissions reductions required for the 2$^o$C Paris climate target[19]. | 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 likely is a bottom-up policy initiative to achieve its stated goals? What policy feedback dynamics and outcomes are to be reasonably expected?* | 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 coupled model framework analyses the effects of fragmented policy adoption on the energy system, future policy uptake, and emissions. |

**Table 1. Approaches to IAM scenario analysis.** Dynamic policy evaluation is introduced to bridge the gap between long-term energy-economic models which excel in depicting techno-economic feasibility and social science research which excels at understanding today's technology and policy landscape. This enables the incorporation of socio-political insights into future-oriented energy-economy scenarios ('merging' strategy[7]). We iteratively couple REMIND to a previously conducted[18] logistic regression analysis of membership in the Powering Past Coal Alliance (PPCA), but other IAMs, empirical models, and coupling routines may also be appropriate.

Recent empirical research has advanced the quantitative codification of causation between techno-socio-economic contexts and policy decisions[18,20,21], and vice-versa[22]. Since IAMs quantify trajectories of today's energy-economic system consistent with anticipated socioeconomic trends, it follows that historical and emerging policy adoption trends can be coherently extrapolated in parallel. Here, we introduce dynamic policy evaluation (DPE), a novel scenario analysis technique which applies empirical methods on prospective IAM scenario data to quasi-endogenously simulate future policy uptake in IAM scenarios (Table/Figure 1). Based on empirical[18] and SPE analysis of frontrunners and their global impacts[16], DPE explores probable expansion dynamics of a bottom-up initiative, the positive[23] and negative[24] feedbacks it triggers, and reasonable expectations for its contribution to global targets.

CEA-derived mitigation strategies[16,17,25] frequently stress the urgency of phasing out coal, 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[19]. The socio-political feasibility, meanwhile, remains underexplored[18]. As some nations continue to commission coal power plants[21,30–32] (Table 2), others have joined 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. SPE and PEA fail to produce valuable insights into this coalition's prospects, as they can only employ stagnant, global, subjective, or normative assumptions on its expansion (Table 1). Here, we demonstrate DPE for the coal phase-out agenda by capturing co-evolutionary feedbacks between the energy and political systems to define reasonable expectations (and uncertainties) for the PPCA.

| 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[33]. 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]. Jewell, et al. (2019) operationalised a dynamic feasibility space[6] (DFS) for coal phase-out policies (Figure 2a) in terms of nations' likelihoods of joining the PPCA. Specifically, the study analysed a pool of 2,036 regression models permutating eleven independent variables seeking to explain PPCA membership, and established that high per-capita GDP and a low reliance on coal for electricity supply (coal-power-share) have particularly strong explanatory power[18]. In a first attempt to quantify future policy feasibility, we feed REMIND[34] scenario data to the DFS via the novel COALogit model, which employs probabilistic thresholds within the DFS (Figure 2) and spatial downscaling routines to iteratively define agnostic, evidence-based, country-level scenarios of PPCA accession for REMIND analysis (Methods).

While 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). How many more countries are likely to join, and what is a reasonable range of expectable outcomes? Can the sector-specific policy foster Paris-consistent coal declines, or is economy-wide ambition necessary? What are the relative effects of carbon leakage and renewable energy learning on coalition expansion and outcomes? Finally, how path-dependent is PPCA evolution and efficacy to near-term coal demand uncertainties after Covid-19[35]?

[i] The participating subnational governments and private sector organisations are not considered in our study.

# 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[36]. |
| | | **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[37] 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.

**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$^{o}$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 6Gt$CO_2$). 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 3040Gt$CO_2$ 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.

# 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$^{o}$C to visualise their aggregate effects and illuminate the remaining transformations necessary. The most glaring divergence between *NPi-G* and 1.5$^{o}$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$^{o}$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.

[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].

# 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-economic models[38,39] – the highest degree of 'integration'[7] – have rarely been successful in improving the realism of mitigation pathways[5]. Our work confronts this challenge by building on a tradition of validating and improving model assumptions using empirical data[15,40–42]. Particularly indispensable to the development of DPE were the pre-established empirical relationships between PPCA accession and certain IAM-native socioeconomic and energy system variables[18].

## 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)[43]. 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[25,29,30], may be explained in part by data accessibility barriers. The only open-access, comprehensive, coal-asset-level datasets[iv] were power-plant-specific[44] 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 short-sightedness 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[45], 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[46] and transport[47]. 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[25]. The present study does not dispute the urgency of power sector decarbonisation, as electrification is vital to myriad mitigation strategies[48], but 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$^{o}$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$^{o}$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[49]. 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[50–52] through for example 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, their coal infrastructure receives significant overseas financing from OECD-based investors[53], where divestment campaigns are historically commonplace[52]. Granted, Chinese banks are the world's largest overall coal financiers[53] 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[54]. China's historical 22-year mean plant lifetime (Table 2) and its 2060 carbon neutrality pledge[36] 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[55], citizenry[19], and global-leader status, OECD governments must cancel their entire coal pipelines[56].

# Future Research

DPE presents a way forward for inter-disciplinary quantitative climate policy research seeking to understand the intersection of techno-economic, socio-political, and climate target feasibility. Empirical efforts should investigate robust correlations between revealed ambition, viz. domestic legislation, and IAM-endogenous energy-economic variables, facilitating evidence-based simulation of future policy uptake. As these efforts must race against the dwindling time remaining to respect the 1.5$^{o}$C target[2], advanced data science techniques may prove crucial to defining new socio-political models[15,57].

Furthermore, parallel research needs to identify supplementary frontrunner policy options – i.e. early entry points[58] – that best augment global efficacy in both the near and long terms. The DPE framework may be applicable for investigating which actions robustly promote the positive feedbacks that encourage free-rider energy transitions. Supply-side fossil fuel regulations and carbon pricing are prime candidates for these efforts given their uptake frequency[52] and anticipated efficacy[51]. Finally, future work should explore full endogenisation of policy adoption and feedback in IAMs.

[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 and uncertainty 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.

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# Methods

The methods are available as a download in the Supplementary Files section.

# Figures

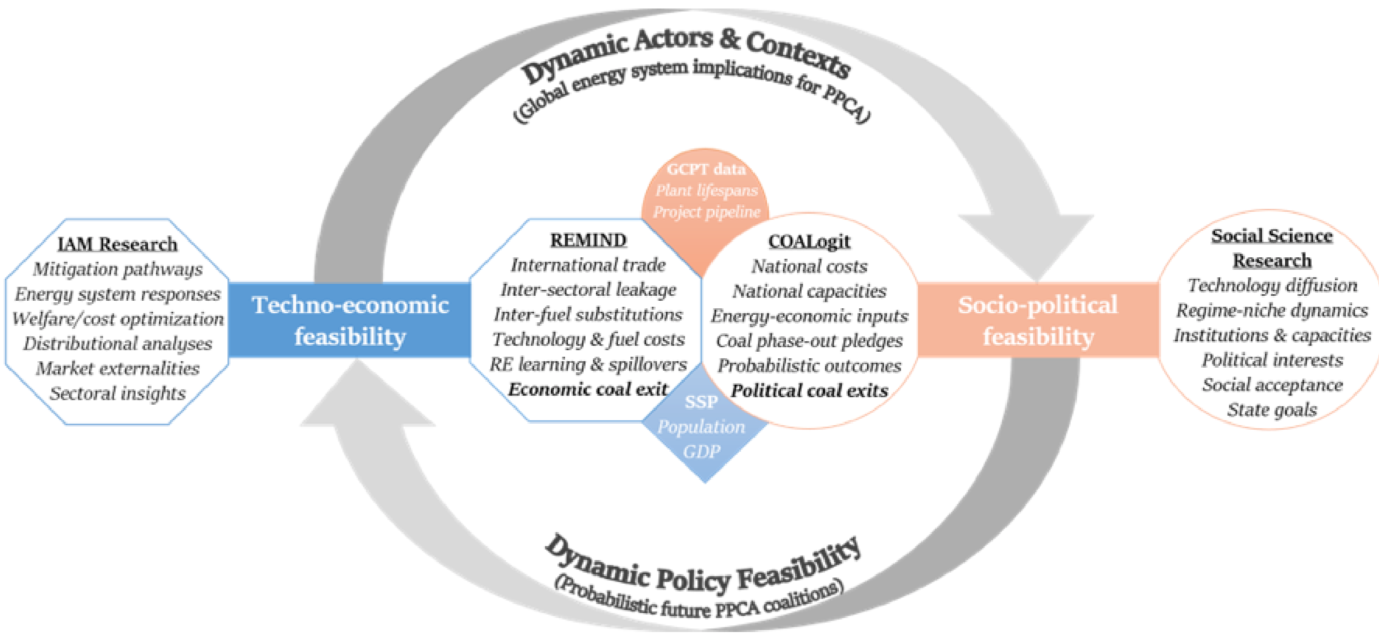
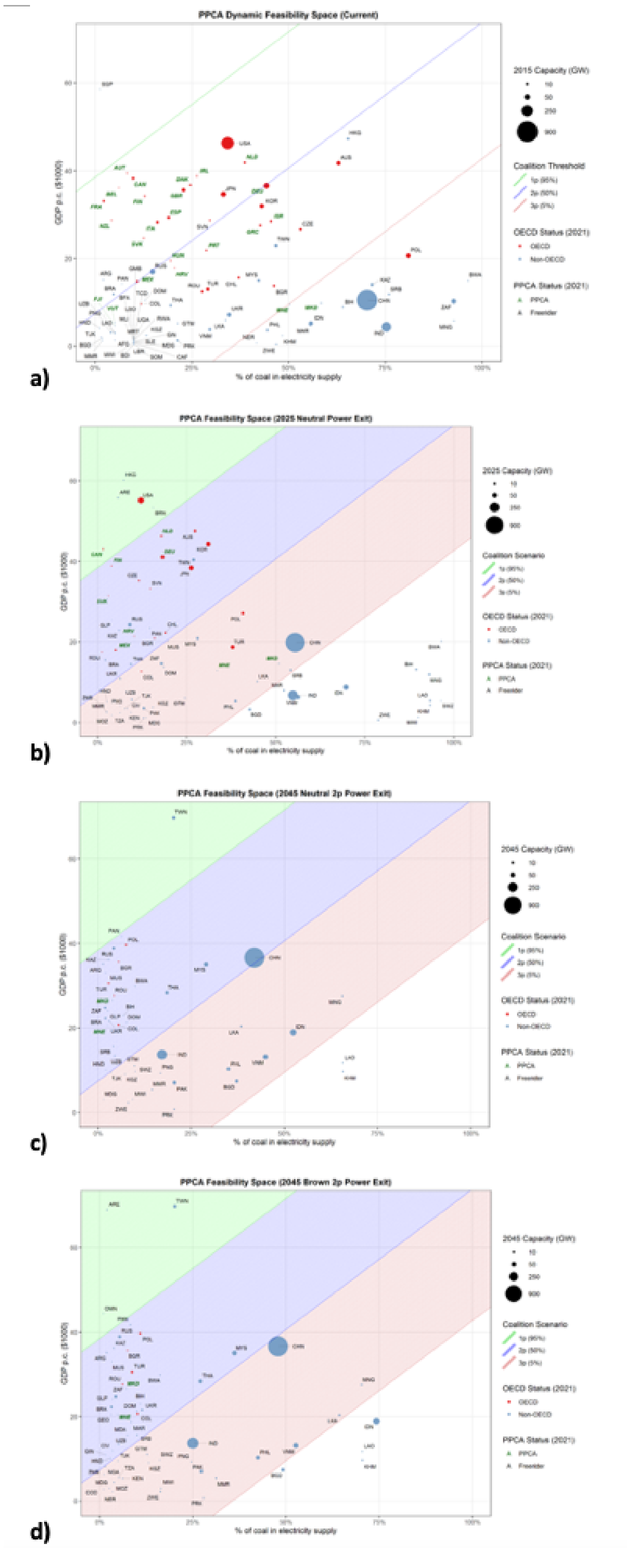


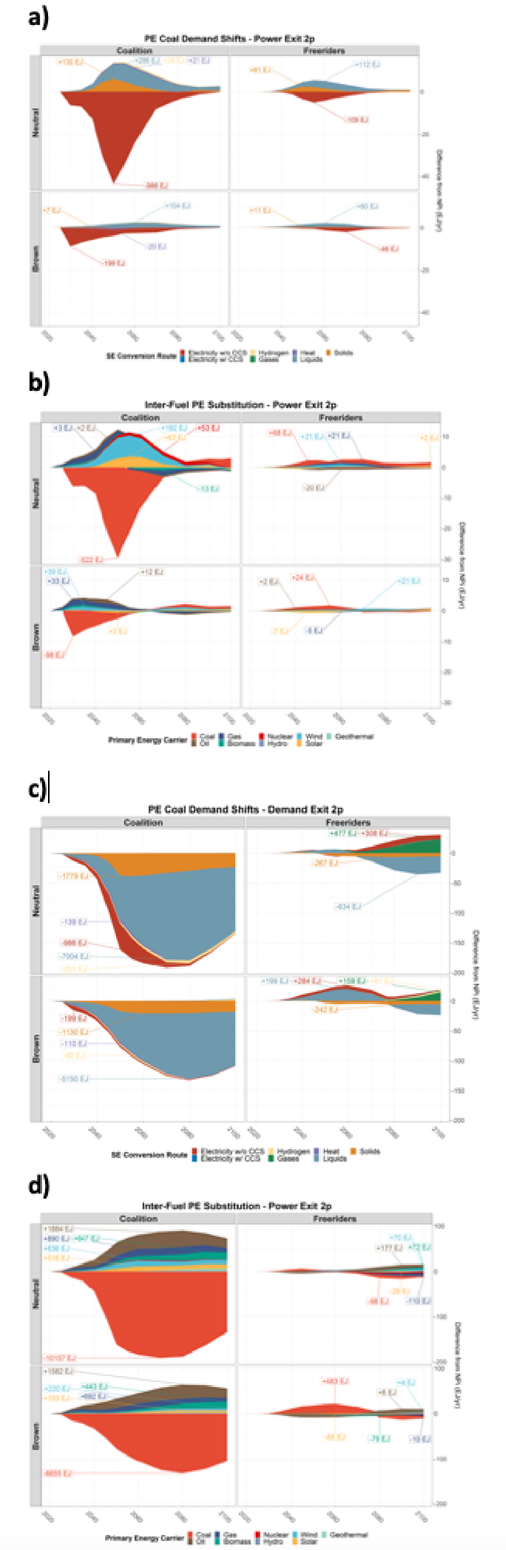

**Figure 1**

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 the REMIND-endogenous effects listed in the inner blue hexagon. REMIND feeds per-capita GDP projections (from the Shared Socioeconomic Pathway SSP2) and future shares of coal in electricity generation to COALogit, which infers national probabilities of PPCA accession. These political prospects are translated to coalition scenarios and policy stringency coefficients (see Methods) which inform regionally-differentiated policy uptake in REMIND. The cycle is repeated for later periods to simulate staged accession.




## 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.




## 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.


**Figure 4**

Compilation of all 18 scenarios, assessed for their efficacy relative to 1.5oC pathways in terms of coal phase-out (indicated by the lower x-axis, solid points, and bold font) and CO2 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 1.5oC. For each row, the 2p points can be considered the DPE median estimate, and the range between 1p and 3p indicates the uncertainty range.

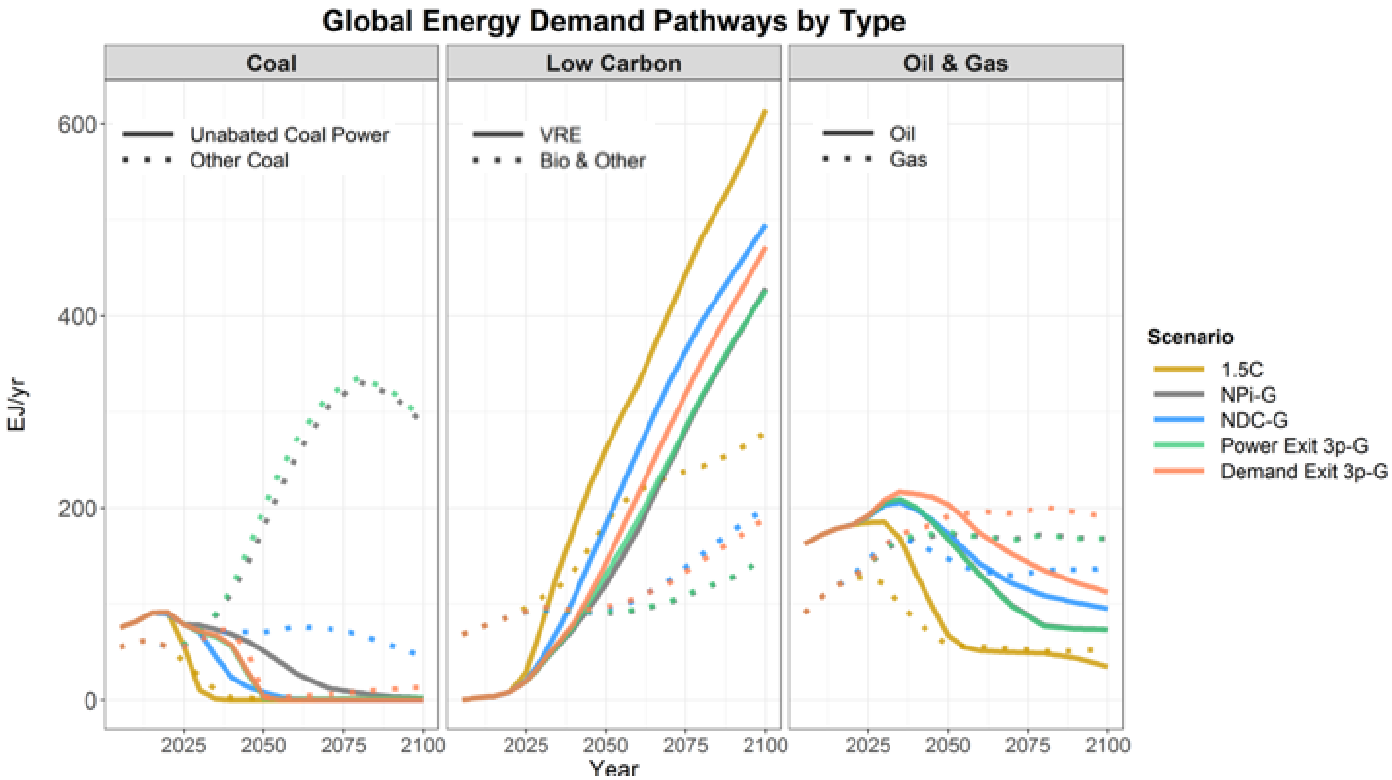



**Figure 5**

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 CO2 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.

# Supplementary Files

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

- NEnergyappendixDPEPPCA.docx
- NEnergysupplementDPEPPCA.docx
- Methodsfinal.docx

- DPEintermediatecascadescenarios.csv