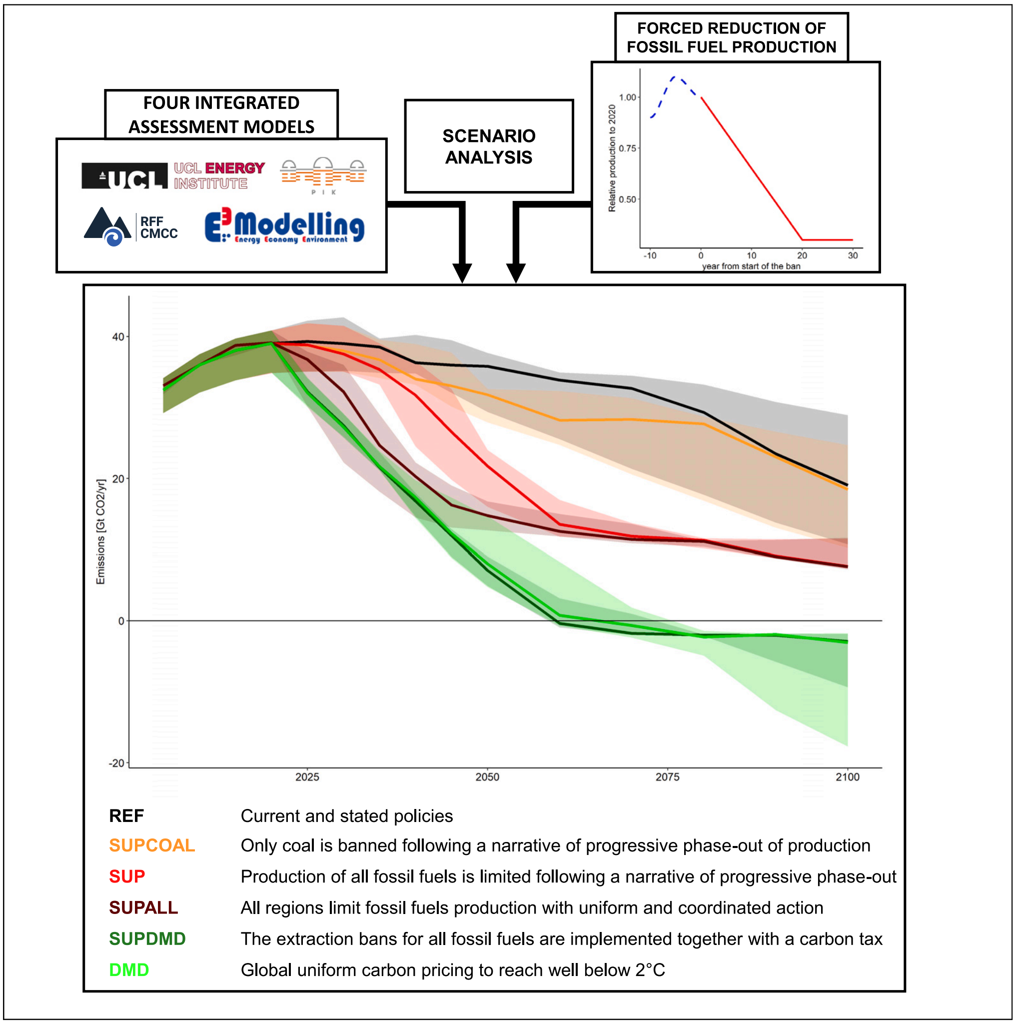
iScience

CellPress
OPEN ACCESS

Article

Fossil extraction bans and carbon taxes: Assessing their interplay through multiple models



Pietro Andreoni, Lara Aleluia Reis, Laurent Drouet, ..., Steve Pye, Renato Rodrigues, Massimo Tavoni

pietro.andreoni@eiee.org

Highlights

We explore the global mitigation potential of extraction bans of fossil fuels

In our scenarios, extraction bans decrease global emissions by up to 60% by 2050

Net zero emissions cannot be reached with extraction bans alone

Extraction bans reduce the required carbon price to meet the climate target

Andreoni et al., iScience *26*, 106377
April 21, 2023
https://doi.org/10.1016/j.isci.2023.106377

iScience

CellPress
OPEN ACCESS

Article

Fossil extraction bans and carbon taxes: Assessing their interplay through multiple models

Pietro Andreoni,[1,2,6,*] Lara Aleluia Reis,[1] Laurent Drouet,[1] Olivier Dessens,[5] Panagiotis Fragkos,[3] Robert Pietzcker,[4] Steve Pye,[5] Renato Rodrigues,[4] and Massimo Tavoni[1,2]

SUMMARY

Given concerns about the ambition and effectiveness of current climate policies, a case has been made for the combination of demand side policies such as carbon pricing with supply side bans on fossil fuel extraction. However, little is known about their interplay in the context of climate stabilization strategies. Here, we present a multi-model assessment quantifying the effectiveness of supply side policies and their interactions with demand-side ones. We explore a variety of fossil fuel bans with four integrated assessment models and find that international supply side policies reduce carbon emissions but not at sufficient levels to stabilize temperature increase to well below 2°C. When combined with demand side policies, supply side policies reduce the required carbon price, dampen reliance on CO_2 removal technologies, and increase investment in renewable energy. The results indicate the opportunity to integrate fossil fuel bans alongside price-based policies when exploring pathways to reach ambitious mitigation targets.

INTRODUCTION

Despite the recent success of the Paris Agreement (PA) in terms of global participation, greenhouse gas (GHG) emissions continue to grow[1] and ambitious climate action is becoming increasingly urgent because the remaining carbon budget to stay well below 2°C is fast depleting[2] Stabilizing the global temperature increase to well below 2°C or to 1.5°C urgently requires the global phase-out of unabated fossil fuels use.[3] The International Energy Agency (IEA) report on "Net Zero by 2050" recommends the immediate end of investments in new extraction fields and fossil power plants[4] to meet the PA goals. However, investments in oil and gas continue to grow[5] and the policies actually put into place by governments have so far proven insufficiently effective.[6]

A wide basket of policy instruments is available to guide the transition of the global economy away from fossil fuels and toward low-emission alternatives, such as taxes, cap-and-trade schemes, market or R&D subsidies to low-carbon technologies, command-and-control regulations (standards and moratoria), and behavioral interventions.

These policies can be classified as *demand side policies* if they target the consumption of fossil fuels, such as carbon taxes and subsidies to renewable energy, or *supply side policies* if they target the extraction of fossil fuels, such as placing taxes on fossil fuel production, cap-and-trade schemes on production rights, or extraction limits.[7]

The IEA study, alongside most of the integrated assessment model scenarios reviewed by the IPCC Sixth Assessment Report (IPCC, WGIII, 2022),[3] achieves the 1.5°C target via demand side policies, and especially carbon pricing. This is because a global uniform carbon tax is, according to economic theory, the first-best solution to internalize the climate externality because it allows us to abate emissions at the margin across fuels, sectors, and countries in a least-cost-option-first approach. For the same reason, the carbon tax (or, equivalently, a cap-and-trade system) has been the primary focus of the game theoretic literature related to international climate negotiation.

Outside the idealized world of models, however, carbon taxes or cap-and-trade schemes face several shortcomings and implementation challenges. First, the sectoral coverage is often partial because transaction and information costs of enforcing the policy are non-negligible in some sectors, especially those

[1]RFF-CMCC European Institute for the Economics and the Environment, Centro Euro-Mediterraneo sui Cambiamenti Climatici, Milan, Italy

[2]Politecnico di Milano, Milan, Italy

[3]E3 Modelling S.A., Panormou 70-72, Athens, Greece

[4]Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany

[5]UCL Energy Institute, University College London, London, UK

[6]Lead contact

*Correspondence: pietro.andreoni@eiee.org

https://doi.org/10.1016/j.isci.2023.106377

involving millions of users. Second, negotiating coordinated international climate policy has proven very difficult because of the *tragedy of the commons*.[8] Therefore, real-world climate policy has so far been implemented at the national or regional scale[6,9] with fragmented climate action and regionally asymmetric policies.[10] In case of non-uniform climate policies across countries, demand side policies cause carbon leakage, because the reduction in fossil fuel demand comes with a decrease in the international market price for the commodity,[11] whereas energy-intensive manufacturing industries may relocate to countries with limited policy ambition.[12] Consequently, consumption of fossil fuels increases in those countries where climate policy is weak or absent. Furthermore, a form of intertemporal moral hazard known as *the Green Paradox*[13] can materialize if producers, in expectation of collapsing future demand, flood the market to extract rent from the resource while still profitable. This effect has been quantified to be limited in magnitude by previous modeling studies.[14] Finally, the perceived fairness of demand side policies is often low: Most of the cost of a carbon tax is passed on to final consumers and especially to the most vulnerable part of the population,[15] who are disproportionately affected by carbon taxation.[16,17]

Therefore, several scholars have remarked that real-world international demand side policies might be insufficient and have argued in favor of supply side policy[11,18–20] to complement demand side instruments in ambitious mitigation scenarios.

Because they directly target the supply of fossil fuels and not their carbon intensity, supply side policies can be less cost efficient than a carbon tax. However, they can mitigate some of the shortcomings of demand side policies because of the opposite mechanism they achieve emissions reductions with: By creating scarcity in the fossil fuel markets, supply side policies would increase the international market price of fossil fuels. Consequently, in case of non-global policy, limiting production decreases fossil fuel consumption even outside the borders of the country/coalition that implements them. Moreover, high fossil fuel prices favor energy exporting countries that so far have largely opposed international mitigation efforts.[7] Furthermore, targeting production should come at low administrative and transaction costs[20] because fossil fuel reserves are geographically concentrated and extraction infrastructure easily monitorable. Finally, supply side policies are not subject to the green paradox, and should therefore avoid anticipation of investments in the fossil fuel upstream sector, reduce future stranded assets, and foster green R&D.[11] Overall, because they are binding only if demand at the unconstrained market equilibrium is higher than the capped supply, supply side measures are disposable and relatively cheap if implemented alongside effective demand side policies.[11]

At the same time, forcing scarcity on fossil fuel supply can cause energy and economic crisis, social turmoil, and geopolitical strain if the production is reduced unilaterally or too abruptly, as the oil crises of 1973 and 1979 or the current Russian crisis show: Fossil fuels are deeply rooted in the geopolitics of the contemporary world, and ill-managed supply side policies could hinder international cooperation. Therefore, for this instrument to be used effectively, it must be included in a recognized multilateral international framework.[21] These arguments support the view that the PA can provide an opportunity to explore the fossil fuel supply side measures and that the UNFCCC should foster the phase-out of both fossil fuel production and consumption.[22]

As with international demand side policies, a supply side climate treaty would be subject to the free rider dilemma, because individual producers would be incentivized to deviate from the cooperative strategy in a rent-seeking behavior. Negotiating and abiding such a treaty would, not unlike with demand side policies, require long-term commitment to climate stabilization and willingness to cooperate from participating countries. However, for supply side action to be effective only the few relevant fossil fuel producers need to enforce the strategy, which are also the regions that would gain the most from exporting fossil fuels with high market prices. In fact, fossil fuel markets have a long history of coordinated oligopolistic behavior and strategic price setting, as demonstrated by the behavior of OPEC. Even if a comprehensive game theoretic analysis on the stability and formation of supply side coalitions is, to the best of our knowledge, lacking, these factors suggest that international supply side policy would imply a different system of incentives to participate or defect relative to negotiations involving demand side policies.

To assess the opportunity of integrating supply side policies into the global negotiation arena, it is important to understand how they would affect the energy system and the economy, and to quantify their global mitigation potential. This knowledge is, for the most part, lacking. Analytical literature has studied the optimal policy mix of supply and demand taxes under partial cooperation,[18,23,24] but there is no exhaustive understanding of how supply side measure would interact with demand side policies in a technology-rich framework. Previous work has explored the effect of fossil fuel subsidies removal,[25] placed production-based taxes on production,[26] quantified the amount of unburnable fossil fuels under PA aligned targets,[27–29] and explored supply side policies in an agent-based model.[30] We contribute to fill this gap by exploring the economic, energy system, and environmental implications of comprehensive fossil extraction bans (From now on, we shall use the terms extraction bans and supply-side policies interchangeably for readability) using four leading Integrated Assessment Models (PROMETHEUS, REMIND, TIAM-UCL and WITCH) that have been used to provide scenarios in key assessments such as the IPCC Assessment reports.[2,3,31] Because they differ in underlying modeling frameworks, methodological approaches, and assumptions, the joint assessment provides robustness to our results.

Results indicate that although banning only coal is largely insufficient to deviate from NDCs trajectory, extraction bans for all fossil fuels substantially reduce emissions if large producers implement these policies. However, supply side policies can reach PA consistent climate targets at a competitive cost only if coupled with carbon pricing, with the combination of demand and supply side policies producing synergies in policy implementation and effectiveness.

Scenarios design

We designed a series of scenarios (Figure 1B) to assess the effects of hydrocarbon extraction bans on the future development of emissions and the energy system. In three scenarios (*SUP*, *SUPALL*, and *SUPCOAL*), extraction bans are modelled with different speeds and hydrocarbons banned. More carbon intensive fossil fuels are banned first (Figure 1A). We model extraction bans as a forced reduction of fossil fuel extraction by up to 70% relative to 2020 production for all fossil fuels, levels that were found to be near the maximum feasible ban level that all four models could achieve. Therefore, it represents relatively conservative assumptions about the technical and socio-political feasibility of phasing out fossil fuels, depicting scenarios in which governments (and private companies) are unwilling or unable to completely shut down their hydrocarbon extraction industries. Despite this, the speed and depth of the extraction phase-out is historically unprecedented (see SI Production cuts implementation for a comparison with historical precedents) and highly ambitious compared to currently implemented and stated climate policies, compatible with 2050 ranges for well-below 2°C scenarios in the IPCC Sixth Assessment Report for coal (68–98% decline in global primary energy supply from 2020 levels), and more ambitious than this range for oil and gas (21–60% for oil, and −13–36% reduction for gas).

Although we do not model endogenously the political economy or the strategic interactions that characterize supply side climate policies, we recognize that the fossil fuel industry has a deep influence on the economics and geopolitics of many countries, and that economic competitiveness and security considerations can obstruct international cooperation on the matter. Therefore, we design a narrative (Figure 1A), which is then imposed exogenously to models, to mimic these frictions in which different regions start banning the fuels at different times (*SUP* and *SUPCOAL*), as well as a "fully cooperative" scenario in which supply side action is coordinated and synchronous across regions (*SUPALL*). In these scenarios, most of the decarbonization effort is carried out by extraction bans but a limited set of demand side policies are included because of the nationally determined contributions (NDCs) extrapolation beyond 2030.

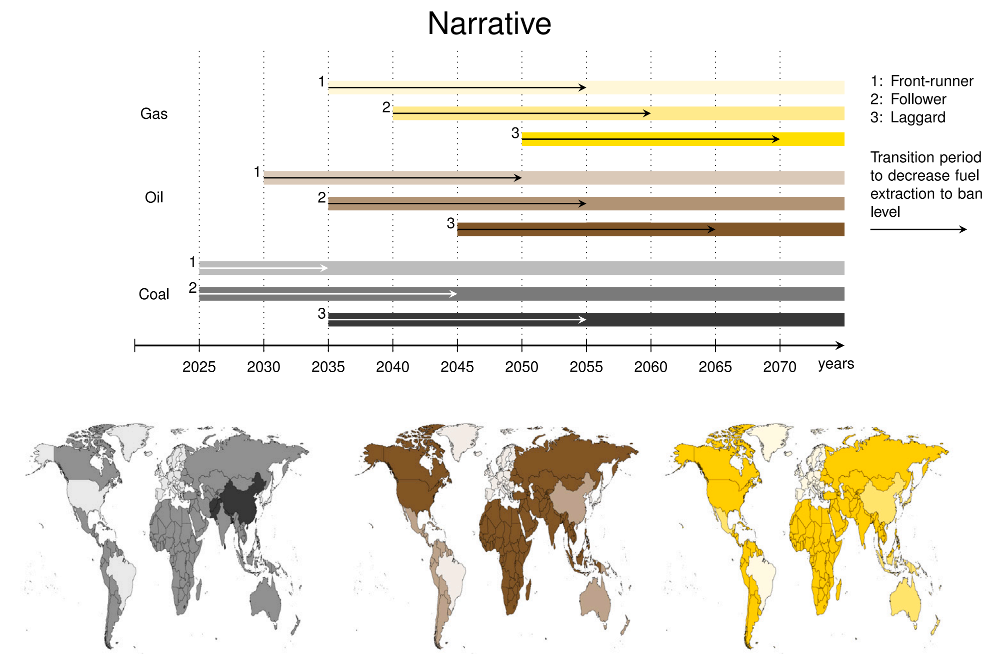
These scenarios are designed to explore how effective and efficient extraction bans are as the primary climate mitigation policy instrument. The timing and speed of the forced reduction in fossil extraction are designed "bottom-up" to describe possible pathways of development of an ambitious supply side treaty given technical and socio-political constraints. Therefore, we do not impose a cumulative emission target in these scenarios, but emissions are derived as a result given the scenario assumptions.

We then model two well-below 2°C consistent scenarios to explore the interactions between supply and demand side policies, where the temperature target is reached through a global carbon tax to consumption, either with (*SUPDMD*) or without (*DMD*) extraction bans on top. In both these scenarios, cumulative global CO_2 emissions between 2011 and 2100 are constrained to 1000 $GtCO_2$.

RESULTS

Emission pathways, carbon budgets and energy system

We begin by exploring the emission and climate consequences of the alternative scenarios (Figure 2). The well-below 2°C scenarios imply a sharp reduction of global CO_2 emissions in the first half of the century, A



B

REF	NDCs and constant effort extrapolation after 2030
SUPCOAL	Only coal is banned following the narrative, shown in figure ***a***
SUP	Production of all fossil fuels is limited following the timing of the exogenous narrative, shown in figure ***a***
SUPALL	All regions limit fossil fuels production as *frontrunners* for all fuels
SUPDMD	The supply side treaty (following the narrative) is implemented together with a global uniform carbon price to reach the 1000 GtCO2 Carbon Budget
DMD	Global uniform carbon pricing to reach a 1000 GtCO2 Carbon Budget from 2011 to 2100 consistent with well below 2

Figure 1. Scenario description

(A) Narrative distribution for different fuels. For each fossil fuel, darker shades of the color identify groups that enter later the international agreement on the ban of fossil fuels. The beginning of the colored line identifies the year in which each group starts limiting production of the fossil fuel, whereas arrows mark the end of the transition period, after which the extraction limit is fully enforced at the final level. Maps are shown identifying the regional distribution of frontrunners, followers and laggards for each fossil fuel, using WITCH regions.

(B) Scenario names and definitions. The colors identify the scenarios in following figures.

reaching net zero CO_2 emissions between 2060 and 2075. These results are consistent with previous assessments[2,32] and with the latest IPCC report.[10]

Banning only coal extraction (*SUPCOAL*) decreases cumulative emissions of CO2 to 2100 by only 2.6–9.4% (model range) relative to the reference scenario. The limited emissions reduction is because of the substitution (see Figure 4B) with unbanned fossil fuels (gas, oil) and the fact that the reference scenario already implies a gradual phase-out of coal because of current policies and NDCs effort. Moreover, the extraction ban design allows for 30% of residual hydrocarbon production, a level aligned with 2100 projections for coal extraction in the Reference scenario (see Figure 4B).

Supply side scenarios that limit production of all fossil fuels (*SUP* and *SUPALL*) tend to bridge the current level of climate effort with the emission pathways of well-below 2°C scenarios. In *SUPALL*, global CO_2 emissions in 2050 are reduced to 59% relative to the reference scenario and 67% relative to 2019 emissions, a level consistent with the 52–76% range of CO_2 emission reduction relative to 2019 reported in IPCC AR6 WG3.[10] Long-term emissions are higher in supply-side scenarios relative to scenarios focusing on

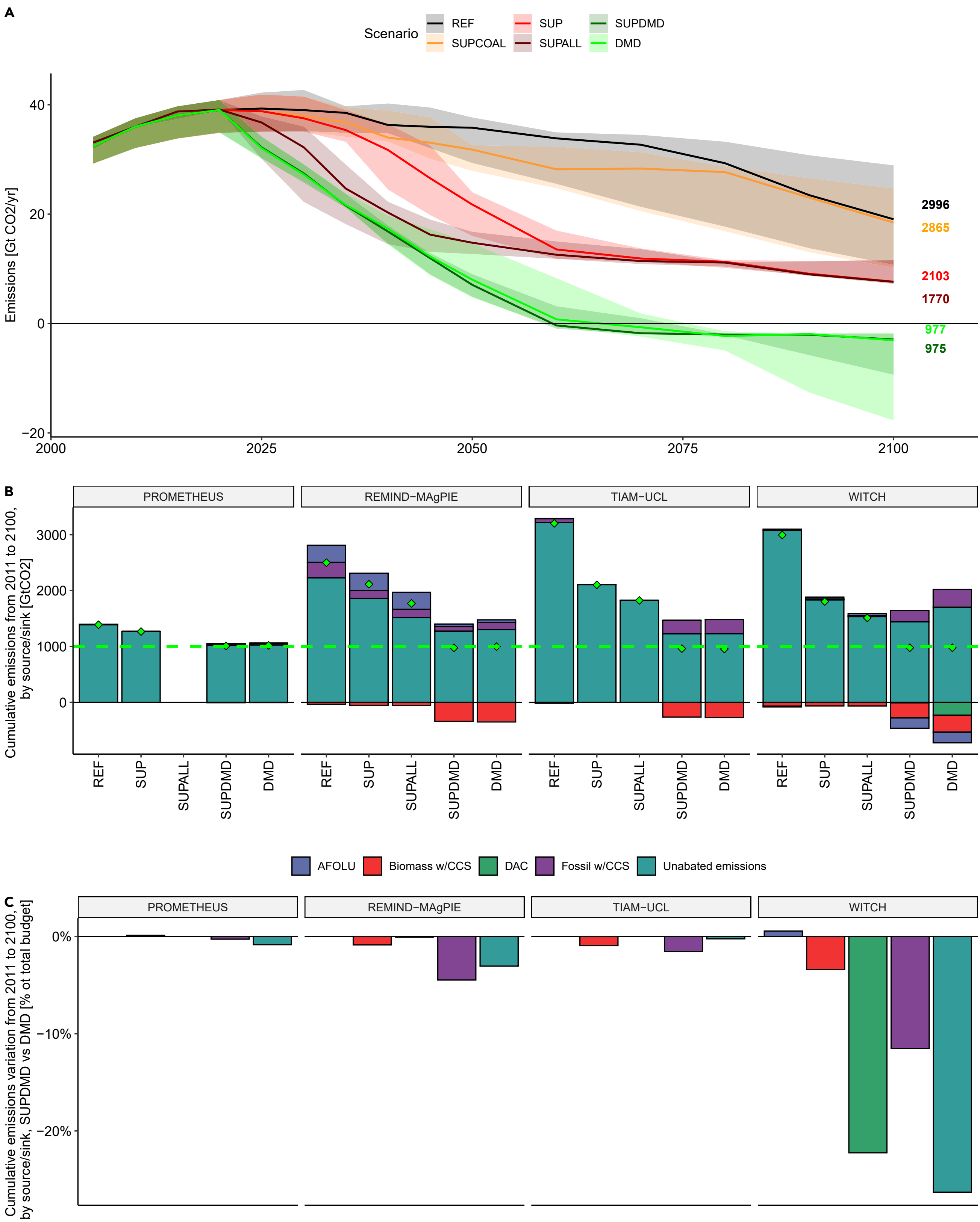

A
Scenario
REF
SUPCOAL
SUP
SUPALL
SUPDMD
DMD
Emissions [Gt CO2/yr]
40
20
0
−20
2000
2025
2050
2075
2100
2996
2865
2103
1770
977
975
B
PROMETHEUS
REMIND−MAgPIE
TIAM−UCL
WITCH
Cumulative emissions from 2011 to 2100, by source/sink [GtCO2]
3000
2000
1000
0
REF
SUP
SUPALL
SUPDMD
DMD
AFOLU
Biomass w/CCS
DAC
Fossil w/CCS
Unabated emissions
C
Cumulative emissions variation from 2011 to 2100, by source/sink, SUPDMD vs DMD [% of total budget]
0%
−10%
−20%

Figure 2. Emissions and carbon budgets

(A) Global CO_2 emissions by scenario. Range (shaded areas) and median (lines) of model ensemble. Carbon budgets are shown for each scenario. Arrows highlight the reduction of emissions in DMD and SUPALL scenarios in 2050. Colored arrows highlight the reduction in CO_2 emissions in SUPALL and DMD scenario relative to the Reference scenario in 2050. (B) cumulative emissions (sources and sinks) in 2100 (2050 for Prometheus model). Green line represents 1000 $GtCO_2$ carbon budget, green dots identify the net budget (sources-sinks). PROMETHEUS model runs until 2050.
(C) Percentage difference of cumulative carbon from sources/sinks in SUPDMD relative to DMD.

demand-side policies, even though the former outperform carbon pricing in terms of electrification, renewables penetration, fossil phase-out, and energy efficiency improvements (see Figure 3A).

After 2050, global emissions in both supply side scenarios (*SUP* and *SUPALL*) stabilize at around 12 Gt CO_2/yr (a level consistent with the 5–16 $GtCO_2$/yr range for residual emissions at the time of net-zero CO_2 in the IPCC WG3 report for 2°C scenarios[33]), whereas carbon tax-based scenarios reach net-negative emissions. No supply side scenario reaches a carbon budget consistent with well below 2°C (Figures 2A and 2B), because extraction bans do not foster Carbon Capture and Storage (CCS), Biomass with Carbon Capture and Storage (BECCS) and other Negative Emissions Technologies (NET) like Direct Air Capture (DAC). CCS allows us to operate coal and gas power plants with low emission intensity, which can provide low-carbon dispatchable capacity for the power sector and reduce the need for costly energy storage. In the industry sector, CCS can be used to decarbonize sectors that require high-temperature thermal inputs and are hard to electrify such as steel and cement production. Negative Emissions Technologies are needed to speed-up decarbonization, offset residual CO_2 emissions from hard-to-abate energy sectors (Industry [such as steel and cement] and heavy transport [aviation and shipping]), land use change and non-CO_2 emissions from agriculture and other sources, and possibly to reach net-negative emissions to recover from temperature overshoot.[10] Therefore, although an extreme policy with 100% cuts to fossil fuel extraction would reduce emissions from fossil fuels to zero (at potentially prohibitive costs), net-zero CO_2 and greenhouse gases (GHG) emissions could still not be reached with supply side policies alone.

The combination of carbon pricing with extraction bans (*SUPDMD*) causes a faster decline of emissions in the first part of the century, because the production constraint created by the extraction ban is more binding than the implicit constraint produced by carbon pricing. Thus, integrating fossil-extraction bans with global carbon pricing increases the mitigation effort early on and reduces the reliance on NETs in the long term (Figure 2C), a desirable feature both because these technologies are currently expensive, commercially immature, and unavailable at scale and because a lower budget overshoot reduces climate risks and damages.[34] This is especially visible for WITCH that relies more on negative emissions, but holds true also for TIAM-UCL and REMIND models, whereas BECCS uptake is limited in PROMETHEUS as the model runs until 2050. The reduction in fossil CCS happens because the higher market prices for fossil fuels decrease the competitiveness of these options relative to renewables, nuclear and energy efficiency. The decrease in the deployment of negative emission technologies can be attributed to two concurring factors: First, these technologies are less incentivized because of the lower carbon price in SUPDMD relative to DMD (See section costs, carbon prices and co-benefits). Second, DACs become less competitive because of the higher cost of thermal inputs (in particular, natural gas). Lower reliance on CCS and NETs implies a faster increase in renewable energy penetration, electrification of end-use consumption, and energy efficiency improvements, as well as lower investments on fossil fuel power plants and upstream sector with respect to a demand side only scenario (see Figure 3) and SI *Additional results A*).

Prices, supply, and producer support

Although both types of policies decrease fossil-related emissions, the underlying mechanism is different: carbon pricing increases the consumers price of carbon-intensive goods and fuels but reduces fossil fuel prices at the international market level, whereas an extraction ban produces fossil fuel supply scarcity and increases the market price of the hydrocarbon banned (Figure 4A).

How much and how fast the price increases depends on the share of global hydrocarbon production subject to the bans, and on how much the production constraints force a reduction in global demand: in a high-demand scenario (*SUP* and *SUPALL*), forcing low supply will cause an high price increase; in a low-demand scenario (*SUPDMD*), the price increase will be smoother and less marked. In the narrative scenario (SUP) the greatest impact for all fuels is seen when the *laggards* initiate their ban, because only a coalition representing a large enough share of global hydrocarbon production has a meaningful effect on prices: for coal,

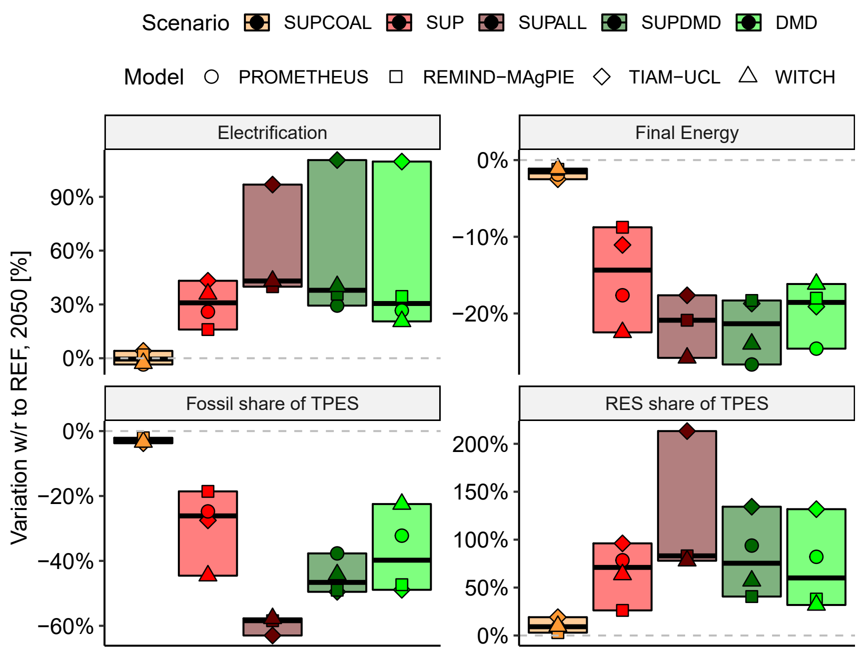


Figure 3. Energy indicators

Energy system indicators in 2050, percentage variation with respect to REF. Dots identify single model observation, and the error bars highlight model variation. "Fossil" includes coal, oil and gas. "Renewables" account for hydro, solar (PV and CSP), wind (onshore and offshore), Biomass without CCS, and Geothermal.

where *frontrunners* are a larger group, the effect on prices is visible early on; for oil and gas, *frontrunners* action has a negligible effect on prices, whereas when *followers* join the agreement the price of gas increases by 12% in the following time step. The entry of *laggards* in the coalition implementing the extraction bans is necessary for oil prices to increase.

Coalition size matters also when demand and supply side policies are combined (*SUPDMD*): international fuel market prices are higher than the demand-side scenarios (*DMD*, light green line), but lower than in the supply side scenarios with the same production constraints (*SUP*). This is because in *SUPDMD* the production bans reduce global supply of fossil fuels, but at the same time the carbon tax significantly reduces their demand. Therefore, meeting a shrinking global demand is possible even in the presence of supply side constraints, until all fossil producers agree to limit production. After that, the market equilibrium is found at a price in between the supply side only (SUP) and demand-side only (DMD) scenarios. If this equilibrium is closer to the former or the latter depends on the relative "strength" of the two policies, i.e., how much fossil fuel demand is reduced by the carbon tax relative to how much supply is constrained by production bans: in our combined scenario (SUPDMD), the carbon tax is the primary policy instrument for emission reductions, which produces a price profile closer to the demand-side only scenario (DMD).

The increase in international prices substantially reduces the primary energy use of the fossil fuels (Figure 4B). Our results suggest that the ban of only one fuel may cause a visible increase in the use of other fuels if it is not coupled with other emission reduction policies (e.g., carbon pricing), as seen by the increase in oil and gas primary use when only coal is banned (6.2% increase in primary energy for gas and 2.6% for oil in 2050, *SUPCOAL* model median). This substitution effect accounts for 16–31% (range across models) of cumulative emissions avoided from reduced coal consumption.

Early and coordinated supply policies reduce by 76% and 74% the global gas and oil use by 2050 (model median), much faster than the demand-side scenario trajectory implies. For coal, the price increase generated when all-regions act as *frontrunners* align with the supply levels with the Paris agreement compatible pathways up to 2035. After that, the primary energy consumption is bounded by the residual production permitted under the bans, whereas demand side policies can further reduce coal supply because carbon pricing puts a higher additional cost on the use of coal, the most carbon intensive fossil fuel.

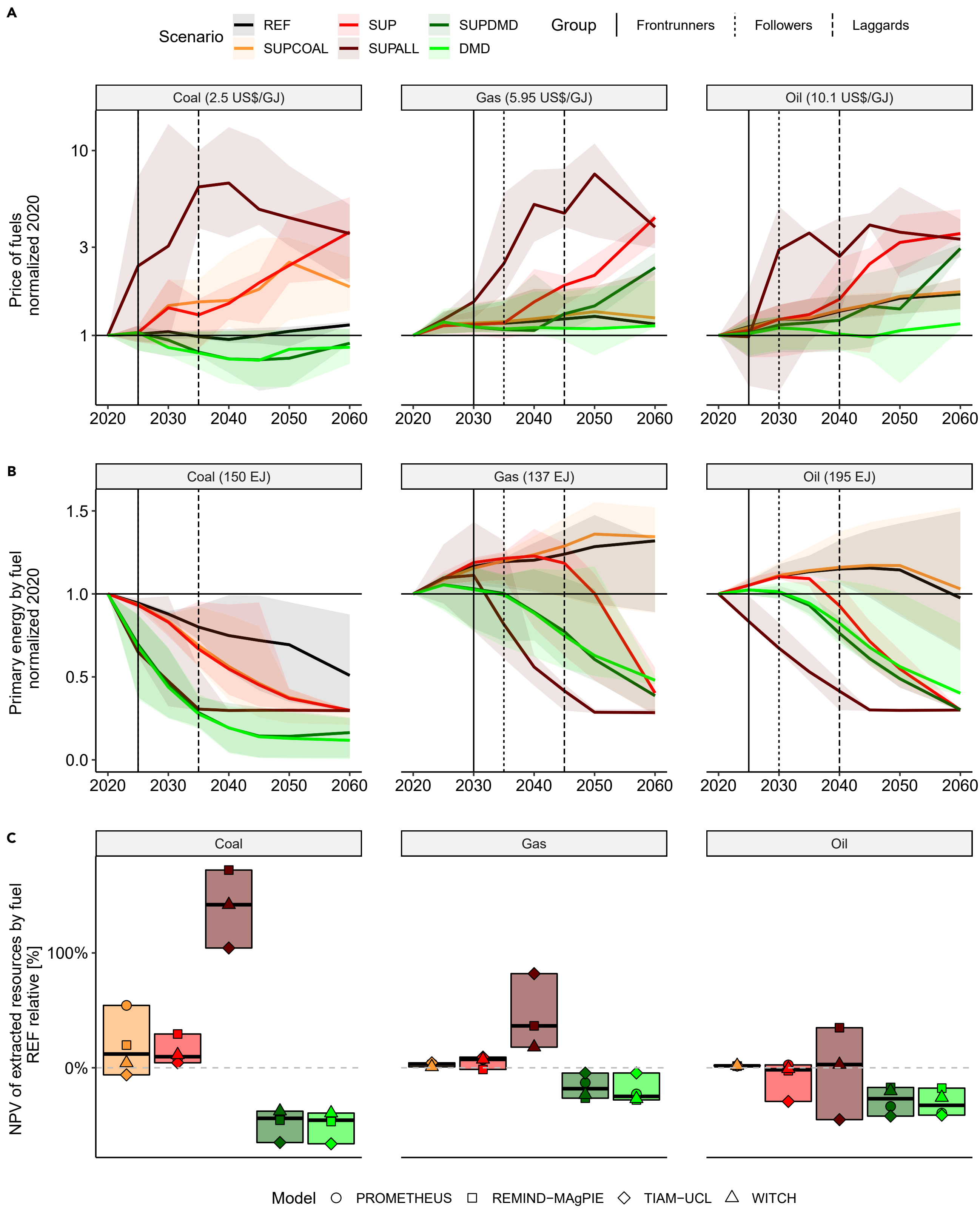

A
Scenario
REF
SUPCOAL
SUP
SUPALL
SUPDMD
DMD
Group
Frontrunners
Followers
Laggards
Coal (2.5 US$/GJ)
Gas (5.95 US$/GJ)
Oil (10.1 US$/GJ)
Price of fuels normalized 2020
10
3
1
2020
2030
2040
2050
2060
B
Coal (150 EJ)
Gas (137 EJ)
Oil (195 EJ)
Primary energy by fuel normalized 2020
1.5
1.0
0.5
0.0
C
Coal
Gas
Oil
NPV of extracted resources by fuel REF relative [%]
100%
0%
Model
PROMETHEUS
REMIND-MAgPIE
TIAM-UCL
WITCH

Figure 4. International prices and producers revenues

(A) International fuel market prices, without considering the effect of the carbon tax, normalized to 2020 values. Range (shaded areas) and median (lines) of model ensemble. On parentheses, model median of 2020 values. Vertical lines show the year when different supply region groups start banning the fuel in the narrative scenario. Semi-log scale.

(B) Global primary energy by fossil fuel relative to 2020. Range (shaded areas) and median (lines) of model ensemble. On parentheses, model median of 2020 values.

(C) Global Net Present Value discounted at 3% between 2020 and 2050 of total value of global extracted resources, relative to REF. Dots identify single model observation, and the error bars highlight model variation.

With extraction ban policies, hydrocarbon producers' revenues are influenced by two opposing forces: higher international fossil prices increase revenues per output, but shrinking demand reduces total volume. Figure 4C shows that the first effect dominates and produces a large increase of total value of extracted resources until mid-century if all regions are *frontrunners*, especially evident for coal (+141% of REF relative NPV, model median), but relevant also for gas (+36%, model median). For oil, there is no robust evidence across models on the sign of the variation. In the narrative scenario (SUP), the effect is less evident because prices increase more slowly as countries join the supply side agreement at different points in time, but it is still relevant for gas (+7%, model median) and coal (+14%, model median). Most of the revenue increase benefits large fossil producing regions such as China for coal and the US, Russia, and MENA region for oil and gas (see SI Additional results B: hydrocarbon revenues). If carbon pricing and extraction bans are implemented together (SUPDMD), the net value of extracted resources is relatively higher than the carbon tax scenario (DMD) (+9% for oil and gas, +3% for coal, model medians), but the increase is not sufficient to completely compensate the losses relative to the reference scenario.

Costs, carbon prices and co-benefits

Figure 5A, finally, shows the global cost of climate policy against cumulative emissions avoided between 2020 and 2050 relative to REF, for each scenario and model. We select costs and global emission reduction until 2050, because before mid-century the demand-side (DMD) and the early supply side scenario (SUPALL) are roughly comparable in terms of emission trajectories (see Figure 1A). Tendency lines highlight the average cost per unit of carbon abated for each scenario, with low slopes indicating high cost-efficiency of the policy mix. The absolute cost of policy varies significantly across scenarios and models. The lower cost of the policies relative to GDP in TIAM-UCL arises from the specificity of the model which does not represent any macroeconomic feedback on GDP from the measures on supply or demand in this study, whereas WITCH features a full link with the economy and represents a lower number of technological options.

The cost-efficiency of supply side policies decreases with the ambition consistently with the notion of convex marginal abatement costs, as can be seen by the higher slope of the tendency line in SUPALL (dark red line) with respect to SUP (red line). In both cases (SUP and SUPALL), the cost-effectiveness is significantly lower than demand-side scenarios that reach the Paris agreement goals (DMD and SUPDMD).

Banning only coal, although providing only incremental emission reductions over the Reference scenario, is very cheap over the century (0.05% GDP loss, model median). If the extraction of all fossil fuels is banned, the median loss across models ranges from 0.5% of GDP (SUP) to 2% of GDP in case that production bans are global and uniform (SUPALL). It should also be noted that none of these scenarios achieve the Paris goals in 2100. Regionally, the cost of early supply side policy (SUPALL) tends to be relatively higher in producing regions such as MENA and Russia (See SI Additional Results C: carbon price and cost of policy), because their energy mix is still largely dependent on fossil fuels, they have a high carbon and energy intensity of GDP, and the cost of fast decarbonization exceeds the increased revenues from exports.

The low cost-efficiency of the supply side scenarios can be explained by various factors. As discussed, hydrocarbon extraction bans implemented without strong demand-side policies incentivize a narrower portfolio of mitigation options with respect to carbon pricing, because they do not foster the phase-in of CCS, BECCS and NETs; while controversial, if available at the scale and at the cost assessed by model projections, these technologies can speed up the transition to net zero and significantly reduce the total cost of decarbonization. Furthermore (especially in SUPALL), the early ban of all fossil fuels provides a greater shock to the energy system sooner in time when the discount effect of the future is lower. Finally, the prescribed linear reduction for fossil fuel bans does not follow exactly a least-cost-option-first approach, even

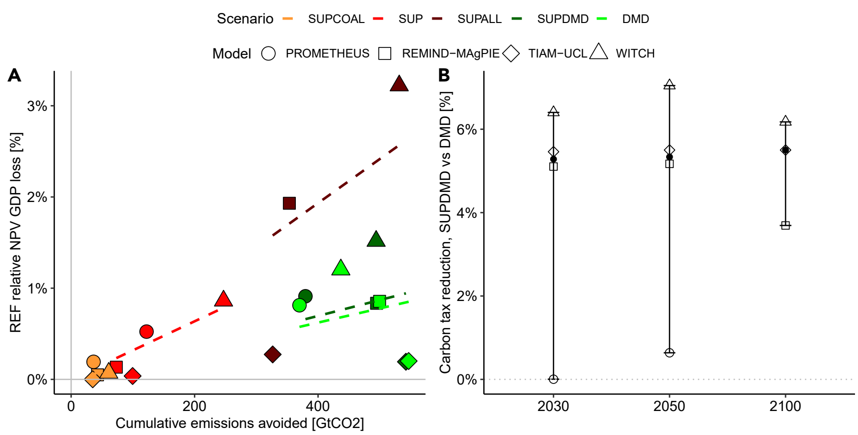


Figure 5. Policy costs and carbon price

(A) Total net present cost of policy from 2020 to 2050 as % of NPV GDP discounted at 3%, against emissions abated or removed from 2020 to 2050 relative to the Reference scenario. Tendency lines are highlighted for each scenario.
(B) Carbon tax reduction in SUPDMD versus DMD. White dots represent model values, whereas black dots identify the model median.

if more carbon intensive fossil fuels are banned earlier in our scenario design. These last two factors are magnified by the fact that we compare the extraction bans with idealized, first-best carbon pricing. A "real-word" set of demand-side policies would be characterized by a potentially inefficient mix of sectorial carbon pricing, subsidies, and moratoria, reducing or nullifying the greater cost-effectiveness shown here for demand side policies. The first argument, however, remains valid because CCS and NETs are, by nature, demand side solutions.

The two scenarios reaching well below 2°C achieve large emission reduction until 2050 at a median cost of around 1% of GDP. Combining supply and demand action provides consistent improvements in decarbonizing the energy system and meeting the Paris goals, whereas introducing a small amount of additional costs for the society. The supply side policy interacts with carbon pricing by carrying a part of the shadow cost of the energy transition. As a result (Figure 5B), the optimal carbon price to reach the target budget is reduced by 6.2% in 2050 and 5.9% in 2100 (model median, *SUPDMD* versus *DMD*), which may increase the socio-political acceptability of ambitious climate policy.

Global deaths from air pollution decrease in the more aggressive supply side scenario (SUPALL) by almost 700.000 people per year against 450,000 people per year because of demand side policies (DMD, relative to the reference, see SI Additional Results D: Air pollution). Even when combined with carbon pricing, extraction bans produce relevant air pollution co-benefits in 2050, with more than 133,000 extra avoided premature deaths because of outdoor air pollution when supply policies are also present relative to demand policies alone (SUPDMD versus DMD). Most of the avoided premature deaths happen in China and India (approximately 98,000), but also Europe avoids 3,200 and 3,900 premature deaths in 2030 and 2050 respectively. This happens because oil and gas demand reductions are anticipated, and emissions from oil extraction are substantially cut, especially in developing countries. Although not explicitly estimated, lower costs from reduced air pollution damages could counterbalance the higher GDP loss seen in scenarios with supply side policies.

DISCUSSION

We have shown that a global phase-out of all fossil fuel production can lead to emission reductions consistent with 2°C but only until mid-century. Banning only coal proves cheap but largely ineffective in increasing the level of climate ambition relative to current pledges, in part because of a significant substitution effect to the other fossil fuels. After mid-century, fossil bans (even if implemented globally) do not provide the necessary incentives to phase-in CCS and negative emission technologies necessary to reach PA's temperature goals.

Integrating supply side and demand side policies such as a carbon tax produces synergies for the energy system decarbonization strategies: Adding fossil fuel bans to the policy mix reduce the early reliance on uncertain and currently immature technologies at an additional marginal cost for the economy, decrease the required carbon tax, increase revenues for fossil fuel producers, and improve air quality compared to demand side policies. Deeper emission cuts are reached with conventional and mature abatement measures such as energy efficiency, electrification of end uses, and substitution of fossil fuels with renewable energy.

Unlike carbon pricing, coalitions of countries banning fossil extraction can stimulate emission reductions outside the coalition, but we find that this holds true only if the coalition contains a large enough share of the global hydrocarbon supply. The stronger the demand-side policies implemented alongside extraction bans, the larger the coalition must be to affect global fossil fuel prices because of the lower demand for fossil fuels. Otherwise, limiting hydrocarbon production may not have meaningful effects on energy prices and demand, which limits the effectiveness of unilateral supply-side action from small producers and calls for an international agreement. This reinforces the importance of multilateral international initiatives like Fossil Fuel Non-Proliferation Treaty Initiative,[35] the Beyond Oil and Gas Alliance, and the Coal elimination treaty,[36] but highlights that their effectiveness will depend on the share of fossil production suppliers they include. Further analysis is needed to assess minimum effective coalition size and quantify positive spill-over effects.

The increase in international fossil fuel prices provides producers with sustained revenues from the sale of hydrocarbons counterbalancing the reduction in volume exchanged, especially in scenarios with weak demand side policies and strong supply side policies. Therefore, although traditionally opposed to climate policy, introducing production quotas in the policy mix could reduce fossil fuel producers' resistance to climate policy. Moreover, governments could benefit from retaining at least part of budget entries from royalties and taxation of hydrocarbons' production, which most fossil fuel producing countries are highly dependent on.

In our scenarios, we find supply side instruments to be an overall more costly and less effective substitute of demand side policies as the main policy instrument to reach 2°C. Instead, *complementing* carbon pricing with supply side policies leads to synergies and climate policy benefits which could be exploited by policy makers toward establishing a cost-efficient and socially acceptable climate policy mix, although the regional incentives to support different climate policies have not been explored in this analysis. Nonetheless, our results support the call for a joint implementation of carbon pricing and fossil extraction bans in a wide multilateral, international framework aimed at meeting the PA goals.

Limitations of the study

In this analysis, we did not model endogenously the strategic interaction that would occur in negotiating and abiding international restriction of fossil fuel production. Furthermore, we assume that once the countries enter the agreement they follow exactly the agreed reduction in fossil fuel production and the global carbon pricing scheme, therefore not considering incentives to defect.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
  - Lead contact
  - Materials availability
  - Data and code availability
- METHOD DETAILS
  - Narrative design

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.106377.

ACKNOWLEDGMENTS

This research has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 730403 (INNOPATHS), No 821124 (NAVIGATE), No 101003866 (NDC ASPECTS) for E3M.

AUTHOR CONTRIBUTIONS

L.A.R., L.D., and M.T. designed the research; P.A., O.D., L.D., P.F., R.P., S.P., L.A.R., and R.R. elaborated the modeling protocol; P.A., O.D., L.D., P.F., R.P., S.P., L.A.R., and R.R. produced the scenario IAM results; P.A. and L.A.R. post-processed the data and performed the data analysis; P.A. and L.A.R. wrote the paper draft; P.A., M.T., P.F., R.P., and S.P. finalized the manuscript. All authors reviewed and approved the manuscript.

DECLARATION OF INTERESTS

The authors have no conflict of interest to declare.

Received: April 22, 2022
Revised: December 7, 2022
Accepted: March 6, 2023
Published: March 11, 2023

REFERENCES

1. Le Quéré, C., Andrew, R.M., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., Pickers, P.A., Korsbakken, J.I., Peters, G.P., Canadell, J.G., et al. (2018). Global carbon budget 2018. Earth Syst. Sci. Data *10*, 2141–2194. https://doi.org/10.5194/essd-10-2141-2018.

2. IPCC (2018). Summary for policymakers. In Global Warming of 1.5C. IPCC SR1.5C (World Meteorological Organization).

3. P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, and R. Fradera, et al., eds. (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press).

4. IEA (2021). Net Zero by 2050. (IEA).

5. IEA (2022). World Energy Investment 2022. (IEA).

6. Roelfsema, M., van Soest, H.L., Harmsen, M., van Vuuren, D.P., Bertram, C., den Elzen, M., Höhne, N., Iacobuta, G., Krey, V., Kriegler, E., et al. (2020). Taking stock of national climate policies to evaluate implementation of the Paris Agreement. Nat. Commun. *11*, 2096. https://doi.org/10.1038/s41467-020-1541CC4-6.

7. Lazarus, M., and van Asselt, H. (2018). Fossil fuel supply and climate policy: exploring the road less taken. Clim. Change *150*, 1–13. https://doi.org/10.1007/s10584-018-2266-3.

8. Hardin, G. (1968). The tragedy of the commons. Science *162*, 1243–1248. https://doi.org/10.1126/science.162.3859.1243.

9. van Soest, H.L., Lara, A.R., Bernardo Baptista, L., Bertram, C., Jacques, D., Douet, L., den Elzen, M., Fragkos, P., Fricko, O., Fujimori, S., et al. (2021). Global roll-out of comprehensive policy measures may aid in bridging emissions gap. Nat. Commun. https://doi.org/10.1038/s41467-021-26595-z.

10. IPCC (2022). Summary for policymakers. In Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, P.R. Shukla, J. Skea, R. Slade, A.A. Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, and R. Fradera, et al., eds. (Cambridge University Press). https://doi.org/10.1017/9781009157926.001.

11. Asheim, G.B., Fæhn, T., Nyborg, K., Greaker, M., Hagem, C., Harstad, B., Hoel, M.O., Lund, D., and Rosendahl, K.E. (2019). The case for a supply-side climate treaty. Science *365*, 325–327. https://doi.org/10.1126/science.aax5011.

12. Paroussos, L., Fragkos, P., Capros, P., and Fragkiadakis, K. (2015). Assessment of carbon leakage through the industry channel: the EU perspective. Technol. Forecast. Soc. Change *90*, 204–219. https://doi.org/10.1016/j.techfore.2014.02.011.

13. Sinn, H.W. (2008). The Green Paradox.

14. Bauer, N., McGlade, C., Hilaire, J., and Ekins, P. (2018). Divestment prevails over the green paradox when anticipating strong future climate policies. Nat. Clim. Chang. *8*, 130–134. https://doi.org/10.1038/s41558-017-0053-1.

15. Fragkos, P., Fragkiadakis, K., Sovacool, B., Paroussos, L., Vrontisi, Z., and Charalampidis, I. (2021). Equity implications of climate policy: assessing the social and distributional impacts of emission reduction targets in the European Union. Energy *237*, 121591. https://doi.org/10.1016/j.energy.2021.121591.

16. Steckel, J.C., Dorband, I.I., Montrone, L., Ward, H., Missbach, L., Hafner, F., Jakob, M., and Renner, S. (2021). Distributional impacts of carbon pricing in developing Asia. Nat. Sustain. *4*, 1005–1014. https://doi.org/10.1038/s41893-021-00758-8.

17. Ohlendorf, N., Jakob, M., Minx, J.C., Schröder, C., and Steckel, J.C. (2020). Distributional impacts of carbon pricing: ameta-analysis. Environ. Resour. Econ. *78*, 1–42. https://doi.org/10.1007/s10640-020-00521-1.

18. Harstad, B. (2012). Buy coal! A case for supply-side environmental policy. J. Polit. Econ. *120*, 77–115. https://doi.org/10.1086/665405.

19. Erickson, P., Lazarus, M., and Piggot, G. (2018). Limiting fossil fuel production as the next big step in climate policy. Nat. Clim. Chang. *8*, 1037–1043. https://doi.org/10.1038/s41558-018-0337-0.

20. Green, F., and Denniss, R. (2018). Cutting with both arms of the scissors: the economic and political case for restrictive supply-side climate policies. Clim. Change *150*, 73–87. https://doi.org/10.1007/s10584-018-2162-x.

21. van Asselt, H., and Newell, P. (2022). Pathways to an international agreement to leave fossil fuels in the ground. Glob. Environ. Polit. *22*, 28–47. https://doi.org/10.1162/glep_a_00674.

22. Piggot, G., Erickson, P., van Asselt, H., and Lazarus, M. (2018). Swimming upstream: addressing fossil fuel supply under the UNFCCC. Clim. Policy *18*, 1189–1202. https://doi.org/10.1080/14693062.2018.1494535.

23. Hoel, M. (1994). Efficient climate policy in the presence of free riders. J. Environ. Econ. Manage. *27*, 259–274. https://doi.org/10.1006/jeem.1994.1038.

24. Hagem, C., and Storrøsten, H.B. (2019). Supply- versus demand-side policies in the presence of carbon leakage and the green paradox. Scand. J. Econ. *121*, 379–406. https://doi.org/10.1111/sjoe.12277.

25. Jewell, J., McCollum, D., Emmerling, J., Bertram, C., Gernaat, D.E.H., Krey, V., Paroussos, L., Berger, L., Fragkiadakis, K., Keppo, I., et al. (2018). Limited emission reductions from fuel subsidy removal except in energy-exporting regions. Nature *554*, 229–233. https://doi.org/10.1038/nature25467.

26. Pye, S., Bradley, S., Hughes, N., Price, J., Welsby, D., and Ekins, P. (2020). An equitable redistribution of unburnable carbon. Nat. Commun. *11*, 3968. https://doi.org/10.1038/s41467-020-17679-3.

27. McGlade, C., and Ekins, P. (2015). The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. Nature *517*, 187–190. https://doi.org/10.1038/nature14016.

28. Welsby, D., Price, J., Pye, S., and Ekins, P. (2021). Unextractable fossil fuels in a 1.5 °C world. Nature *597*, 230–234. https://doi.org/10.1038/s41586-021-03821-8.

29. UNEP, E3G, IISD, ODI, SEI (2021). The Production Gap Report 2021 (UNEP).

30. Lamperti, F., Napoletano, M., and Roventini, A. (2020). Green transitions and the prevention of environmental disasters: market-based vs. Command-and-control policies. Macroecon. Dyn. *24*, 1861–1880. https://doi.org/10.1017/S1365100518001001.

31. IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

32. Rogelj, J., Popp, A., Calvin, K.V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., et al. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °c. Nat. Clim. Chang. *8*, 325–332. https://doi.org/10.1038/s41558-018-0091-3.

33. Clarke, L., Wei, Y.M., Navarro, A.D.L., Garg, A., Hahmann, A.N., Khennas, S., Azevedo, I.M.L., Löschel, A., Singh, A.K., Steg, L., et al. (2022). Energy systems. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, P.R. Shukla, J. Skea, R. Slade, A.A. Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, and R. Fradera, et al., eds. (Cambridge University Press). https://doi.org/10.1017/9781009157926.008.

34. Drouet, L., Bosetti, V., Padoan, S.A., Aleluia Reis, L., Bertram, C., Dalla Longa, F., Després, J., Emmerling, J., Fosse, F., Fragkiadakis, K., et al. (2021). Net zero emission pathways reduce the physical and economic risks of climate change. Nat. Clim. Chang. *11*, 1070–1076. https://doi.org/10.1038/s41558-021-01218-z.

35. Newell, P., and Simms, A. (2020). Towards a fossil fuel non-proliferation treaty. Clim. Policy *20*, 1043–1054. https://doi.org/10.1080/14693062.2019.1636759.

36. Burke, A., and Fishel, S. (2020). A coal elimination treaty 2030: fast tracking climate change mitigation. Earth System Governance *3*, 100046. https://doi.org/10.1016/j.esg.2020.100046.

37. Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Change *42*, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

38. McCollum, D.L., Zhou, W., Bertram, C., de Boer, H.S., Bosetti, V., Busch, S., Després, J., Drouet, L., Emmerling, J., Fay, M., et al. (2018). Energy investment needs for fulfilling the Paris agreement and achieving the sustainable development goals. Nat. Energy *3*, 589–599. https://doi.org/10.1038/s41560-018-0179-z.

39. BP (2019). Energy Outlook 2019 (BP).

40. IEA (2015). World Energy Outlook 2015 (IEA).

41. Paroussos, L., Mandel, A., Fragkiadakis, K., Fragkos, P., Hinkel, J., and Vrontisi, Z. (2019). Climate clubs and the macro-economic benefits of international cooperation on climate policy. Nat. Clim. Chang. *9*, 542–546. https://doi.org/10.1038/s41558-019-0501-1.

42. Burke, M., Hsiang, S.M., and Miguel, E. (2015). Global non-linear effect of temperature on economic production. Nature *527*, 235–239. https://doi.org/10.1038/nature15725.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
GAMS	https://www.gams.com/	
R	https://www.r-project.org/	
Microsoft Office	https://www.office.com/	
WITCH model	https://github.com/witch-team/witchmodel	
PROMETHEUS model	https://e3modelling.com/modelling-tools/prometheus/	
TIAM-UCL model	https://www.ucl.ac.uk/energy-models/models/tiam-ucl	
REMIND model	https://github.com/remindmodel/remind	

RESOURCE AVAILABILITY

Lead contact

Further information and request for resources should be directed to the lead contact, Pietro Andreoni (pietro.andreoni@eiee.org).

Materials availability

We used the WITCH, REMIND, TIAM-UCL and PROMETHEUS integrated assessment models to run the scenarios. A referenced description of the models used in the analysis is available in the supplementary information. A version of the WITCH and the REMIND models are available open source at https://github.com/remindmodel/remind and https://github.com/witch-team/witchmodel.

Data and code availability

- The datasets for the scenarios generated in this study are available from the lead contact at reasonable request.
- This paper does not report original code.

METHOD DETAILS

We have designed six scenarios (Figure 1(B)). First, we defined a counterfactual scenario (REF) that reflects current established and planned policies, including the NDCs (as submitted in 2015).[9] The reference scenario is based on the socio-economic assumptions of SSP2 (middle-of-the-road scenario).[37]

The period post-NDC (after 2030) is modeled extrapolating the "equivalent" carbon price in 2030 and projecting its growth with the GDP growth rate of the regions. The equivalent carbon price represents the value of carbon that would yield in a region the same emissions reduction effort as the NDC policies beyond 2030. In regions with implicit NDC carbon price of zero in 2030, we assume a minimum carbon price of 1 $/tCO_2$ in 2030. For land use, a carbon price ceiling of 200 $/tCO_2$ is applied.

Then, we build supply-side narratives where the production of coal, oil and gas is cut, starting from different enforcement years (scenario SUP), up to at least 70% of 2020 production level after 20 years (the resulting primary energy levels are shown in the table below for the WITCH model, and in SI "Production cuts implementation" is described the implementation strategy for each model).

	Coal	Gas	Oil
2020 level [EJ]	150	137	195
full ban level [EJ]	45	41.1	58.5
reduction in 2050, REF relative [%]	58.1	75.3	74.8

The residual production takes into account the challenges to fully phase out fossil fuels in hard-to-decarbonize sectors (e.g. heavy industry, aviation, maritime) and the difficulties of countries and private companies (that own fossil resources and reserves) to completely shut down their resource extraction industries. We use a systematic approach to design a realistic and policy relevant narrative according to each region position in energy trade, reserves and resources, fossil fuel dependency and climate policy commitment. While we are aware that supply-side narratives may be hard to enforce given the status-quo, we keep a realistic approach based on qualitative and quantitative information that can help us hypothesize how such policies would unfold. The world regions are classified into ''front-runners'', ''followers'' and ''Laggards'', defining the speed at which the region will enforce the production cuts (Figure 1).

Recognizing that some fossil fuels are more difficult to ban (oil) and more important for the energy transition (gas) than others (coal), the timing for the phase-out varies with the fuel: *laggards* for coal finish banning in 2055, while the extraction ban for oil completely enters into force in 2060 and in 2065 for gas.

To analyze the effects of different regional timings in the production cuts and to analyze how far supply-side policies can go if action is uniform and coordinated, we model a supply-side policy scenario where all the regions are *frontrunners*. Furthermore, we design a SUPCOAL scenario in which only coal is phased out following the same narrative as in SUP.

Finally, we combine the supply-side narrative with a demand-side policy in line with the Paris Agreement target of well below 2°C, applying a carbon budget of 1000 $GtCO_2$ from 2011 to 2100 in line with Mc Collum et al. (2018).[38] In carbon budget scenarios, carbon prices are not prescribed but calculated endogenously by each model to provide the least-cost pathway compliant with the climate target.

Narrative design

To design the Narrative for the SUP scenario, participating regions were categorized by the dimensions described in the table below.

DIMENSIONS	RATIONALE	INDICATOR	SOURCE
Substitution effect between fuels	Countries with high exporting potential for one fuel may agree to ban others fuel to exploit substitution effect and consequent high prices	% of trade volume with respect to internal consumption	BP, 2019[39]
Proven reserves and their extraction cost	Countries will tend to oppose ban the more reserves they have and the lower their average cost of extraction is	Cost of Barrel of oil and proven reserves	BP, 2019, IEA, 2015[39,40]
Trade position	Big exporters and big importers (to mitigate their energy dependency) will oppose a ban, while internal consumption countries will have no bias	% of trade volume with respect to internal consumption	BP, 2019[39]
Current commitment	Countries with higher present commitment are assumed to retain interest to climate policy in the future	NDC pledges strenght	Paroussos et al., 2019[41]
Impacts	Countries with higher expected impacts have more reasons to mitigate	Climate change damage estimates from empirical literature	Burke, 2015[42]
Air pollution	Countries with Air pollution problems may be more favourable to coal bans	Expert assessment	–
Fossil fuel dependency	Countries with higher share of fossil fuels in the primary energy supply will have more difficulties in mitigating	Fossil share of TPES	IEA, 2015[40]
Economic position	Richer countries will have less problem mitigate	GDP per capita	World bank
Clean energy position	Exporters of renewables components/tech leader will find incentives to aggressive mitigation	Expert assessment	–

According to the rationale explained in the same table, each of these dimensions favors or hinders the participation to the supply international agreement. Each dimension was parametrized by a numerical indicator that served as a starting point to assign a total score to each region/country, measuring the estimated propensity to join the coalition for each fuel. According to this aggregate indicator, countries were assigned to followers, frontrunners, or laggards (see SI "Production cuts implementation").

Countries and regions analyzed were chosen because they are relevant as producers of at least one fossil fuel, large energy consumers, or because they hold large hydrocarbon reserves and resources.

Regional disaggregation of the models, however, differs from the regions identified as well as among each other. The countries analyzed were thus translated into the model regions as closely as possible by each team. All results are then reaggregated to the 17 regions of the WITCH model using GDP weighting, to provide a coherent aggregation.

		2020		2050		2100	
		Demand	Supply	Demand	Supply	Demand	Supply
Frontrunners	Oil	20.4	7.8	13.4	9.6	6.4	3.8
	Gas	11.3	5.9	8.1	3.9	1.8	3.9
	Coal	24.2	17.4	8.5	23.4	8.5	29.8
Followers	Oil	21.7	14.7	22.7	18.1	22	27.2
	Gas	16.2	11	18.1	12.6	21.6	11.4
	Coal	28.4	34.5	38.2	35.8	52.3	31.6
Laggards	Oil	57.7	77.3	63.7	72.1	71.4	68.9
	Gas	72.4	83	73.7	83.4	76.5	84.6
	Coal	47.3	47.9	53.1	40.6	39	38.4

This table shows the share of total demand and supply for each fossil fuel, distributed among the narrative groups, relative to the reference scenario.

For oil and gas, frontrunners account for 7.8% and 5.9% of total production respectively, and followers for 14.7% and 11.0% of total production in 2020. Laggards thus represent most of the oil and gas producers, as well as the largest portion of total demand.

For coal, on the other hand, *laggards* account for 47.9% of total 2020 production and a similar share of total demand. *Frontrunners* and *followers* are thus a more important coalition for coal with respect to the other fossil fuels. A major reason for this is the US, which is modeled as a *frontrunner* for Coal, given that both consumption and production are historically declining, but a *laggard* for oil and gas, because of the shale revolution and the renewed role of the United States as a major oil and gas producer as well as a key consumer. This reflects the reality that coal is a less powerful industry than oil and gas and the political feasibility of banning it may be higher than the other two fossils.