Fossil-extraction bans are not enough to achieve the Paris agreement but can facilitate it

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Fossil-extraction bans are not enough to achieve the Paris agreement but can facilitate it

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Abstract

Given concerns about the ambition and effectiveness of current climate pledges, a case has been made for the integration 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. Here, we present the first multi-model assessment quantifying the effectiveness of supply-side policies and their interactions with demand-side ones. We design narratives of fossil fuel bans and explore a variety of scenarios with four process-based integrated assessment models. We find that supply side treaties reduce emissions but not enough to stabilize temperature increase to well below 2°C. When combined with demand-side policies, supply side policies reduce the required carbon price to meet the Paris goals, dampen reliance on CO_2 removal and increase investment in renewable energy while increasing fossil producer revenues. The results indicate the opportunity to integrate price-based policies with fossil bans when exploring climate neutrality pathways.

Despite the recent success of the Paris Agreement (PA) in terms of global participation, Greenhouse Gases (GHG) emissions continue to grow[1] and ambitious climate action is becoming increasingly urgent as the remaining carbon budget to achieve the well below 2°C target is fast depleting[2]. Policy instruments put into place to reduce emissions have so far proven insufficiently effective[3] and investments in fossil fuels (oil and gas) continue to grow[4]. The International Energy Agency report on "Net Zero by 2050" recommends the immediate end of investments in new extraction fields and fossil power plants[5] to meet the PA goals. The IEA study, alongside most climate stabilization evaluations by integrated assessment models, achieves ambitious climate goals via demand-side policies such as carbon pricing.

However, several scholars have remarked that international demand-side policies might be insufficient[6] and have argued for a supply-side treaty[7–10] to complement demand-side policy in ambitious mitigation scenarios.

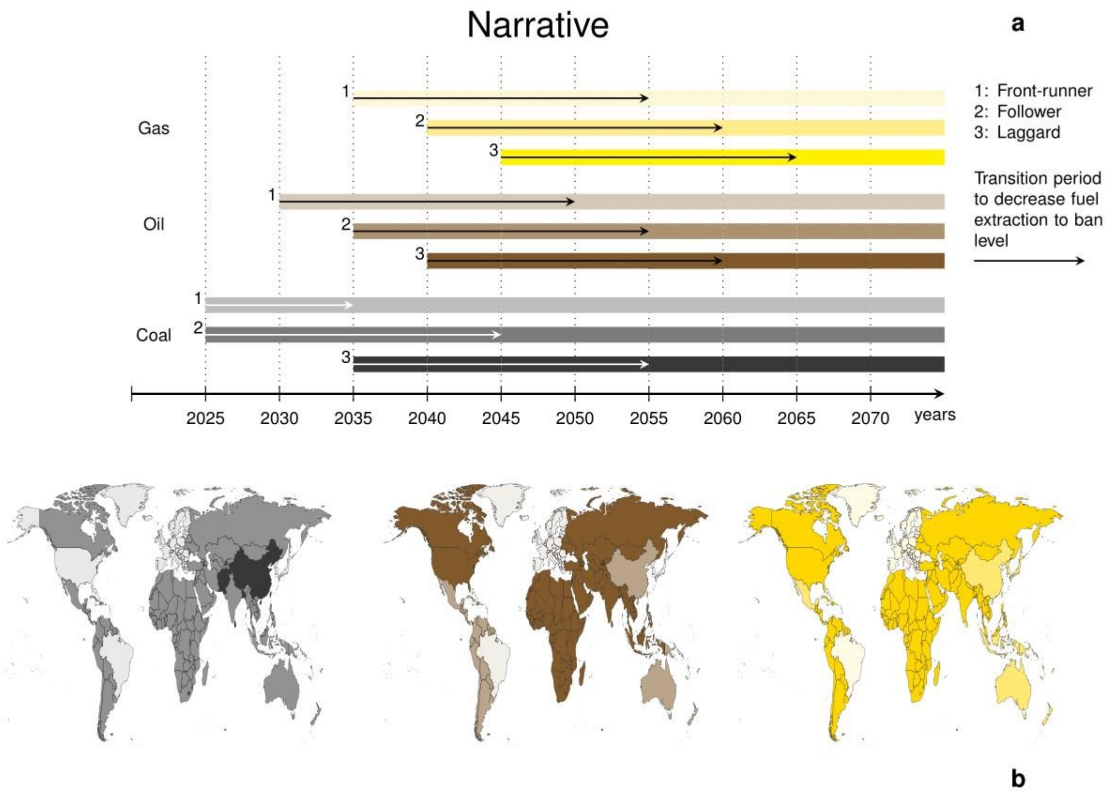
Unlike carbon pricing, targeting directly fossil fuel extraction via production quotas can increase the international market price of fossil fuels by forcefully reducing their supply. As a result, they can attenuate free-riding, avoid anticipation of investments in the fossil fuel upstream sector, reduce future stranded assets, and foster green R&D[10]. Furthermore, supply-side measures provide a back-up for possible demand-side policy failures while being disposable if demand side policies are effective. Finally, increasing fossil fuel prices favors energy-exporting countries, which so far have largely opposed international mitigation efforts. These arguments support the view that the Paris Agreement can provide an opportunity to explore the fossil fuel supply-side and that UNFCCC should foster the phase-out of both fossil fuel production and consumption[11].

Here we use established integrated assessment models to explore the efficiency and effectiveness of supply-side policies in the form of extraction bans for fossil fuels. Previous work has explored the effect of fossil fuel subsidies removal[12], placed production-based taxes on production[13], quantified the amount of unburnable fossil fuels under Paris aligned targets[14–16], and explored supply-side policies in a neo-Keynesian framework[17]. To our knowledge, this is the first multi-model attempt to explore the economic, energy system and environmental implications of comprehensive extraction bans, complementing the theoretical literature with quantitative modelling evidence.

We used four 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[2,18]. As they differ in underlying modelling frameworks and assumptions as well as in the representation of the economy and the energy system, the joint assessment provides robustness to our results.

We designed a series of scenarios (Figure 1 *(b)*) to assess the effects of hydrocarbon extraction bans on emissions and the energy system, both alone and coupled with demand-side policies (in the form of carbon pricing). We model supply-side policies as a forced reduction of fossil fuel extraction by up to 70% of 2020 production for all fossil fuels, a value that was found to be near the maximum feasible ban level that all models could achieve. Given that the design allows for a modest residual production, it depicts scenarios in which governments are unwilling or unable to completely shut down their hydrocarbon extraction industries.

Results show that, while banning only coal is largely insufficient to deviate from NDCs trajectory, extraction bans for all fossil fuels substantially reduce emissions if large producers participate in the treaty. However, they can reach Paris consistent targets at a competitive cost only if coupled with carbon pricing, as the combination of demand and supply-side policies produces synergies in policy implementation and effectiveness.



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: (a) Narrative distribution for different fuels. For each fossil fuel, darker shades of the color identify groups that enter later the treaty. The beginning of the colored line identifies the year in which each group starts limiting production of the fossil fuel, while 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.

Emission pathways and carbon budgets

We begin by exploring the emission and climate consequences of the scenarios (Figure 2). The 2°C scenarios imply a sharp reduction of global emissions in the first half of the century, reaching net-zero between 2060 and 2075, depending on the model. These results are consistent with previous assessments[2,19].

Banning only coal extraction decreases cumulative emissions to 2100 by 2.6%-9.4% (model range) over the reference scenario. On the one hand, this is due to a rebound effect (see Figure 3) on unbanned fossil fuels. On the other hand, the reference scenario already implies a gradual phase-out of coal due to the NDC effort extrapolation to 2100. Moreover, the extraction ban design allows for 30% of residual hydrocarbon production, a level aligned with long-term projections for the Reference scenario.

Supply-side scenarios that limit production of all fossil fuels tend to bridge the current level of effort with the emission pathways of a 2°C, reducing global CO_2 emissions in 2050 by up to 59%.

When all suppliers join the treaty at the same time the emission range overlaps with the well below 2°C emission pathways range up to 2045, suggesting that a strong commitment from all suppliers could drive emissions to an optimal decarbonization pathway towards PA goals in the first part of the century, but not after that. In fact, both supply policy scenarios reach similar emission levels by the end of the century of around 12 Gt CO_2, a level consistent with the residual production of fossil fuels allowed by these scenarios, while carbon tax-based scenarios reach net-zero emissions. Long-term emissions are higher in supply-side scenarios even though in terms of electrification, renewables penetration, fossil phase-out, and energy efficiency improvements extraction bans outperform carbon pricing (see *Additional results A*). This is because extraction bans do not foster Carbon Capture and Storage (CCS), Biomass with Carbon Capture and Storage (BECCS) and other Negative Emissions Technologies (NET) needed to offset the residual CO_2 emissions from industrial processes and other hard-to-abate sectors, as well as land use and non-CO_2 emissions from agriculture and other sources. Therefore, while an extreme policy with 100% cuts to fossil fuel extraction would reduce emissions from fossil fuels to zero, net zero GHG emissions could still not be reached with supply-side policies alone.

The combination of carbon pricing and extraction bans anticipates decarbonization because the production constraint created by the extraction ban in the supply regions 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 (Figure 2 *(b)*), a desirable feature both because these technologies are currently expensive and unavailable at scale and because lower budget overshoot reduces climate risk[20].

This is especially visible for the WITCH model (11% reduction of carbon sequestered by Biomass with Carbon Capture and Storage, 36% reduction of carbon avoided by fossil CCS, 96% reduction of carbon sequestered by Direct Air Capture, cumulative values to 2100) which relies more in negative emissions, but holds true also for TIAM-UCL (3% reduction in carbon sequestered by BECCS and 6% reduction of carbon avoided by fossil CCS), REMIND (35% reduction of carbon sequestered by DAC, 35% reduction of carbon avoided by fossil CCS and 2.5% reduction of carbon sequestered by BECCS), and PROMETHEUS (9% reduction of Fossil CCS and 18% reduction of BECCS in 2050).

Lower reliance on CCS and NETs implies an increase in renewable penetration, electrification, energy efficiency improvement and lower investments on fossil fuel power plants and upstream sector with respect to a demand-side only scenario (see *Additional results A*).

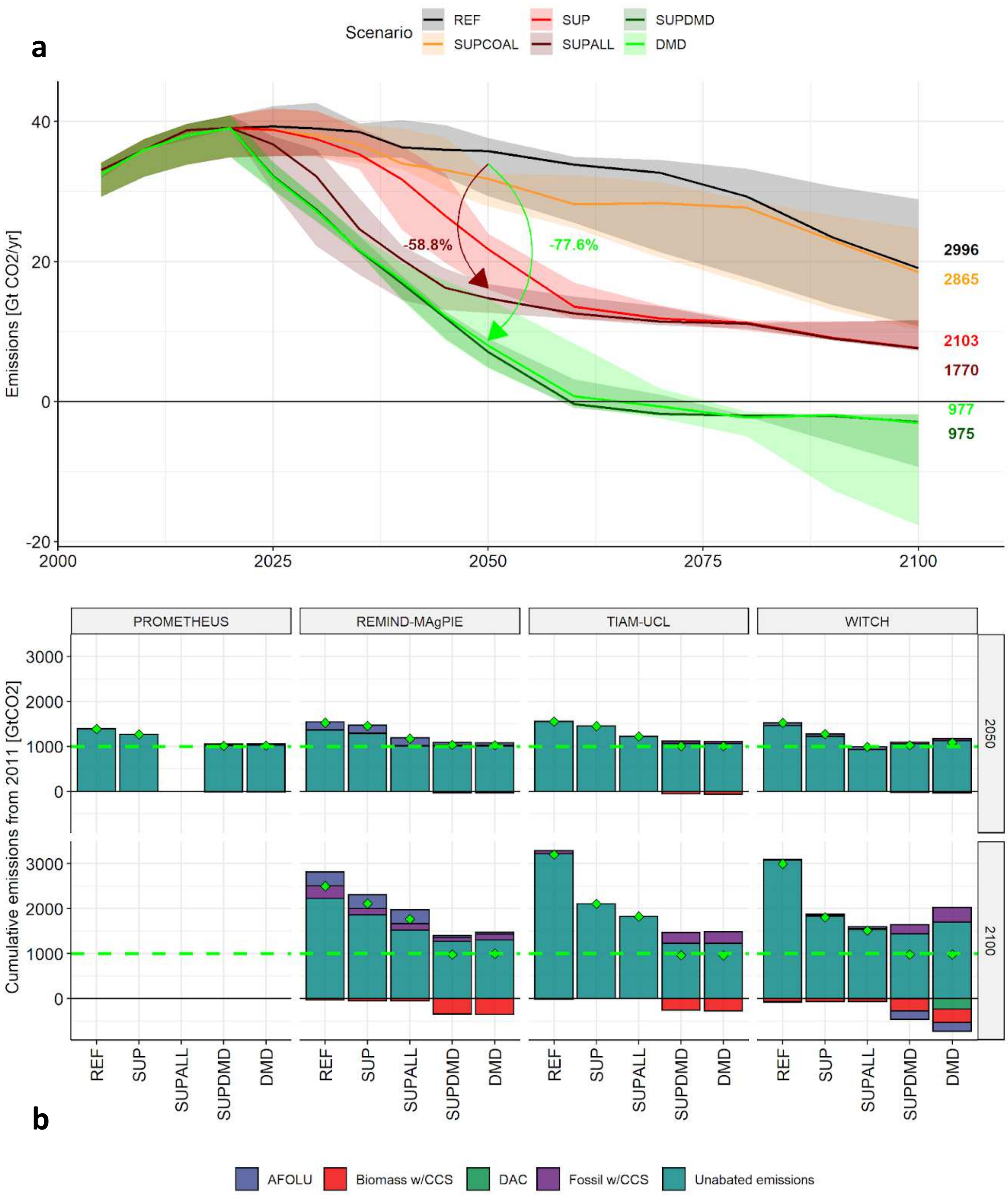


Figure 2: (a) Global emissions by scenario. Range and median of model ensemble. Carbon budgets are shown for each scenario. (b) cumulative emissions (sources and sinks) in 2050 and 2100. Green line represents 1000 $GtCO_2$ carbon budget, green dots identify the net budget (sources-sinks). PROMETHEUS model runs until 2050.

Prices, trade, and producer support

While both types of policies tend to decrease emissions, the underlying mechanism is different: carbon pricing affects the consumers price of carbon-intensive goods and fuels but depresses fossil fuel prices at the international market level, while an extraction ban produces fuel supply scarcity and increases the price of the fuel banned (Figure 3 *(a)*).

Uniformity of participation to the treaty governs the speed of the price increase, as can be seen by the substantial difference between the two supply side scenarios prices. In the narrative scenario the greatest impact for all fuels is seen when the *laggards*, that account for most low-cost producers, initiate their ban. Only a coalition representing a large enough share of global hydrocarbon production has a meaningful effect on prices: for coal, 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, while when *followers* join the treaty the price of gas increases by 12% in the following time step. A global participation in the supply treaty is necessary for oil prices to increase. The same effect is visible when demand and supply-side policies are implemented together. In this case, the price change can be compared to the price change in the demand-side scenario, on top of which the supply side treaty is implemented: prices increase only when all regions participate the bans.

The increase in prices clearly reduces the primary energy use of the fossil fuels (Figure 3 *(b)*).

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 another type of policy, 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 rebound effect accounts for 16% to 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 demand side scenario trajectories imply. For coal, the price increase generated when all-regions act as *frontrunners* align the supply levels with the Paris agreement compatible pathways up to 2035. After that, the primary energy consumption is bounded by the residual production allowed in the scenario design, while demand side policies can further reduce coal supply because carbon pricing puts a higher additional cost on coal, the most carbon intensive fossil fuel.

With extraction ban policies, trade patterns and hydrocarbon producer revenues are influenced by two opposing forces: higher fossil prices increase revenues per output, but shrinking demand reduces volume traded. Figure 3 *(c)* shows that the first effect dominates and produces a large increase of trade revenues if all regions are *frontrunners*, especially evident for coal (+143% of NPV value of global exports, model median), but relevant also for gas (56%) and oil (39%). In the narrative scenario, the effect is less evident because prices increase more slowly as countries join the treaty at different points in time, but still relevant for gas (+28%) and coal (+16%). If carbon pricing and extraction bans are implemented together, the net value of trade is in line with the carbon tax scenario. In any case, in international energy markets supply side policies show the opposite tendency of demand side policies, that tend to depress both prices and demand.

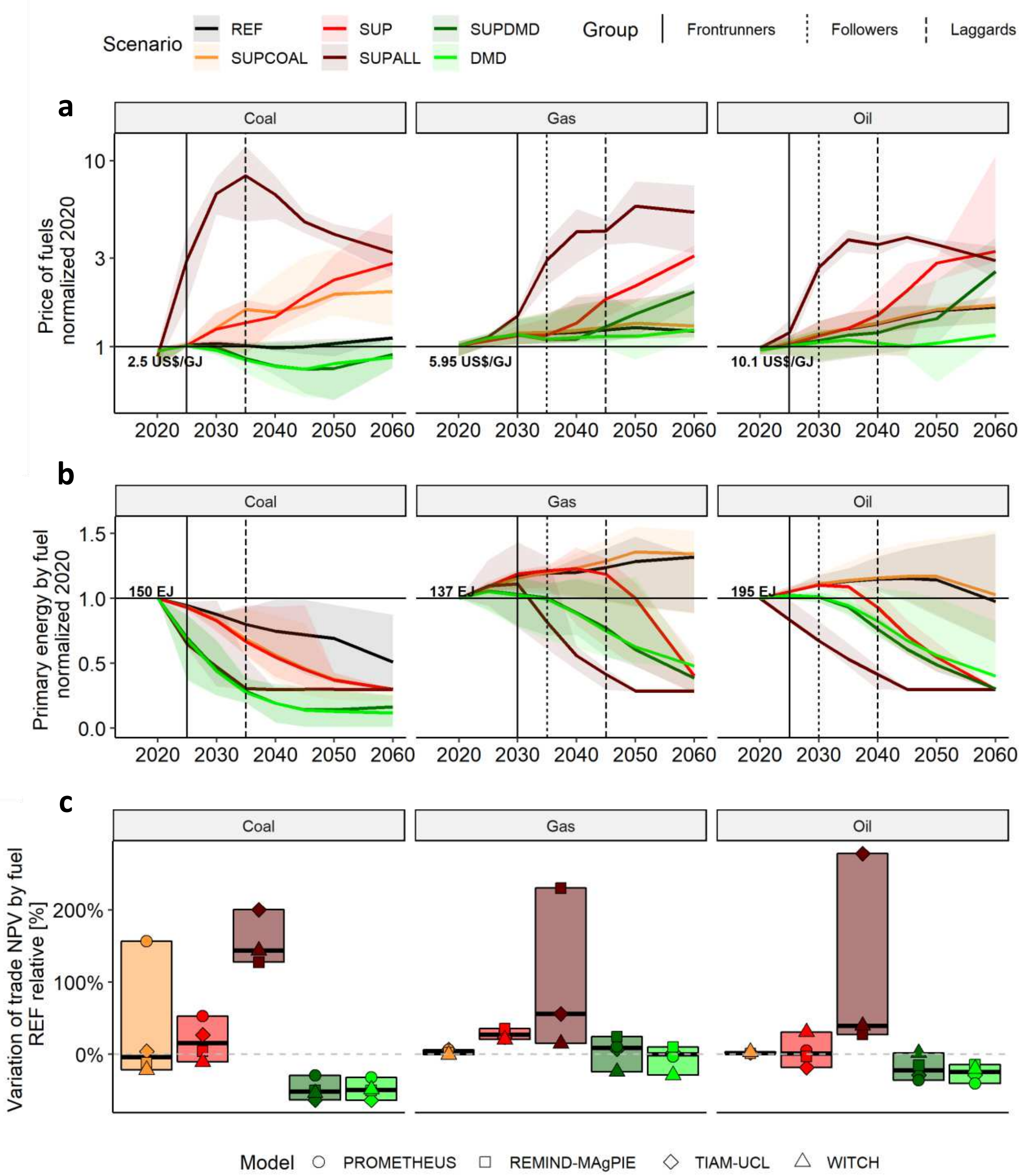


Figure 3: (a) International fuel market prices, without carbon tax, normalized to 2020 levels. Range and median of model ensemble. Vertical lines show the year when different supply region groups start banning the fuel in the narrative scenario. Semi-log scale.(b) shows primary energy by fuel relative to 2020. (c) Shows Net Present Value (discounted at 3%) between 2020 and 2050 of total value of exports, for all regions. REF relative.

Costs, carbon prices and co-benefits

In both the scenarios that implement a global carbon tax, the global carbon budget is constrained at 1000 $GTCO_2$ by 2100. If combined, the supply-side policy interacts with carbon pricing by carrying a part of the shadow cost of the energy transition. As a result (Figure 4 *(b)*), the optimal carbon price to reach the target budget is reduced by 6.2% in 2050 and 5.9% in 2100 (model median, *SUPDMD* vs *DMD*).

Figure 4 *(a)*, finally, shows the global cost of policy for the different scenarios. Demand side policies cost around 1% of global GDP, while the costs and effectiveness of supply side policy is highly dependent on timing: with a fragmented phase-out of fossil fuel production the median across models is 0.5% of GDP loss while if production bans are global and uniform the cost increase to 1.5% points of GDP, with neither scenario achieving Paris goals.

The higher cost of supply side scenario with early participation can be explained by three factors. As discussed, hydrocarbon extraction bans incentivize a narrower portfolio of mitigation options with respect to carbon pricing. Moreover, the prescribed linear reduction for fossil fuel bans does not follow a least-cost-option-first approach, introducing inefficiencies in the decarbonization process. Finally, the simultaneous ban of all fossil fuels provides a greater shock to the energy system sooner in time when the discount effect for the future is lower.

Banning only coal, while providing only incremental emission reductions over the Reference scenario, is very cheap over the century (0.05% GDP loss, model median).

Similarly, joining supply and demand action provides consistent improvements in decarbonizing the energy system and meeting the Paris goals, while at the same time introducing only a small amount of additional costs for the society (1.1% vs 1% of GDP loss when cost optimal DMD scenario is implemented).

Global deaths from air pollution decrease in the more aggressive supply side scenario by almost 700.000 people per year against 450.000 people per year due to demand-side policies (relative to the reference, see *Additional Results D: Air pollution*). While not explicitly estimated, lower costs from reduced air pollution damages could counterbalance the higher GDP loss seen in scenarios with supply side policies.

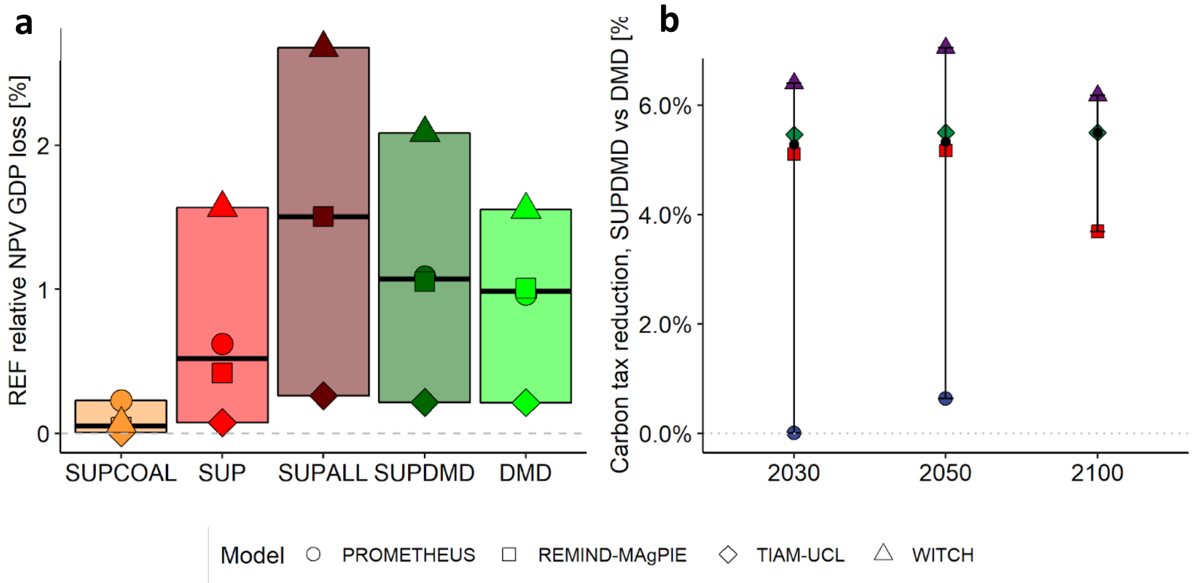


Figure 4: (a) Total net present cost of policy from 2020 to 2100 as % of NPV GDP, discounted at 3% (b) Carbon tax reduction in SUPDMD vs DMD. Colored dots represent model values, while black dots identify the model median.

Conclusions

We have shown that a global supply side treaty can improve current climate ambition and induce emission reductions, substituting carbon pricing up to 2050 in case of early and uniform participation. After mid-century, however, supply policies alone fail to phase-in CCS and NETs and reach stringent budgets compatible with Paris goals, and they are significantly less cost-effective than a carbon tax. This suggests that, if not backed by a carbon tax of similar ambition, limiting extraction of fossil fuels might not be an efficient solution to reach deep mitigation targets by the end of the century. Banning only coal proves cheap but largely ineffective in increasing the level of ambition relative to current NDCs and stated policies, in part due to a significant rebound effect to the other fossil fuels. Unlike carbon pricing, non-global coalitions applying extraction bans on fossil fuels can stimulate emission reductions outside the boundaries of the coalition but only if it contains a large enough portion of the global fuel supply. Otherwise, limiting hydrocarbon production may not have meaningful effects on energy prices and demand, which limits the effectiveness of unilateral supply-side action and calls for an international treaty. This reinforces the importance of multilateral initiatives like Fossil Fuel Non-Proliferation Treaty Initiative[21] and Beyond oil and gas alliance, provided 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 fossil fuel prices provides producing regions with sustained revenues from international hydrocarbon trade, counterbalancing reduction in the traded energy volumes. This could lead energy producing regions to root for this kind of policy rather than a carbon tax but could cause opposition from importing countries that would suffer from the increase in fossil fuel prices. However, the fact that both importing and exporting countries would, at least in the short term, benefit from exceeding their allowed production quotas poses a challenge to the stability of the treaty.

If supply-side policies are integrated with carbon tax, in a 2°C scenario the reliance on expensive, high-risk, and currently immature CCS and negative emission technologies and investments in fossil fuels are reduced at a marginal additional cost for the economy and with a lower carbon tax. These synergies between supply and demand-side policies should be exploited by policy makers towards establishing a cost-efficient and socially acceptable climate policy mix, without the need for excessive carbon pricing that may have depressive impacts for low-income households and vulnerable sectors[22].

Our results support the call for a joint implementation of carbon pricing and extraction bans in a wide multilateral framework towards a resilient pathway to meet the Paris Agreement goals.

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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 modelling 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. postprocessed the data and performed the data analysis; P.A. and L.A.R. wrote the paper draft; P.A., L.A.R., and M.T. finalized the manuscript. All authors reviewed the manuscript.

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SUPPLEMENTARY INFORMATIONS

Methods

We have designed six scenarios (Table 1). First, we defined a counterfactual scenario (REF) that reflects current established and planned policies, including the NDCs (as submitted by mid-2010)[23]. The reference scenario is based on the socio-economic assumptions of SSP2 (middle-of-the-road scenario)[24].

The period post-NDC (after 2030) is modelled extrapolating the "equivalent" carbon price in 2030, using 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 (*Table 2*).

Table 1: target level for different fuels.

	Coal	Gas	Oil
2020 level [EJ]	150	137	195
full ban level [EJ]	45	41.1 EJ	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 to completely shut down their resource extraction industries. We use a systematic approach to design this 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 analyse the effects of different regional timings in the production cuts, we analyse a supply-side policy scenario where all the regions are front runners. 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)[25]. 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.

Table 2: dimensions and rationale for narrative design

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)
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	(IEA,2015) (BP,2019)
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)
Current commitment	Countries with higher present commitment are assumed to retain interest to climate policy in the future	NDC pledges strenght	(Paroussos,2019)
Impacts	Countries with higher expected impacts have more reasons to mitigate	Climate change damage estimates from empirical literature	(Burke, 2015)
Air pollution	Countries with Air pollution problems may be more favourable to coal bans	Expert assessment	-
Economic position	Richer countries will have less problem mitigate	GDP per capita	World Bank, 2019
Clean energy position	Exporters of renewables components/tech leader will find incentives to aggressive mitigation	Expert assessment	-

Narrative design

To design the Narrative for the SUP scenario, participating regions were categorized by the dimensions described in Table 2. According to the rationale explained in the same table, each of these dimensions favors or hinders the participation to the supply treaty. 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 treaty for each fuel. According to this aggregate indicator, countries were assigned to followers, frontrunners, or laggards (see Table 3).

Table 3: Regional position for the narrative scenario.

Ban year (start 20 years before except for coal front runners which starts 10 years before	COAL			OIL			GAS		
	2035	2045	2055	2045	2050	2060	2050	2055	2065
Role:	Front-runner	Follower	Laggard	Front-runner	Follower	Laggard	Front-runner	Follower	Laggard
USA	x					x			x
CANADA		x				x			x
CHINA			x		x			x	
INDIA		x				x			x
BRASIL	x				x		x		
LACA		x			x			x	
MEXICO		x			x			x	
JAPAN		x		x				x	
KOREA	x			x				x	
INDONESIA		x			x			x	
SOUTH AFRICA			x			x			x
SSA			x			x			x
MENA		x				x			x
SAUDI ARABIA			x		x				x
TURKEY			x			x			x
RUSSIA		x				x			x
OCEANIA		x			x			x	
EU	x			x			x		
ROW		x				x			x

Countries and regions analyzed in Table 3 were chosen because they are relevant as producers of at least one fossil fuel, large energy consumers, or because they hold large hydrocarbon reserves. Regional disaggregation of the models, however, differs from that in Table 3 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 coherent plotting and figures.

Table 4 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.

Table 4: Shares of supply and demand among groups in REF scenario for the WITCH model, selected years

		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	22.0	27.2
	Gas	16.2	11.0	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	83.0	73.7	83.4	76.5	84.6
	Coal	47.3	47.9	53.1	40.6	39.0	38.4

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 modelled 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.

Model descriptions

WITCH

WITCH (World Induced Technical Change Hybrid, https://github.com/witch-team/witchmodel) is an integrated assessment model designed to assess climate change mitigation and adaptation policies. WITCH is maintained and developed at the RFF-CMCC European Institute on Economics and the Environment (EIEE). It was originally co-developed by Fondazione Eni Enrico Mattei and the Centro Euro-Mediterraneo sui Cambiamenti Climatici. For descriptions of previous model versions, please refer to (Bosetti et al. 2006)[26], (Bosetti, Massetti, and Tavoni 2007)[27] and (De Cian et al. 2009)[28].

WITCH consists of a dynamic global model that integrates in a unified framework the most important elements of climate change. The economy is modelled through an inter-temporal optimal growth model which captures the long-term economic growth dynamics. A compact representation of the energy sector is fully integrated (hard linked) with the rest of the economy so that energy investments and resources are chosen optimally, together with the other macroeconomic variables. Land use mitigation options are available through a soft link with a land use and forestry model (GLOBIOM). A climate model (MAGICC) is used to compute the future climate. Climate change impacts the economic output through a damage function, depending also on the rate of investments in adaptation. This allows accounting for the complete dynamic of climate change mitigation and adaptation.

WITCH represents the world in a set of representative native regions (or coalitions of regions); for each it generates optimal mitigation and adaptation strategies for the long term (from 2005 to 2100) as a response to either climate damage or some external constraints on emissions, concentrations or temperature. These strategies consist of investment profiles resulting from a maximization process in which the welfare of each region (or coalition of regions) is chosen strategically and simultaneously according to other regions. This makes it possible to capture regional free-riding behaviors and strategic interaction induced by the presence of global externalities. The non-cooperative, simultaneous, open membership game with full information, is implemented through an iterative algorithm which yields the open-loop Nash equilibrium. In this game-theoretic set-up, regional strategic actions interrelate through GHG emissions, dependence on exhaustible natural resources, trade of oil and carbon permits, and technological R&D spillovers.

The endogenous representation of R&D diffusion and innovation processes constitute a distinguishing feature of WITCH, allowing to describe how R&D investments in energy efficiency and carbon free technologies integrate the currently available mitigation options. The model features multiple externalities, both on the climate and the innovation side. The technology externalities are modelled via international spillovers of knowledge and experience across countries and time. In each country, the productivity of low carbon mitigation technologies and of energy depend on the region stock of energy R&D and by the global cumulative installed capacity, two proxies for knowledge and experience respectively. The R&D stock depends on domestic investments, domestic knowledge stock, and foreign knowledge stock through international spillovers. The spillover term depends on the interaction between the countries' absorptive capacity, and the distance of each region from the technology frontier. This formulation of technical change affects both decarbonization as well as energy savings.

The total primary energy supply of the different fuels is the sum of the consumption from all the sectors:

$$Q_f(t,n) = \sum_j Q_{j,f}(t,n)$$

The consumption of fuel *f* Q_f equals the total level of extraction by balancing domestic extraction and fuel imports X_f:

$$\sum_n Q_f(t,n) = \sum_n X_f(t,n)$$

If the country is a net exporter, X_f is negative. The net cost of the different fuels is equal to the cost of extracted fuels consumed fuels minus the cost of the (net-) imported fuels at the world market price $P_f(t)$

$$C_f(t,n) = MC_f(t,n) \times Q_f(t,n) - P_f(t) \times X_f(t,n)$$

The price of fossil fuels and exhaustible resources (oil, gas, coal and uranium) is determined by the marginal cost of extraction, which in turn depends on current and cumulative extraction. A regional mark-up is added to mimic different regional costs including transportation costs.

PROMETHEUS

PROMETHEUS (https://e3modelling.com/modelling-tools/prometheus/) is a fully-fledged world energy system model combining top-down simulation of energy demand and supply with bottom-up representation of energy, electricity and transport technologies[29]. The model includes a complete accounting of energy demand and supply by sector and energy product and endogenous representation of energy prices. It simulates the complex interactions between energy demand and supply to form market equilibrium at the regional (for ten distinct regions) and global energy markets[30]. PROMETHEUS represents: the EU, China, India, the USA, Western Pacific region (Japan, S. Korea, Australia, New Zealand), Russia and CIS economies, MENA region (Middle East and North Africa), Emerging economies and Rest of world[31].

PROMETHEUS includes specific modules for the macro-economy, energy demand by end-uses power and hydrogen production, energy prices, hydrocarbon supply and technology learning. The modules are linked together to form a comprehensive global energy system model and interact through their common variables and sectoral or system constraints (e.g. on emissions). PROMETHEUS estimates energy-related CO_2 emissions and identifies several subsectors of energy consumption (i.e. industrial uses, heat, steam, specific electricity uses, household appliances, space and water heating, cooking, road, rail and air transport, bunkers). The modelling of energy end uses includes explicit technologies, i.e. in the road passenger sector different types of cars are represented, including conventional ICE vehicles, hybrids, plug-in hybrids, battery electric and fuel-cell powered vehicles.

In PROMETHEUS power requirements are determined by electricity consumption in industry, buildings and transport, own consumption of power plants and grid losses. The evolution of electricity demand by sector, the decommissioning of power plants, the security of supply margin and other flexibility constraints determine the new capacity required. The allocation of new capacity investment in specific technologies is modelled as a quasi-cost-minimizing function to represent real-world cost heterogeneities and ensure realism in investment decisions. The uptake of alternative power technologies (including gas, coal, biomass or oil-fired power plants, nuclear, renewable technologies such as solar PV, wind onshore and offshore, hydro and solar thermal,, CCS) is driven by the levelized electricity production cost of competing options that includes capital costs, fixed and variable Operation & Maintenance costs, and fuel costs. The operation of the electricity system is represented through the dispatching of power plants in each time segment, determined by the load duration curve, their installed capacities and operating costs. Technology progress for energy technologies is endogenous in PROMETHEUS through learning by doing and learning by research, with learning rates derived from literature review in Paroussos et al. (2019)[32].

The regional developments of energy demand and supply, the inter-fuel substitutions, energy and climate policies and hydrocarbon resource assumptions influence the evolution of international fossil fuel prices. The price of crude oil depends on the petroleum production cost by region, the reserves to production ratio, the capacity supply and role of OPEC in the global market. Gas prices are influenced by oil price developments, gas resources and production prospects and costs to produce and transport conventional and unconventional gas in each region. The model includes different gas pricing mechanisms and can represent oil indexation, gas-to-gas competition or their combination (e.g. in the EU). Coal price is driven by global coal demand, coal reserves and production prospects and is partly linked to oil price developments as observed in energy markets. Overall, the dynamics of international fossil fuel prices are influenced by energy demand and supply, thus they are directly influenced by supply constraints.

The modelling combines economic foundations with the representation of agents' behavior (e.g. energy consumers, power producers) as well as technical and engineering constraints of the energy, transport and electricity systems. Energy and electricity supply, demand and energy efficiency are explicitly represented through related technologies in each sector, including conventional (e.g. heat pumps, fossil-fired plants, nuclear power) and innovative low-emission options (i.e. green hydrogen, storage, electric vehicles, advanced biofuels). The model can represent various energy and climate policy instruments, including carbon taxation, emission trading systems, energy efficiency standards, taxation for energy products, subsidies for renewable energy, phase-out policies for specific technologies and fuels, constraints in fossil fuel extraction, and measures promoting the use of clean fuels and low-carbon technologies.

REMIND

REMIND (REgional Model of Investment and Development, https://github.com/remindmodel/remind) is a numerical model that represents the future evolution of the world economies with a special focus on the development of the energy sector and the implications for our world climate. The goal of REMIND is to find the optimal mix of investments in the economy and the energy sectors of each model region given a set of population, technology, policy and climate constraints. It also accounts for regional trade characteristics on goods, energy fuels, and emissions allowances. All greenhouse gas emissions due to human activities are represented in the model.

REMIND aims to help policy and other decision makers to plan ahead by understanding the roles, synergies and trade-offs between various factors, including population, resources, technologies, policies and the environment. Using REMIND, research and policy-relevant questions related to sustainability can be explored: Which technologies should we use in the future? What is the impact of policy proposals that are meant to prevent (mitigate) climate change? What are the consequences on economic development, air pollution, and land use? For some questions, REMIND is used in connection with other models to provide a detailed answer. One such model is MAgPIE (Model of Agricultural Production and its Impacts on the Environment).

TIAM-UCL

TIAM-UCL is the TIMES Integrated Assessment Model (TIAM) developed at the UCL Energy Institute (code underlying the model available at https://github.com/etsap-TIMES/TIMES_model). This is a global multiregional technology-rich bottom-up cost optimization model. It is a partial equilibrium model that represents energy resource extraction through conversion processes (refineries, electricity, and heat generation) and infrastructure to end-uses in the residential, commercial, industry, transport and agriculture sectors. With perfect foresight over the modelling period, the model designs a cost-optimal transition of the energy system so that future service demands are met, while obeying technical, economic and policy constraints.

On the resource side, a total of eleven conventional and unconventional oil resource categories, eight conventional and unconventional gas resource categories, and two coal resource categories are specified. Each of these categories is specified with an individual supply cost curve within each region. Table M.5 outlines the key model assumptions on renewable technology costs, which are so important for strong mitigation scenarios. The regions represented are: Africa (AFR), Australia (AUS), Canada (CAN), China (CHI), Central and South America (CSA), Eastern Europe (EEU), Former Soviet Union (FSU), India (IND), Japan (JAP), Mexico (MEX), Middle-east (MEA), Other Developing Asia (ODA), South Korea (SKO), United Kingdom (UK), USA (USA), Western Europe (WEU) (see table below).The 16 geographic regions are linked through trade in crude oil, hard coal, pipeline gas, LNG, petroleum products (such as diesel, gasoline, naphtha, and heavy fuel oil), biomass, and emission permits.

Energy service demands are exogenous inputs to the model; they are projected for the future using drivers such as GDP, population, household size, and sectoral outputs; in this study, the SSP2 socioeconomic pathway has been used. The base-year (2005) primary energy consumption, energy conversion, and final consumptions are calibrated to the latest IEA Energy Balance at sector and sub-sector levels. The power generation mix, and end-use sector fuel consumption are in line with the historic data (calibrated to 2015 values). In addition to the global social discount rate, various hurdle rates (or WACCs) are used for sector specific technologies (extraction, transformation, generation or end-use sectors).

Production cuts implementation

WITCH

In the WITCH model, the method for implementing production quotas on the supply side vary with fossil fuels: the oil upstream sector (as well as investments) is completely endogenous in the model [33], and limiting production simply requires the implementation of an upper bound on the variable regulating extraction.

For coal and gas on the other end the extraction sector is modelled via global and regional extraction costs curves, calibrated from (Rose project). Those curves are read after each iteration of the parallel bunch of solutions for the coalitions, which implies that extraction price and regional production are, within each iteration, fixed. This implies that, with the old algorithm, reducing production by simply binding the extraction variable would not affect prices. Therefore, the production algorithm was modified with two interventions: on the one hand, the reading of the curves was modified to allow for the reallocation of regional production according to the prescribed production limits. On the other hand, coal and gas market were integrated into the existing ADMM algorithm that grant market clearance for global markets in the model, so that, if an imbalance exists between global demand and available supply due to the extraction bans, the price of the fuel increase eventually leading to market balance through iterations.

To gradually reduce the supply, all fuels were banned with linear trajectories: in the start year of the ban, production is bound to 2020 level, while at the end year each region has to produce at most 30% of that value. In the intermediate periods, the reduction is linear.

PROMETHEUS

In the PROMETHEUS model, the production of crude oil, coal and natural gas is modelled via global and regional extraction cost-supply curves, calibrated to data from the IEA, USGS and (Rose project). These curves describe a non-linear relationship between fuel production cost and the amount of available reserves and resources by region and fuel. Therefore, we added a constraint in the production of fossil fuels (differentiated by region and fuel) to simulate the extraction bans in the

SUP scenarios. This simulates that in the first year of the ban, fuel production is bound to 2020 level, while in the end year of the ban each region is constrained to produce at most 30% of this value (we assume a linear annual reduction in the intermediate period). PROMETHEUS represents the interactions in the international energy markets through market-derived prices to ensure equilibrium between fuel demand and supply. Therefore, fossil fuel extraction cuts in the SUP or SUPALL scenarios would directly lead to increased global fossil prices, which are also then reflected in increased import prices and final consumer prices for oil, gas and coal.

TIAM-UCL

The fossil fuel upstream sector in TIAM-UCL incorporates the availability and costs of primary energy resources, all extraction processes, and any processing required to produce, trade and distribute energy products for use in end-use sectors. Individual supply cost curves for each type of reserves (or potential resources) are estimated for each region. The distribution of resources assigned to different cost categories varies by region and is influenced by technology maturity and technical difficulty of extracting the resource. To introduce the supply policy in TIAM-UCL, we added constraints limiting fossil fuel production differentiated by region and resource. The supply policy main regional constraints are applied from a specific year (function of the group the region is included and the fossil fuel type) and represent an upper limit of production equal to 30% of 2020 production level in the region for the specific resource. Additional constraints are applied 10 years prior (5 years only in the case of coal) and are equal to 55% of 2020 production levels. In between these two constraints the supply levels are controlled following linear interpolation.

REMIND

REMIND characterizes the exhaustible fossil resources (coal, oil and gas) in terms of region-specific extraction cost curves that relate production cost increase to cumulative extraction[34,35]. In the model, these fossil extraction cost input data are approximated by piecewise linear functions that are employed for fossil resource extraction curves. The supply policy is simulated by introducing an endogenous constraint that limits yearly extraction levels relative to 2020, for each region and fossil resource, according to the extraction ban in the SUP scenarios. In the first year of the ban, the region is constrained to produce at most 30% of the 2020 production. Previous years assume a non-necessarily binding, linear annual reduction extending two decades before the ban.

Additional results A: energy and investments

Despite the different underlying mechanisms, both demand and supply side policies provide a stimulus to decarbonize the energy system. Figure 5 *(a)* shows the relative variation of key global energy system indicators in 2050 with respect to the reference scenario: the share of electricity in final energy consumption, final energy demand, share of fossil (coal, gas and oil with and without CCS), share of renewable energy (wind, solar, geothermal, biomass without CCS, and hydro) in the primary energy mix and emission intensity of primary energy.

Fossil fuel share of primary energy is drastically reduced in all scenarios with strong climate policies, ranging from -26% to -58% in supply side scenarios against a reduction of -40% in the demand side only scenario (model median values). The wide range shows once again that the timing and uniformity of participation in the supply treaty is key to transform the global energy system, but also that, if action is coordinated, supply side policies can be more effective than carbon pricing at least until 2050.

As far as renewable penetration is concerned, banning fossil fuel production consistently outperforms carbon pricing regardless of the speed and uniformity of the participation: supply-side scenarios increase renewable penetration by 83% (*SUPALL*) and 71% (*SUP*) relative to Reference in 2050, while carbon pricing increases the renewable share by 60%, as the uptake of CCS reduces the requirements for renewable energy.

This increase in renewable penetration is accompanied by a similar increase in the electrification share, which ranges from 30% of total final consumption in the reference scenario to 50% in the *SUPALL* scenario and 45% in *DMD* in 2050. Once again, early and coordinated participation of all countries in the supply side treaty clearly provides better performances, but also the fragmented narrative scenario performs similar to a carbon budget scenario.

In terms of final energy demand reduction due to energy efficiency improvements, supply side policy performs slightly better than carbon pricing, providing a median reduction in final energy consumption with respect to the reference scenario of 21% (*SUPALL*), against a reduction of 19% for the demand-side scenario.

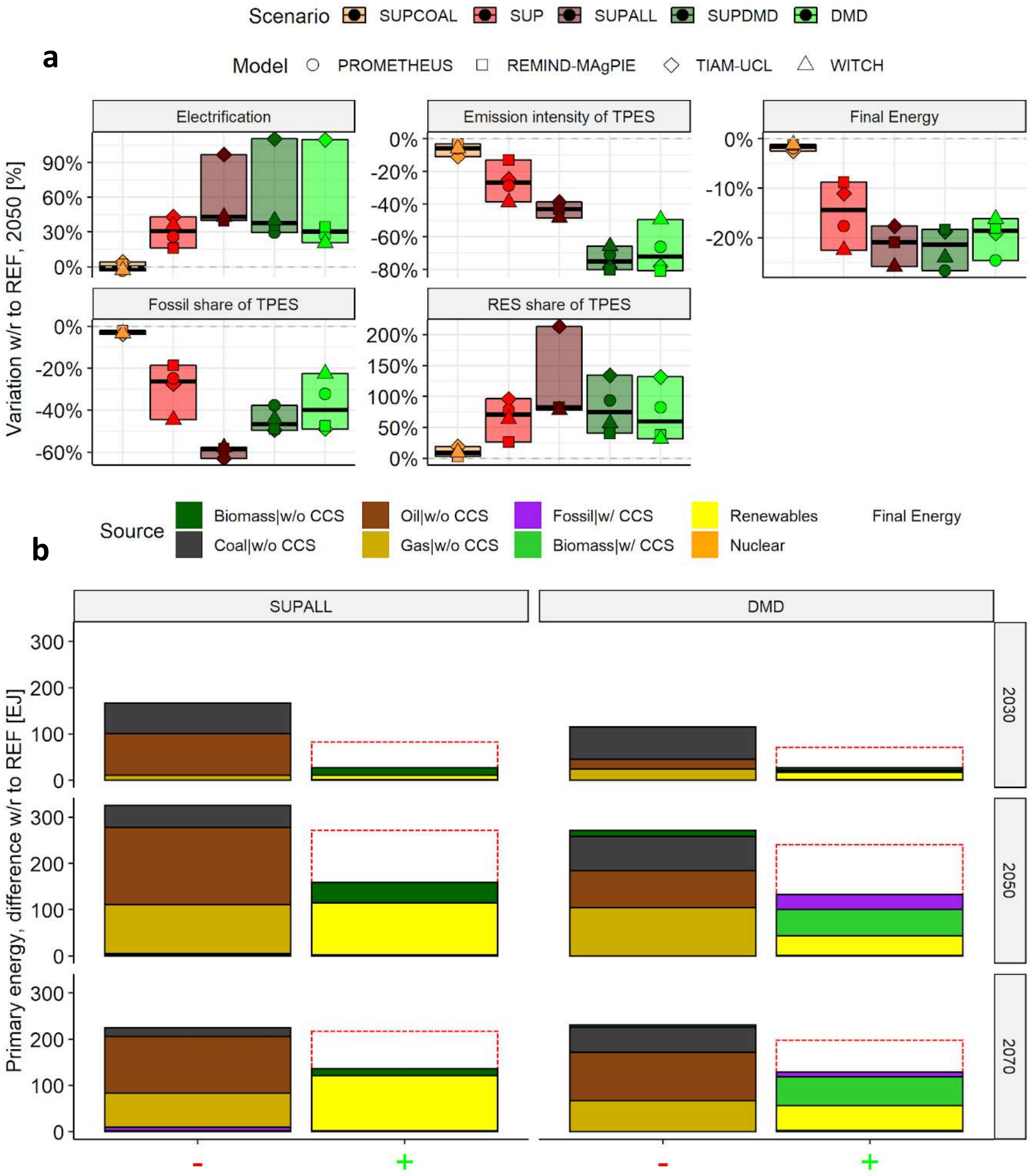

Figure 5: (a) Energy system indicators in 2050, percentage variation with respect to REF. "Fossil" include Coal, Oil and Gas. (b) Difference in primary Energy by source, left graphs indicate reduction, right graphs indicate additions relative to REF for SUPALL and DMD scenarios. Median of model ensemble. "Renewables" account for Hydro, Solar (PV and CSP), Wind (onshore and offshore), Biomass without CCS, and Geothermal. Final energy efficiency improvements are converted 1 to 1 to primary energy. Unbalance between additions and subtractions implies a change in overall efficiency of the energy system.

Even though in terms of electrification, renewables penetration, fossil phase-out, and energy efficiency improvements, supply-side policy performs at least as effectively as carbon pricing, emission intensity of primary energy remains relatively high in supply side scenarios, with a reduction of up to 43% with respect to the reference. Pathways that include carbon pricing policies approach a 75% reduction in 2050.

This can be explained by looking at Figure 5 *(b)*, which shows additions and subtractions per fuel with respect to the reference in the primary energy mix in selected years. Supply side policies substitute fossil fuels with renewables, biomass and to a minor extent nuclear. Biomass with Carbon Capture and Storage (BECCS) and fossil energy with Carbon Capture and Storage (CCS) are not incentivized by phasing out fossil fuel production, but they play a key role in speeding up the decarbonization in the demand-side scenario, accounting collectively for around 80 EJ in 2050. Moreover, the prescribed trajectory for extraction bans results in higher reduction for oil and gas and lower for coal relative to DMD, while demand-side policy targets first and more aggressively coal, as the most climate polluting fossil fuel.

In all cases, combining supply side action with a carbon tax improves the performance of carbon pricing across the indicators: renewable penetration increases together with energy efficiency, while fossil supply decreases. Investments follow the same trend, with an especially pronounced reduction in the oil upstream sector.

Similarly, banning only coal slightly improves the indicators' performance relatively to the reference scenario. This improvement, however, is not sufficient to diverge from the overall trend traced by the NDCs and cannot trigger the transition to net zero emissions and thus cannot ensure compatibility with PA goals.

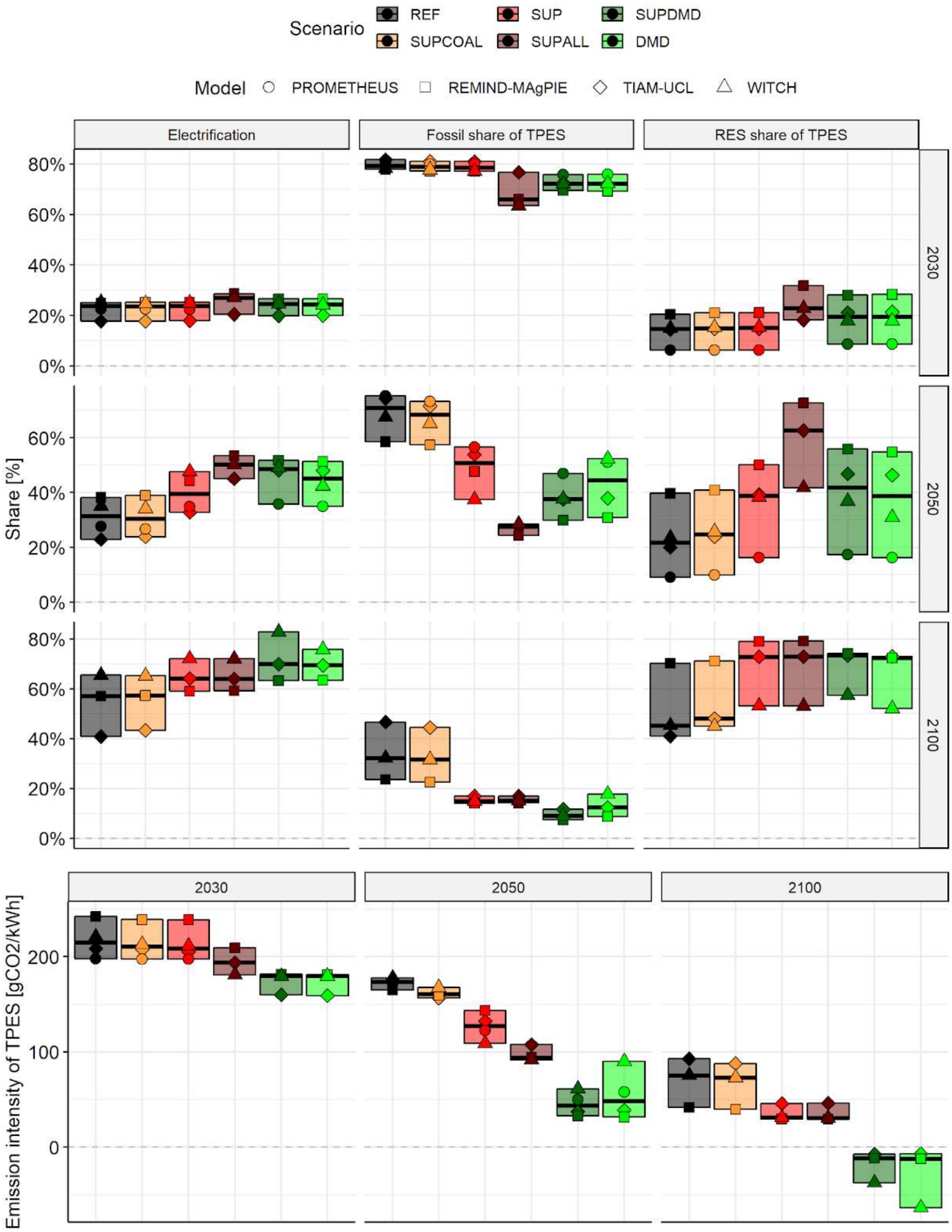

Figure 6: Indicators values in selected years, absolute values.

Figure 6 complements *Figure 5* and provides additional informations on the time evolution of the indicators through scenarios.

As far as fossil share of primary energy is concerned, the 2030 values are significantly lower in SUPALL for most models with respect to carbon tax scenarios, except for TIAM-UCL that uses a slower transition trajectory before reaching the final extraction limit levels. Renewable share follows the opposite trend. This shows that, while the level of ambition in the 2030s is similar for SUPALL and DMD scenarios, the former targets first and more aggressively the fossil fuel sector.

In 2100, the same indicator shows a fossil fuel penetration in the energy system slightly higher in supply scenarios (SUP and SUPALL) with respect to DMD, at around 18% of TPES.

This proves that the residual level of production allowed by the extraction ban design produces a long-term energy system that is roughly comparable in terms of relative presence of fossil fuels, as well as renewable penetration.

Interestingly, SUPDMD has a lower long-term level than all other scenarios: this result is driven mainly by the WITCH model and its due to lower gas requirements in SUPDMD due to reduced DAC deployment.

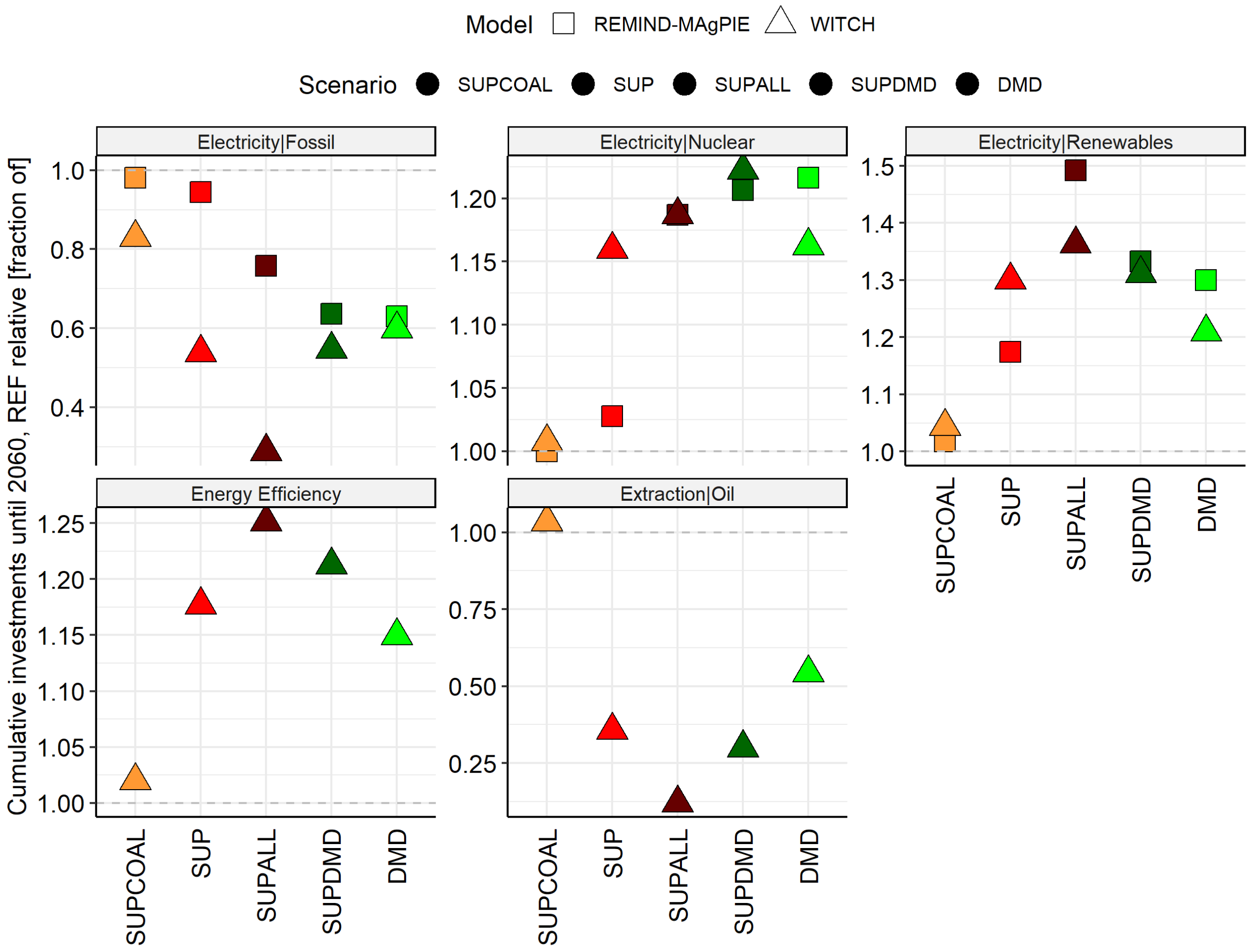

Figure 7: Cumulative investments from 2020 to 2060 in various energy sectors, discounted at 3% and expressed as a fraction of the reference level. Only results of models that explicitly report investments are shown.

Figure 7 complements the information provided in *Figure 2* and *Figure 6* with an overview of the cumulative investments in various sectors of the energy system. Results are shown only for the WITCH and REMIND models, because they are the only ones able to produce these variables. Both models foresee a reduction in investments related to fossil fuel plants in the electricity sector with both supply and demand side policies, as well as an increase in nuclear and renewables investments. There is no accordance, however, on which type of policy produces the larger effect: for Remind, SUP and SUPCOAL have very similar levels of cumulative investments in fossil fuels power plants with respect to REF, while SUPALL, DMD and SUPDMD show a 20% reduction. The WITCH model, on the contrary, is more responsive to supply side policies for fossil fuel investments and shows a reduction of up to 70% in the SUPALL scenario.

The same trend is visible in oil upstream sector investments: scenarios containing extraction limit for all fuels reduce significantly cumulative investments on the extraction sector with respect to both the reference (-63% to -85%) and DMD scenarios. While produced only by the WITCH model and thus lacking robustness, this result is significant because it implies that deploying supply side policies, alone or coupled with carbon pricing, would halve the total size of the oil upstream sector with respect to a scenario with carbon pricing only, reducing the relative importance and the lobbying power of the extraction industry.

Banning only coal instead produces a small increase in total investments, because of higher extraction requirements due to the rebound effect in consumption of oil and gas.

Additional results B: trade and revenues

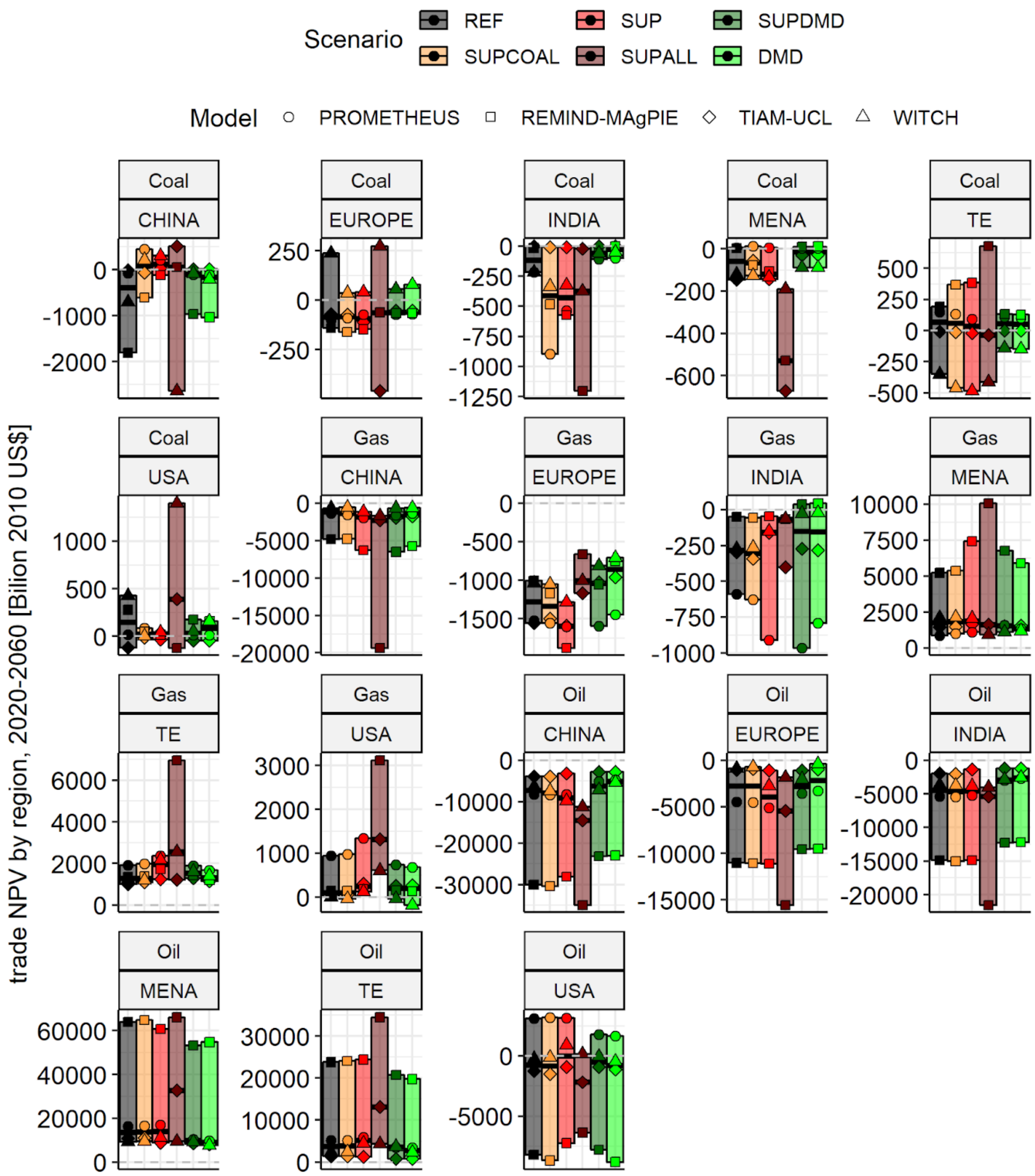

Figure 8: NPV of trade from 2020 to 2060 for selected region, all fossils. Discount rate 3%

Figure 8 shows the Net Present Value of total revenues from trade in selected regions and different fossil fuels. All NPV values are discounted at 3% between 2020 and 2050.

In general, hydrocarbon producing countries gain from supply side policy scenarios, while energy importers worsen their exposure.

For coal, the biggest winners from supply side treaties (SUPALL) among large economies are the USA.

The other scenarios tend to disrupt much less trade patterns that remain similar to the reference scenario for most regions (given the fairly large uncertainty across models).

For gas, the general trend for demand side policies is to reduce exposition for importing countries (China, Europe, India) and depressing revenues for exporters (MENA).

SUPDMD and DMD perform very similarly in this regard, slightly increasing revenues for some producing and exporting regions (Russia, MENA) and worsening exposure for others, mostly large gas importers (Europe).

Supply side policies tend to have the opposite effect, with most producers gaining a considerable amount of trade value until mid-century regardless of the velocity of application of the extraction bans (SUP vs SUPALL).

For oil, finally, the picture remains similar. Notable exception is the US, that in the SUPALL scenario loses a considerable amount of trade position.

Additional results C: carbon pricing and cost of policy

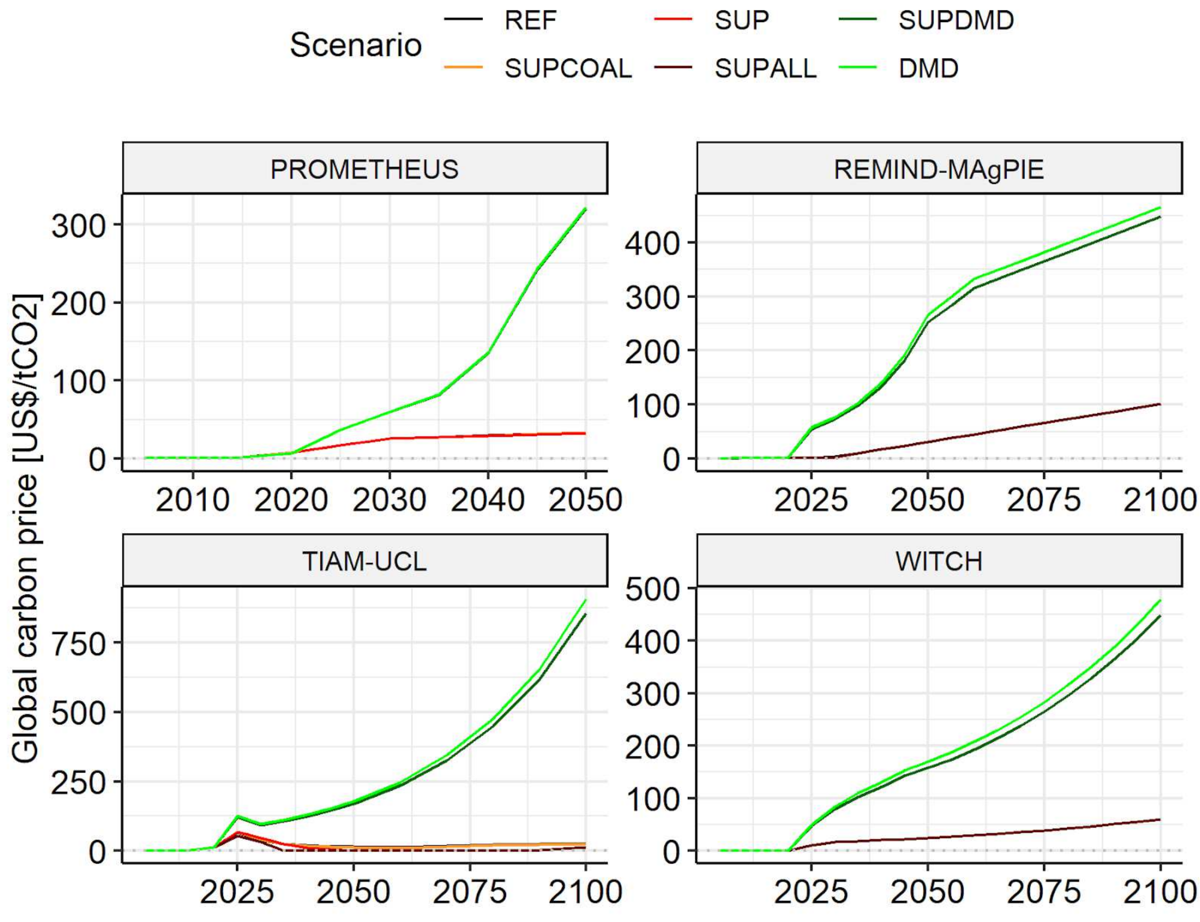

Figure 9: carbon price by model and scenario.

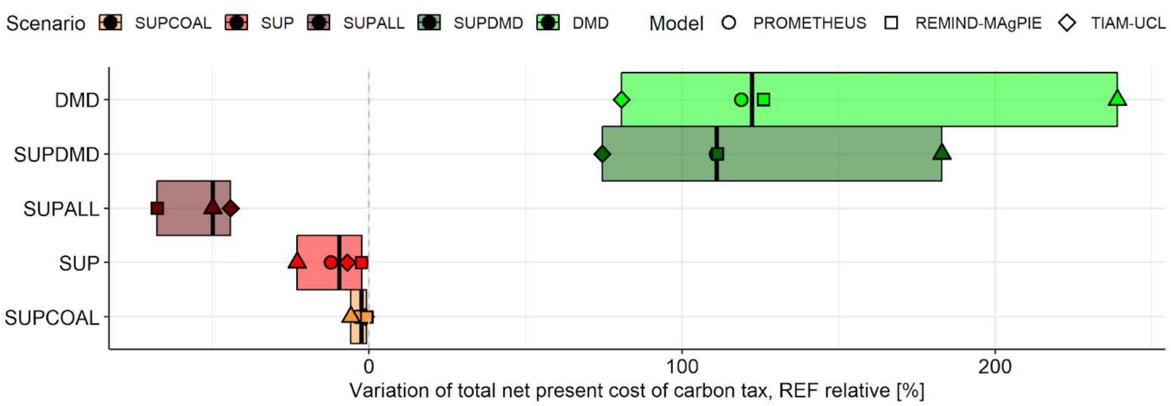

Figure 10: variation of total net present cost of the carbon tax from 2020 to 2100, discounted 3%.

Figure 9 and Figure 10 show the trends for carbon taxes in different models and the total cost of the carbon tax (REF relative) respectively. The total cost of the carbon tax is measured as the Net

Present Value between 2020 and 2050 of the price of carbon times the CO_2 emissions, discounted at 3%.

Lower total costs of the carbon tax imply a lower distortion of the economy through taxation, but not necessarily lower costs faced by consumers, because of the simultaneous increase in price due to the production bans.

Both figures show that the reduction of the carbon tax in SUPDMD compared to DMD scenario happens consistently in all four models, even if the size of the reduction is not extreme.

The combined lower price of carbon and decreased use of fossil fuels, however, contributes in decreasing the total cost of the carbon tax by more than 10% in SUPDMD with respect to DMD.

Figure 11 shows a regional disaggregation of policy costs by scenario, measured in terms of NPV of scenarios over 2020-2050 discounted at 3%, relative to REF. Overall, the SUPALL scenario is consistently costlier for all regions, even if it's the only scenario for which certain models (TIAM-UCL) foresee an overall net benefit for big producing regions (MENA, Russia, USA, and CANADA). In average, SUP is less costly than a carbon budget scenario (but does not achieve the Paris mitigation goal), while SUPDMD can increase the overall cost of climate policy for big importers (Europe, India, China) or slightly decrease it for exporters (USA, Russia, Canada) with respect to DMD.

SUPCOAL is, for most regions, only slightly costlier than the REFERENCE but achieves very limited emission reductions.

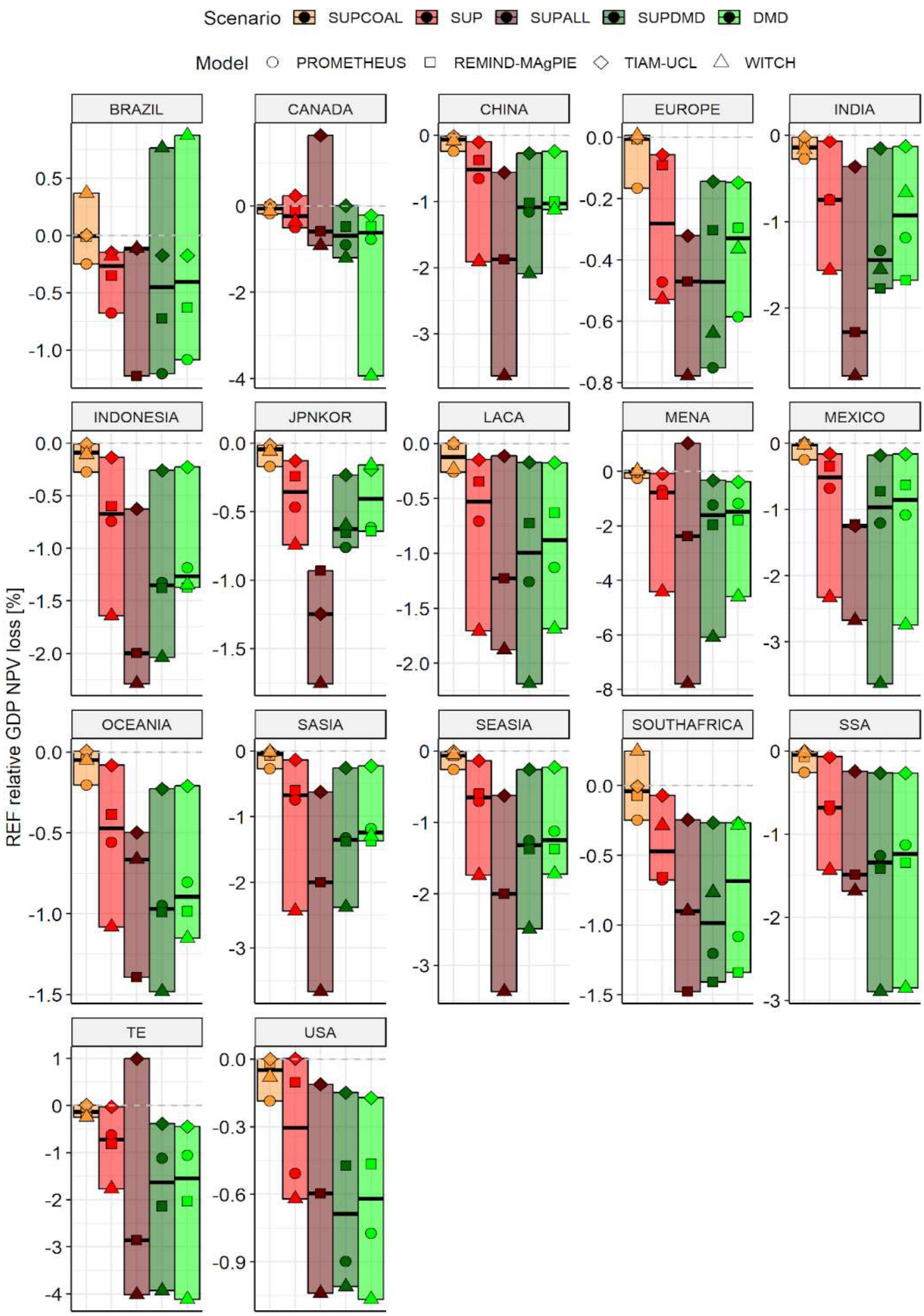

Figure 11: regional cost of policy, GDP loss. Discount rate 3%

Additional results D: air pollution

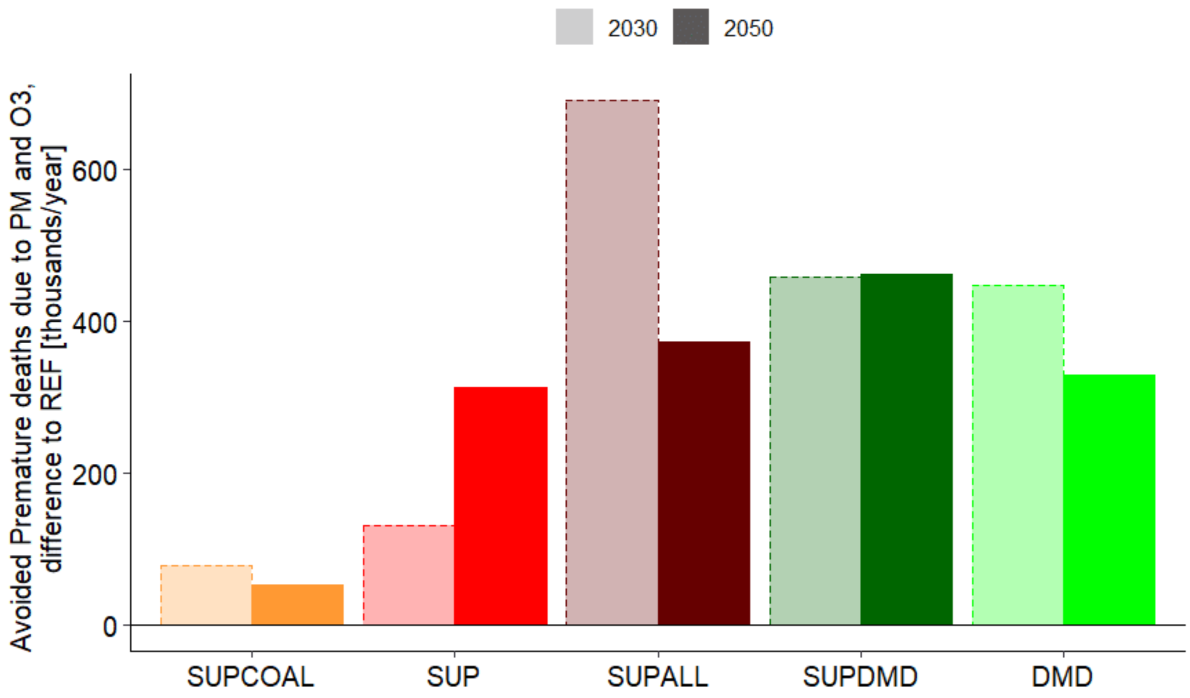

Figure 12: global avoided death per year from air pollution and ozone in selected years, by scenario. Results from the WITCH model only.

Figures 12 and *13* show avoided deaths per year from PM and ozone air pollution in the years 2030 and 2050, regional and global respectively, derived with FASST-R air pollution calculator from WITCH results only.

Globally, all l mitigation policies provide co-benefits as avoided deaths from air pollution. For supply side policies, banning only coal provides a visible improvement in people's health, with results mainly driven from India, while other big countries with air pollution problems like China show only incremental benefits because coal is already being phased out at a similar pace in the reference scenario.

The effect is much stronger if all fossils are banned together, and in 2030 the SUPALL scenario shows a reduction in deaths much larger than all other scenarios, including the ones implementing the carbon tax.

The stronger reduction of deaths compared to DMD in 2030 can be explained by the steeper reduction in fossil fuels' consumption in the first part of the century, when the air pollution controls are still weaker in many countries, especially in the less developed countries. The SSP2 baseline is a current air pollution policy continuation scenario. It assumes a three speed world in terms of air pollution control deployment, a full implementation of maximum feasible reduction end-of-pipe technologies is assumed to be reached only after mid-century even in high income regions. Furthermore, faster pollutant emission reductions are happening, via structural changes, in highly polluted regions (e.g. Mena, Mexico and China) that do not have yet advanced air pollution controls, thus structural measures may yield large co-benefits.

In some regions, however, banning only coal may cause an increase in air-pollution related deaths in 2050, because the substitution of coal happens partially with biomasses that are also associated with particulate matter emissions.

Finally, combining supply and demand side policies (SUPDMD scenario) results in long-term co-benefits for avoided deaths relative to DMD, because of reduced use of fossil fuels and CCS (especially gas). The global results are mainly driven by China and India but are also robust across developed countries as well.

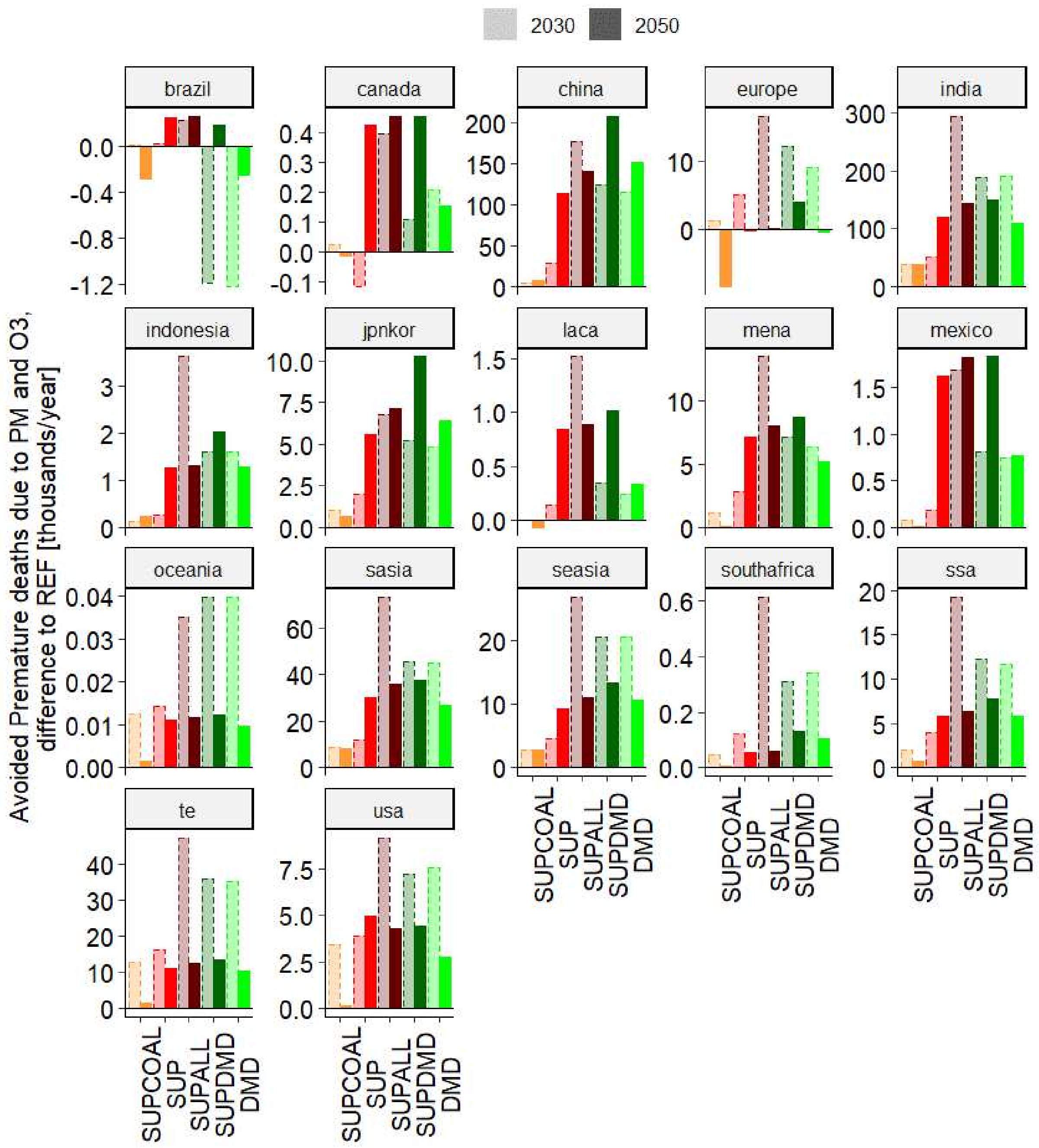

Figure 13: regional avoided deaths per year from air pollution and ozone in selected years, by scenario. Results from the WITCH model only.

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