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Fossil fuel extraction bans as a climate mitigation strategy: a model based appraisal

Supervisor
Massimo Tavoni

Co-Supervisors
Laurent Drouet
Lara Aleluia Reis

Candidate
Pietro Andreoni – 905423

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Executive summary

This thesis evaluates the consequences of a supply side treaty for climate change mitigation, in the form of a global fossil fuel extraction ban. In order to explore the complex interaction between policy design, energy system and climate, I performed a first-of-its-kind assessment on an Integrated Assessment Model, designing multiple novel scenarios and a new algorithm. I used and enhanced the WITCH model (`www.witchmodel.org`), a leading open-source integrated climate-energy-economy model which has provided many of the scenarios reviewed by the IPCC. The scenario design I helped craft was implemented by several models by different research institutes.

The main research objective of the exercise is to study the effect of command-and-control, supply side regulation on fossil fuel production and its interaction with demand side policies, such as carbon pricing. Demand side policies are the one which are commonly examined in policy evaluations. However, these policies might be ineffective at solving the climate problem, due to emission leakage to non-participating countries and to accelerated extraction of fossil fuels, resulting in a 'green paradox'. This recognition motivates the quest of this thesis, to assess policies targeted at fossil fuel extraction.

In order to perform this assessment, the work for this thesis was conceptually and chronologically divided into two parts. First of all, I had to implement an extensive modification of the algorithm for coal and gas extraction. This intervention allowed for the possibility of banning fossil fuel extraction in the WITCH model. Then, I co-designed the scenarios and performed an extensive analysis of the results.

The main ones are summarised below:

- global production bans do provide a meaningful increase in mitigation effort, bridging current policy ambition with Paris consistent emissions trajectories.
- supply side policies alone, however, fail to reach deep decarbonization targets and net zero emissions because they are unable to incentivize the deployment of key technologies such as Carbon Capture and Storage and Direct Air capture.
- supply side policies show good complementarity with carbon pricing, as they anticipate decarbonization and reduce reliance on negative emission technologies.
- supply side policies tend to be costlier than a global uniform carbon pricing scheme.
- a global supply treaty can have positive but regionally differentiated effects on energy security and gain producers support.

These results provide novel insights on the implications of supply side policies, offering potential support to policy-makers when more countries are starting to pledge exploration or production ban (e.g Denmark). Moreover, being the first attempt of modelling supply side policies in an energy-detailed Integrated Assessment Model, this work opens a rich possibility of research follow-ups that expand and deepen the questions here analyzed.

Extended Abstract

Introduction

Despite the recent success of the Paris agreement, Greenhouse Gases (GHG) emissions continue to grow (Quéré et al., 2018) and climate action is becoming more and more urgent as the remaining carbon budget to achieve the "well below 2°C" target is fast depleting (IPCC, 2018). The GHG emissions are mainly produced by fossil fuels burning (IPCC, 2014) and many regions are still locked-in with using fossil fuel (Lazarus and van Asselt, 2018), while investments in fossil fuels (oil and gas) continue to grow (IEA, 2020) [1].

National policies are being put into place worldwide, such as energy efficiency subsidies and labels, promotion of renewable energy, green infrastructure public investments and carbon markets and taxes. These have, however, proven ineffective so far (Roelfsema et al., 2020). Moreover, early retirement of fossil fuel infrastructure will lead to stranded assets (Fofrich et al., 2020) increasing the cost of decarbonization. Keep investing in fossil fuels will thus exacerbate carbon lock-in and stranded assets, increasing the costs to be bared by future generations.

Despite this, climate target scenarios (both 2°C and 1.5°C) foresee important investments in fossil energy (McCollum et al., 2018) even in regions such as the European Union (EU), that is currently engaged in achieving carbon neutrality by 2050. However, a great share of these investments are highly dependent on the availability and reliability of Carbon Capture and Storage (CCS) at large scale. As

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[1] Excluding 2020 from this statement which was the year of the COVID-19 pandemic outbreak

in the last decade only shy advancements have been seen for CCS (Bui et al., 2018), fossil fuel investments will become even riskier.

In this context, some researchers made the case for the implementation of supply side command and control instruments targeting fossil fuel extraction as an appealing contribution for carbon emissions reduction. In particular, recent literature (Asheim et al., 2019) (Lazarus and van Asselt, 2018) proposes that demand side and supply side policies can work effectively as complementaries, increasing robustness of the policy portfolio and mitigating the risk of decarbonization failure. At the same time, the idea of targeting directly fossil fuel industry is gaining momentum between advocates and the general public (Ayling and Gunningham, 2017), following the ethical argument that applies some or most of the responsibility of fossil carbon emissions to producers and polluting industries (Frumhoff et al., 2015).

This work aims to explore in a first-of-its-kind numerical analysis the effect of command and control supply policies, in the form of extraction bans, on the economy and energy system and their interaction with the golden standard of climate policy, carbon taxes.

The results presented here are part of a multi-model exercise, involving four global Integrated Assessment Models (IAMs) from different universities and research institutes: WITCH, REMIND-MAgPIE from PIK, TIAM-UCL from UCL, and PROMETHEUS from E3M. I use the WITCH multi-regional Integrated Assessment Model, initially developed by a team including my supervisors and then maintained and improved by the SEME division of CMCC foundation, under which my thesis work took place as a Visiting Student.

The contribution of this thesis is twofold: one one hand, I implemented the possibility of banning at production fossil fuels; on the other, I co-designed and modelled scenarios that simulate a global supply side treaty, developing a narrative to assess timing of participation for different regions.

Literature review

Following Green and Denniss (2018), we can visualize climate policy instrument contained in a matrix resulting from the cross-product of two dimensions: supply or demand side policy on one hand, supportive on restrictive policies on the other.

Another relevant debate that somehow crosses the latter is the distinction between price and quantity instruments, or command and control vs market based policies. This point is central in environmental economics and it is as old as the discipline itself: it is widely known since Piqou (1920) that market based instruments are, in theory, more cost-effective than command and control and allow an efficient reallocation of resources between substitutes at the least information cost. However, influential authors have challenged this position (Weitzman, 1974), arguing that under certain characteristics of the abatement cost curve a quantity instrument is to be preferred.

In the specific context of climate policy, Lazarus and van Asselt (2018) claim that, among supply side instruments, command and control in the form of ban or moratoria could have a stronger political appeal than market based instruments.

An semi-analytical support to this argument is provided by Lamperti et al. (2020), who argue that under path dependency of clean R&D command and control regulation are more robust than market based instruments, due to limited window of opportunity that bounds the effectiveness of the latter.

In the same direction, Asheim et al. (2019) provides five main reasons for the development of a supply side treaty in the form of an international fossil fuel production ban:

1. it attenuates the free-rider effect if coupled with a fragmented (and coalitional) demand side-policy, as supply-side action should countervail carbon leakages by keeping international market prices high.
2. it fosters green R&D. Higher fossil fuel prices encourage R&D investment in green technologies raising expectations about future lower clean energy prices;

3. opposed to demand side policies, extraction bans leading to higher fuel price have a positive spillover effect on emissions of the other regions, even if they don't directly participate to the treaty;
4. it provides a back-up for possible demand-side policy failures. It restricts the production reducing carbon emissions, and in the case of non-failure of the demand-side policy it comes almost for "free" because it avoids stranded assets;
5. unlike demand-side policies, supply side policies increase fossil fuels prices increasing the income per output therefore gaining producers support.

Among all the possible reasons for demand side-market based climate policy failures (excluding political reasons and low commitment), inter-regional and inter-temporal leakages are the most highlighted. The former arise due to the depressing effect for prices of carbon taxes. Especially in case of a fragmented carbon tax, regions outside the coalition implementing it will face lower prices for fossil fuels, thus a higher willingness to emit carbon and jeopardize the efforts of the most "virtuos" countries. The second effect was initially proposed by Green Sinn (2008) as "the Green Paradox", and state that producers might flood the market with fossil fuels if they believe that strong climate policy will emerge in the future. This is due to expectations of low future prices changing the cost opportunity of the resource and the optimal path of extraction as a consequence. This would, in turn, lead to lower fossil prices in the present and decrease the competitiveness of green substitutes. While in the context of a global uniform carbon tax Bauer et al. (2018) shows that the green paradox has limited effect if demand side action is taken soon enough, Hagem and Storrsten (2019) argues that supply side policy can indeed limit the green paradox effect in the context of a fragmented policy scenario.

Lastly, high costs of information and accounting errors for carbon markets and inter-border carbon tariffs provide further argument in favor of choking the pipe of climate pollution at its source, targeting directly the extraction sector.

Methods

The work for this thesis can be conceptually divided into two parts.

First of all, I had to implement an extensive modification of the algorithm for coal and gas extraction. This intervention allowed for the possibility of banning fossil fuel extraction in WITCH, a design feature that requires a good degree of integration of the extraction sector with the main solver, and whose absence prevented the possibility of engaging in this kind of analysis before.

As the model is multi-regional and optimizes separately each region, the task is non trivial: it requires developing a feedback loop between regional supply and global demand, adjusting the price with a market clearing algorithm such that the sum of the former equals the latter. This feedback must thus be introduced iteratively outside the main optimization, demanding a manual algorithm to allocate the production between regions, clear the market and grant convergence of the overall solution for each region.

In particular, a first modification of the algorithm was necessary to let - given a certain amount of total demand - the regional production levels comply with the extraction ban, reading from calibrated global and regional supply curves. After every region is optimized for a certain iteration, the global demand and supply are computed post-solve: if an imbalance exists due to the extraction bans, a market clearing algorithm manipulates prices to adjust demand accordingly to global supply availability. While the ADMM algorithm (Boyd et al., 2010) used for this task was already implemented in WITCH to grant convergence of the oil and carbon markets, it was necessary to integrate coal and gas markets into it and adequately calibrate the parameters. If the total amount of available supply cannot meet global demand, then, the prices are raised to reduce consumption and consequently the imbalance; the whole process is repeated iteratively until the value of the imbalance over total consumption is below a tolerance threshold of 0.5%.

Secondly, I have co-designed six scenarios, four of which are novel in the literature

(Table 1). First, a counterfactual scenario (REF) was designed reflecting current established and planned policies, including the NDCs projected thorough the century. A scenario implementing a global uniform carbon pricing scheme and a carbon budget of 1000 Gt CO2 in 2100 was also considered as the ”golden standard” of climate policy (DMD). Then, supply-side narratives were built where the production of coal, oil and gas are cut, starting from different enforcement years (SUP), up to at least 70% of 2020 production level. According to their trade position, reserves, fossil fuel dependency and climate commitment, world regions were classified into “front-runner”, “follower” or “laggard”, defining the year in which each region will enforce the production cut. In order to cancel out the effects of different regional timings in the production cuts a supply-side policy scenario where all the regions are front runners was developed (SUPALL), which serves the purpose of testing the assumptions about regional behaviour contained in the SUP narrative. Finally, the supply-side narrative was combined with a demand-side policy in line with the Paris agreement target of well bellow 2°C to search for potential complementarities (SUPDMD). Lastly, a scenario in which only Coal is banned was implemented (SUPCOAL); the results relative to this scenario are described in section 3.5.

Table 1. Scenarios names and definition.

Reference scenario	REF
Supply-side scenario - Narrative	SUP
Supply-side scenario - Coal only	SUPCOAL
Supply-side scenario - All front-runners	SUPALL
Demand-side scenario	DMD
Combined scenario	SUP+DMD

Results

Figure 3.1 show the emissions trajectories for the scenarios. The supply side treaty (SUP) contributes significantly to decarbonization. Moreover, if the partecipation in the global supply treaty is homogeneus (SUPALL), the speed and timing of emissions

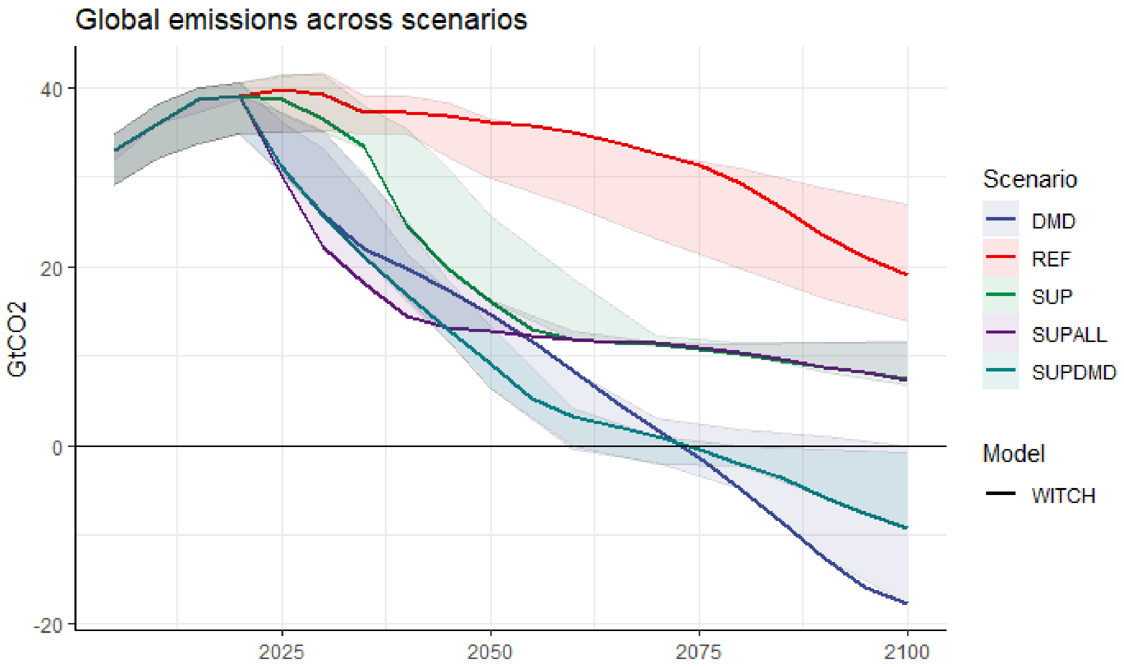

Figure 1. Global CO2 emissions among scenarios in WITCH. Shaded area refers to other models results participating the study

reduction is in line with Paris consistent pathways (DMD and SUPDMD). In the second half of the century, however, emissions stabilize around 15GtCO2, diverging significantly from the trends of deep mitigation scenarios and leading to a carbon budget of 1803,8 GtCO2 for the supply side narrative (SUP) and 1511,7 GtCO2 in case of early participation (SUPALL)

The lack of substitutability between strong supply side policy and demand side instruments is to be searched within the energy system: cutting fossil fuel production alone does provide a comparable signal for green substitutes in the energy and industrial sector, such as renewables, efficiency and nuclear power (Figure 3.3) other than electrification to reduce the impact of hard-to-decarbonize sectors. It does not, however, incentivize anyhow the deployment of Carbon Capture and Storage (CCS) or negative emissions technology such as Bioenergy with CCS (BECCS) and Direct Air capture (DAC).

Comparing the carbon pricing scenario (DMD) with its counterpart including the supply side treaty (SUPDMD) show instead that adding strong supply side action to

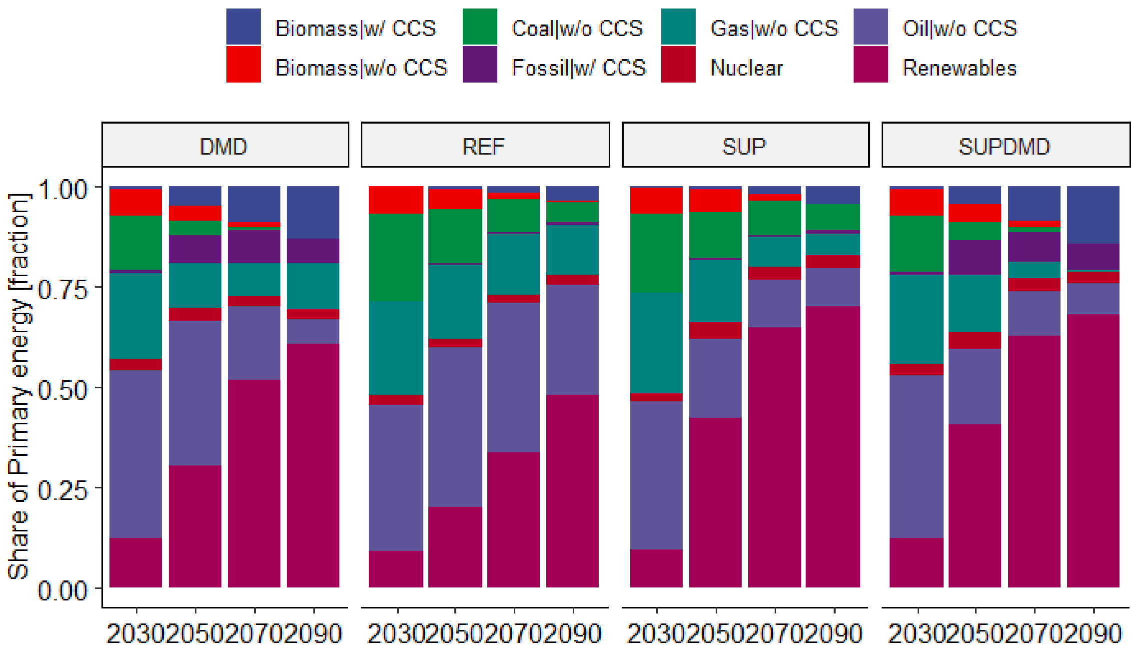

Figure 2. The energy sector in main scenarios

a low carbon budget scenario produces steeper and earlier decarbonization before net zero and less reliance on net negative emissions in late century (purple and red lines on Figure 3.1). Moreover, it does so by reducing the optimal carbon price and the overall carbon cost(Figure 3). The net effect is a consistent halving of the "carbon economy" throughout the whole century, in the form of taxes before net zero and subsidies to carbon removal after carbon neutrality.

While the societal burden of the carbon tax is reduced, the same cannot be said about the overall cost of policy: Figure 3 shows that extraction bans tend to anticipate and increase the costs of transition. This cost, however, never exceeds 2% of global GDP and tends to decline significantly in the late century. The reduced burden of negative emissions technologies in the late century lead to lower long-term cost if supply and demand side policies are implemented jointly (SUPDMD), relative to a carbon price scenario only (DMD).

The remaining fraction of the shadow cost of the energy transition is then vehiculated by the direct increase of fossil fuel prices, whose level spikes during the transition

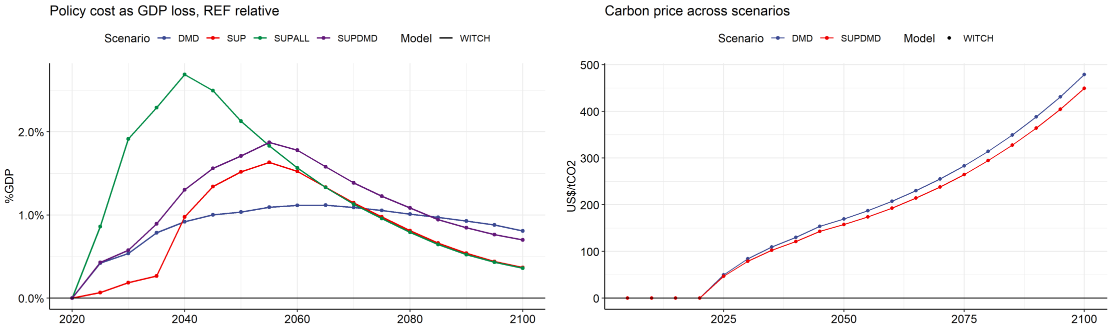

Figure 3. Policy cost and carbon price

and tend to decrease towards the end of the century. They remain, however, several times higher than the reference scenario as in Figure 4. This is particularly visible when coupling supply and demand side policies (SUPDMD), where the depressing effect of the carbon tax on fuel prices is overcompensated by the ban if compared to a carbon pricing only scenario (DMD).

This increase in energy prices also grants an increase in revenues for fossil fuels producers compared to the Reference scenario, even though the volume traded sharply decreases.

In terms of energy system, coupling supply and demand policies implies reduced reliance on fossil CCS, in particular gas, whose share in primary energy is mainly substituted with efficiency improvements. Less need of net negative emissions late in in the century leads to lower levels of Carbon Dioxide Removal (CDR) technologies deployed: in particular, DACs almost disappear from the technology portfolio, reducing primary energy requirements (Figure 5).

Lastly, a global supply side treaty has large implications in terms of energy security. To assess its effects, we used the SH index and global trade to TPES ratio as in Cherp et al. (2016): results show that supply policies tend to decrease global energy security in the transition phase and increase it when the treaty stabilizes.

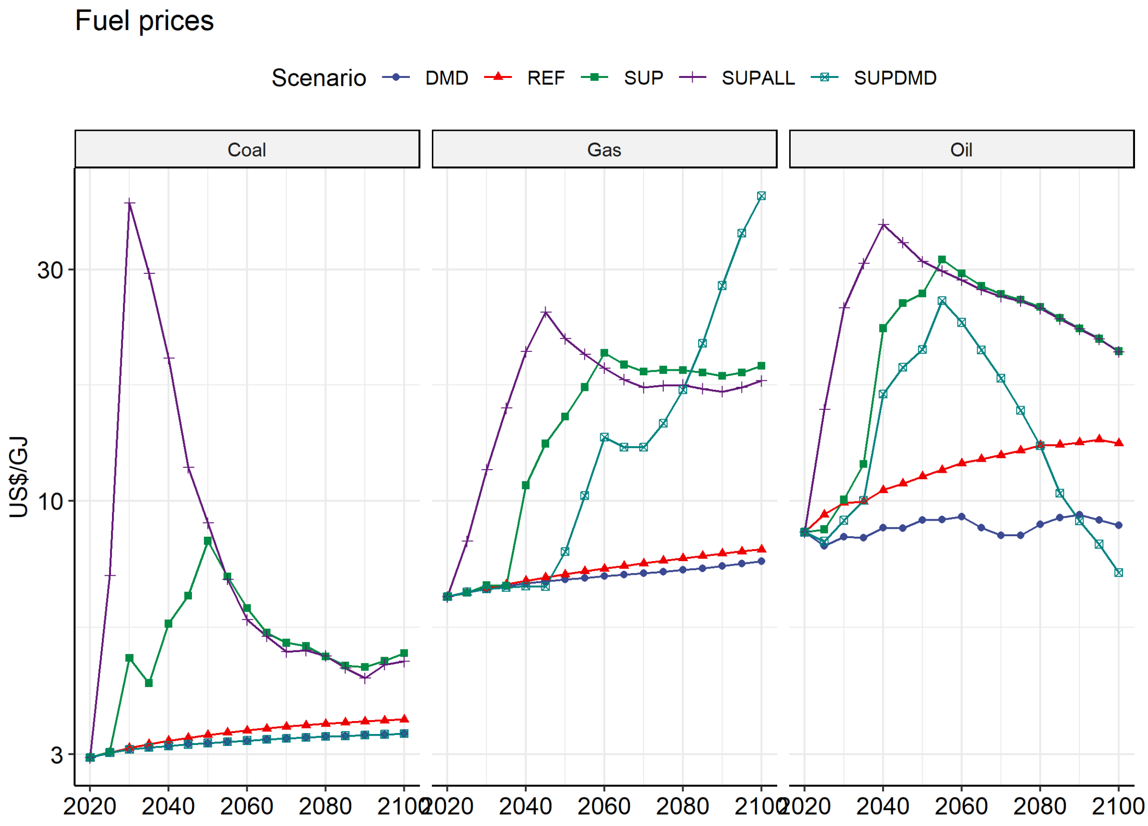

Figure 4. Fuel prices

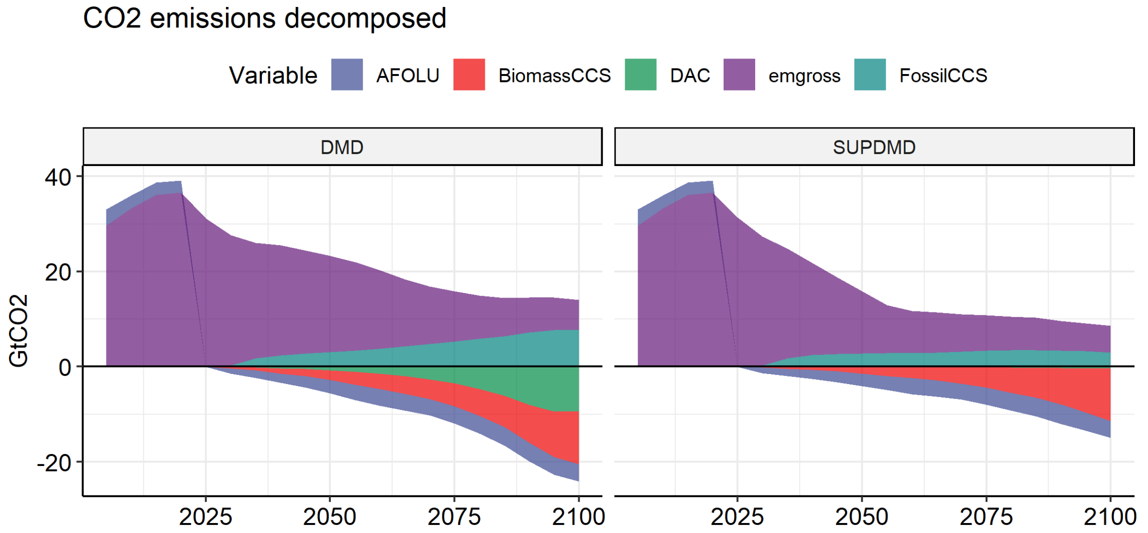

Figure 5. Negative emissions portfolio

Discussion

This analysis aimed to assess the consequences within the energy system of a global supply side treaty: it couldn't, however, analyze the validity of all the arguments proposed for a supply side treaty due to model structure and limitations. The added value of these arguments is to be considered as an external factor in judging the results of this work and their validity has to be assessed from the literature or explored in further work.

That being said, this work provides some novel insights on supply side policy: first and foremost, results suggest that a global extraction ban can, if timing, speed and participation are framed correctly, substitute carbon pricing in the near-medium term. In the long run, however, a demand-side price mechanism is required to stimulate the remaining part of the mitigation technologies portfolio, namely CCS, BECCS and DAC.

At least under the assumptions that produce this results within IAMs, it can be stated that supply side global action on climate mitigation acts as a good substitute to carbon pricing until the 2050s, but fails to do so for hard-to-decarbonize sectors and negative emissions later in the century. This "short term substitutability" partially answers to the insurance argument, as we can infer that damages due to strong carbon policies delays could be substantially mitigated if a supply side treaty was into place. On the other hand, complementing a strong carbon pricing policy with supply side action seems to produce positive effects, anticipating decarbonization and reducing the burden of the "carbon economy" for societies both in the short and long run. Furthermore, it reduces reliance on dubious technology like DACs for late century carbon dioxide removal.

In terms of the international implications, the main surplus offered by a supply side treaty is that higher prices provide a positive spillover for countries not (yet) partecipating the bans, provided the market share of the coalition is large enough that remaining producers cannot meet global demand for the fuel. Moreover, the high prices grant higher profits to the fossil fuel industry and exporting country, despite the reduction in global demand.

On the other hand, supply side treaties comes with additional costs for the global stage. The increase in monetary costs is not surprising, since carbon taxes are - within a neoclassical modelling framework - the least cost and most efficient solution to internalize the carbon externality. About that, however, the reader has to keep in mind that we are comparing an exogenous trend for supply side policies (which imply inefficiency within the model) with an endogenously fitted carbon tax (which provide the least cost solution within the model assumptions). In the real world, where it's impossible to know exactly the social cost of carbon or the shadow cost of transition, a carbon tax would be equally if not potentially more inefficient than its supply side counterpart.

Conclusions

This assessment of supply side policy on fossil fuel extraction seems to suggest potential of application as medium-term substitutes or as complementary to demand side policies. It highlights positive spillover for countries external to the coalition if the latter is large enough to impact the global quantity of fossil fuels extractable. Potential critical points lie in higher cost of policy per emission reduced and reduced energy security for early participant in the treaty in the transition phase. The main modelling caveat of this analysis is that no strategic interaction between producers is allowed. This may be an acceptable hypothesis for coal and partly for gas, but it clearly doesn't reflect the reality of the oil market. However, as our scenario models global (albeit non uniform) participation, the effect of strategic interaction would be seen only in the transient phase between frontrunners and follower action. Regarding future work, this assessment provides the ground base for further exploration of various aspects to which here we provide only preliminary answers: in particular, the role of supply side policies as insurance against failure of carbon pricing and a framework to study

the effectiveness (given certain conditions and shape) of a non-global coalition of the willing relying on both mitigation instruments here proposed.

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Chapter 1

Context, literature and research questions

In this chapter, we start with a very broad introduction on climate change and its interaction with human system, with a particular focus on how the characteristics of the problem shape the research and the methods used to assess its implications, namely the Integrated Assessment Models.

Afterwards, we focus on the available policy toolkit for climate change mitigation, highlighting the distinction between demand side policies, such as carbon pricing, and demand side policies such as extraction ban for fossil fuels. We then focus on the latter instrument and review the literature that has been calling for an exploration of the potentiality of these instruments in substituting or complementing the "standard" policies.

Finally, we summarise the scope of the work and the research questions.

1.1 Climate change and mitigation

We define climate change as the geophysical process of increase in energy input in earth's energy balance due to higher anthropogenic concentration in the atmopshere of CO2, CH4 and others greenhouse gases (GHGs) observed during the last 150 years. This phenomenon, due to the interaction of these atmospheric gases with the portion of solar radiation re-emitted by earth's surface, was firstly recognized in the XIX century and it is now widely accepted as the primary cause of empirically observed global mean temperature increase with respect to pre-industrial age, ice cap melting, sea level rise and others phenomena associated with the increase of energy in the atmosphere and oceans (IPCC, 2014).

Equally accepted is, as of today (IPCC, 2014), the anthropogenic nature of the increase of atmospheric concentration of GHGs, the largest share of it being associated to fossil fuel's burning for energy production, industry and transportation.

The projected impacts of climate change span from decades to centuries in timescale and effect a great number of aspects of the biophysical sphere: sea level rise, permanent ice and permafrost melting, increased extreme weather events, desertification, loss of biodiversity, ocean acidification (IPCC, 2014, 2018).

The magnitude of these impacts is in the vast majority of cases smoothly proportional to the cumulative quantity of GHGs emitted (CO2 being the most relevant for its greenhouse potential and very slow decay due to natural processes), at least until a tipping point [1] is reached for that specific phenomenon or for the underlying energy balance dynamics as a whole.

The economical dimensions of climate change

As most of the above listed impacts would cause damages to human societies, ranging from significant to potentially catastrophic and civilization threatening in case of extremely high radiative forcing, the conclusion when it comes to anthropogenic

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[1] a threshold that activates positive feedback loops

emission would seem to be that the less is better.

Our economies and societies, however, heavily rely on fossil energy to ensure the unprecedented level of distributed wealth humanity have ever experienced. Shutting down overnight every coal power plant, natural gas boiler and internal combustion engine is clearly not an option.

This conflicting necessities of stopping climate change at a manageable level of impacts (given uncertainty) and ensuring at least constant level of wealth for the developed countries and a shot at development for underdeveloped ones creates, at his very root, the fundamental issue of climate change.

The solution require to transform as quickly as possible our societies to reduce and eventually get to zero GHG emissions without jeopardizing (even improving, if possible) the continuation of existing trends in wealth increase and human development. As a certain amount of damages from climate change is unavoidable even at the current level of warming, *adaptation* of human societies to residual unmitigated impacts - by technological, behavioural and institutional means - will contribute to human resilience in the face of climate change. Both these complementary strategies are, however, costly for societies, at least for aggressive targets: if we imagine mitigation costs as an increasing function of avoided emissions and adaptation costs as an increasing function of climate impacts, these costs imply a trade-off with the the benefits they provide in the form of avoided impacts.

This framework was firstly conceptualized by Nobel laureate William Nordhaus (Nordhaus, 1993) within the context of the DICE model, father of Integrated Assessment Models for climate change: the resulting formalization takes the form of a time-discounted cost benefit analysis in which the optimal level of mitigation [2] is found where the marginal net present costs of mitigation equal the net present marginal benefits of avoided impacts.

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[2] Nordhaus' original version of DICE did not include adaptation as a coping strategy to climate impact. As adaptation can however be modelled as a downward shift in impacts cost curve (assuming it is undertaken only when its cost are lower than the adapted impacts), its absence does not jeopardize the validity of the conceptual framework

This formulation has been at times criticized because it fails to include co-benefits of the energy transition [3] and tends to consider transition costs as a static component of the scheme, while it is argued that in some cases technological development and economic-societal transformative capacity can very well transform liabilities into opportunities [4]. However, the backbone of Nordhaus' theoretical structure is by far the most used in modelling and academia to conceptualize and assess quantitatively the problem.

The inter-temporal dimension of climate change

Brilliant and fundational to the discipline, Nordhaus' highly aggregated (top-down) approach captures in its simplicity the fundamental dynamics we described. Furthermore, it highlights another key factor that contributes to make climate change, so to speak, *the perfect storm* of contemporary global issues: its inter-temporal dimension. As mentioned before, most climate impacts will be fully felt by human systems in many decades if not centuries, because of the huge inertias in our planet's geophysical system. Mitigation costs, on the contrary, are sustained mostly in the medium-short run (a few decades). This generational strain between who bears the costs and who reaps the benefits of climate action is arguably one of the main causes of inaction in climate mitigation, and it is reflected formally within the modelling framework of IAMs via the discount rate of pure preference, meaning the relative weight assigned to a certain amount of utility in the future with respect to the same amount in the present. This parameter allows to reduce future costs and benefit occurring at different times to a Net Present Value (NPV). Clearly, cultures with different social preferences over future consumption will choose very different path of action regarding the exploitation of exhaustible goods such as extractable natural resources or, in this

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[3] with air pollution to cite the most common, or see the democratic energy theory for a less obvious proposal (Burke and Stephens, 2018)

[4] see for example the debate on coal vs renewables jobs

case, remaining carbon budget [5]: if the discount rate is zero or lower - modelling a society for which the welfare of future generation is as or more important than the present ones - the agent(s) will tend to be willing to sustain higher costs to grant the lowest future impacts; if on the contrary the discount rate tends towards 1, future consumption is valued asymptotically to levels approaching zero and such a myopic society will behave up to the extreme consequences as if the problem didn't exist at all.

It is evident that the choice of such a parameter entails very strong ethical consequences, and the proper value to be used within IAMs as well as the moral legitimacy of using a discounted framework in the first place is a constant point of debate in the integrated assessment community (Emmerling et al., 2019). Methodologically, such a delicate matter also invite the reflection on the dualism between descriptive and normative approach to the choice of the parameter: the former implies an empirical estimation of a best guess value from economics and it's the path followed by Nordhaus; the latter can lead to considering near zero or even negative discount rates (Weitzman, 1998).

Threats, challenges and opportunities posed by the very nature of climate change and its interaction with human systems don't, however, stop here. Of all the dimension of human activity that climate change crosses, at least three more must be included in a sufficiently complete conceptual framework: the technological dimension, the international or cooperative dimension and epistemic dimension.

As a proof of their importance to the matter, the study and integration of these aspect in integrated assessment models has absorbed much of the effort of the researchers' community in the past two decades, leading to the transition from simple top-down global models like DICE to technology detailed and regionalized bottom-up or hybrid models like, among many, the WITCH model used in this study.

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[5] meaning the cumulative residual emissions allowed to remain, with a certain probability, below a certain level of radiative forcing, temperature or concentration of CO2

The technological dimension of climate change

As already pointed out, mitigation of climate change implies first and foremost phasing-out fossil fuels. The technological implication of this transition are self-evident: reducing and eventually eliminating the reliance on fossil fuel burning requires a viable bundle of low emissions substitute technologies for electricity production, transportation, heating and industry. These technologies must be competitive both in the quality standards they provide to the final user and in their relative costs with respect to the existing technologies they are supposed to replace. This means fostering already mature technologies such as hydro power and nuclear on the one hand, favouring the scaling-up and development of existing technologies like wind and solar and conceiving new solution for sectors, like aviation and shipping, that as of now lack for it.

In order for it to happen, government can rely on a portfolio of policies (described in detail in section 1.2) to support technology development at his earliest stage and to alter the market environment incentivizing or enforcing low emission solutions while discouraging fossil fuel based technologies.

As much as the technical challenges posed by the required pace of transformation of our means of producing and consuming energy are monumental, huge progresses have been made in this direction in the last twenty years. In particular, intermittent renewables penetration in the electricity system continues to increase at an exponential level and their costs kept decreasing at a level that it's now competitive with fossil fuel generation. While an electric system with very high level of intermittent generation capacity poses a challenge to security and availability of supply, there's increasing confidence that decreasing cost of storage means that batteries will make the issue manageable. Batteries will play a fundamental role also in the electrification of the transport sector, effectively shifting the energy load of road transport to the electricity production sector. On top of that, efficiency improvements across all sectors and industries have played and will play a huge role in emissions reduction, reducing the economy's requirement for primary energy.

Moderate optimism in the technical feasibility of the energy system decarbonization is also backed by past experiences in scaling up, phasing in and phasing out of new or old technologies, notable examples being gas turbine development for the first process, increase in nuclear penetration in France during the 70s for the second and the quick disappearance of oil from the power system in western states after the oil crises in '73 and '79. The speed of these technologies shifts (none of whose were climate driven) occurred in around a decade and are compatible with the pace of change required for aggressive climate change mitigation. Intermittent renewables penetration increase and coal phase-out in most advanced economies are hoped to follow a similar trend in the next decade.

At the end of the day, there seems to be ground for hope that human ingenuity, if properly directed, can overcome the technological challenges posed by the necessity of climate change mitigation.

The international dimension of climate change

The last aside, however, is not a small nor inconsequential one. I have already highlighted how much the intertemporal asymmetry of costs and damages can cause a disincentive for political action on climate mitigation if national institution act like short term miopic optimizers (or, more or less equivalently, show very high implicit social pure rate of time preference); another potential cause of inaction, widely understood in the scientific literature, is the global dimension of climate change effects and impacts coupled with the anarchic structure of the international system.

The recognition of the problematicity of this *iatus* between the existence of global common goods on one hand and the westfalian state-centered international system on the other dates back at the origins of environmental economics and was evocatively defined in 1968 by Garret James Hardin as *the tragedy of the commons.*

The idea behind it is that states who have collective interest in ensuring the provision of a costly common good - such as maritime trade security, world institutions or, in our case, climate change mitigation - may underprovide for that good in the expectation that someone else will bear the costs of its provision while the *free-rider(s)* can still enjoy its benefits (given the *non-excludability* [6] of a common good). Such a situation can lead to different equilibria as a function of the costs (relative to the actors' ability to pay) and benefits of the provision of the common good. If the total cost is bearable by a single country or a small and stable coalition and lower than the benefits they will reap from the consumption of the good, they will tend to ensure the availability of the good regardless of the other States' participation, *de facto* allowing them to free-ride on their efforts [7]. If, however, the total cost of provision is such that it's impossible for a single country (whereas powerful and rich) to sustain its burden, the resulting strategic interaction will resemble the dynamic of a prisoner dilemma game, where the stable equilibrium entails a deviation from the maximization of social (and individual) welfare. State actors will thus tend to engage in an equilibrium that implies an overall under-provision of the global common good. Climate change mitigation belong to this latter category.

To make it worst, abatement potential [8] and expected damages are highly asymmetrical between countries: the vast majority of emissions and wealth necessary to sustain the transition is concentrated in the global north, while developing or underdeveloped equatorial nations are projected to sustain potentially crippling physical damages. Northern countries like Canada, Russia or Scandinavia are even projected to face gains from temperature increase according to recent empirical estimations of climate impacts on productivity and GDP (Burke et al., 2015). Needless to say, such distribution of costs and benefits exacerbates the incentive for inaction and hinders the stability of effective coalitions (Bednar et al., 2019). Interestingly, this statement

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[6] meaning the impossibility of excluding an agent from the consumption of such good

[7] such is, in certain institutionalist interpretation of international relations, the situation that occurs when a global hegemon - Romans in the mediterranean, the British empire in XIX century and the USA today - grants the openness of sea trade routes via the military control of the seas

[8] an inverse function of mitigation costs and directly proportional to emissions

holds essentially true even if a certain degree of (inter-state) inequality aversion is considered, relaxing the hypothesis of pure egoistic actors and modelling empathy within the system.

Extensive literature has been developed to study and propose solutions to the coordination dilemma that emerges from the international structure of climate change mitigation, while Paris agreement structure was an attempt to circumvent the problem creating a voluntary and modular framework that would involve the largest possible coalition. The retirement of the US from the treaty, however, cast serious doubt about its efficacy. Notable attempts of proposing a feasible solution to the coordination dilemma draw from successful regimes [9] or clubs the idea of designing a scheme of incentives and threats in order to increase the willingness of participating the coalition and deter free-riding, ultimately altering the cost-benefit structure of the problem to increase coalitional stability (see for example Nordhaus (2015) for an elegant attempt to prove the stability and effectiveness of tariff based climate clubs).

The epistemic dimension of climate change

I have briefly tried to sketch the implications of the long term and long lasting nature of climate change impacts. This characteristic, however, calls for the discussion of another kind of issue that intimately relates to all the previously discussed dimensions.

Poorly speaking, the problem is that the future is, by definition, uncertain. Very distant futures even more so, and if our conjectures about those possible futures involve considerations of complex systems dynamics and voluntary action of sentient beings the space for sensible forecasting dramatically tightens. When prediction is not an option (unless one desires to learn the art of reading birds entrails), coping with structural uncertainties becomes imperative and instruments must be developed to integrate them within every decision making framework that deserves some credibility, be it implicit or explicit like a formal model.

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[9] see Keohane (1984) for a definition

The amount of uncertainties involved in thinking and modelling the energy-economy-climate nexus is huge and embroils every link of the chain. Starting from the underlying and complex physics of the carbon cycle, the best guess estimate for the nexus between CO2 emissions, concentration and equilibrium temperature increase has remained somewhat constant (see CMIP5 vs CMIP6) in the last decade in its median value, but the tails of these estimates are significant. Assumptions about future costs of existing or hypothesized technologies also entail some degree of uncertainty (as well as the possibility of future development in breakthrough technologies) even if the mechanisms of endogenous technological development and scaling down of costs has been widely studied by great economists like Romer and Krugman, thanks to whom we now possess means to model quantitatively those dynamics (Romer, 1989). Projecting key socio-economic variables like GDP, population and development patters is also a huge challenge, as they depend from both unpredictable shocks - economical or political crises, pandemics, wars - and underlying dynamics - education trends, political stability, international environment, economic opportunities, quality of the ruling elites - which interact between each other in non trivial and often non quantifiable ways. Finally, general costs of the energy transition and above all the impacts of climate change on the economic system constitute perhaps the most critical area of uncertainty, with damage estimates ranging from few percentage points of global GDP in 2100 in the most diresome emission scenarios up to 20-30% (Burke et al., 2015; Nordhaus, 1993).

Modellers have developed a basket of techniques to cope with these uncertainties. As for parametric uncertainty, sensitivity and robustness analysis around the central mean estimate of the uncertain value(s) help to validate the results or at least highlight if a critical parameters is driving results. Model uncertainty, which relates both to the unavoidable simplification of the dynamics in play on the one hand and to the multiplication of uncertainties in multiple interacting parameters [10], has

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[10] as these model use thousands of different parameters, cross-sensitivity for each it's clearly not an option

been historically dealt in the Integrated Assessment Models community with parallel development of multiple models by different research groups and by using them as robustness tool in multi-model assessments, of which this study is an example. These techniques help dealing mostly with the first two areas of uncertainty described before, namely the climate response and technological or economical assumptions, which then translate into marginal abatement cost curves in bottom-up, detailed IAMs.

Long-term projection of socio-economic trends as well as assumptions about political behaviour pose, however, a particular challenge and thus require ad hoc solutions. The challenge resides not only in that the range of possible evolution of such dynamics is too vast to be summarised in a best guess estimate, but also in that these factors interact within each other in ways that imply a *narrative coherence* among them. So, for example, is very hard to imagine a fast demographic transition in condition of sluggish growth and development, or sustained global economic growth in a world of rising tension, conflict and deglobalization. If such an inter-linkage of systemic variables is in a way beneficial because it restricts the range of likely futures, it demands an approach that tries to capture and explicitly maintain this complexity, instead of reducing it.

Such considerations brought the modelling community to develop the Shared Socioeconomic Pathways (Riahi et al., 2017), a scenario framework that groups key socio-economic projections into 5 different storylines, each internally coherent and sufficiently differentiated from one another in quantitative terms to provide meaningful research insights.

Regarding uncertainty about impacts, I already highlighted the enormous range of economic damage estimates. Adopting a Nordhaus style top-down approach or a econometric bottom-up damage functions can lead to very different results in a Cost Benefit Analysis as described in section 1.1, as far as considering the optimal temperature for the overall planet welfare around +3C with the former and near 1.5C for the latter. While debate persists in the climate community, it is generally accepted that the latter are - while more pessimistic - closest estimates of the shear magnitude of climate change effect on socio-economic human systems. Moreover, economic damage functions typically employed in IAMs typically express damages as a function of temperature. Some climate scientists have argued that this is a flawed approach, because effects of equilibrium temperature on economic output fail to consider other kinds of damages correlated but not directly caused by temperature increase (sea level rise, extreme events, ocean acidification, natural capital destruction). Once again, the constant effort of the scientific and modelling communities is currently working to bridge these knowledge gaps, both at the empirical and modelling level, making it an active and evolving area of research.

In this sense, it has been argued that different estimates of economics impacts of climate change do not reflect uncertainty but *ignorance*, meaning not only lack of knowledge about likelyhood but also about outcomes (Stirling and Scoones, 2009). However, the cogency of this argument has been progressively diminishing because of recent introduction in the literature of better and more complete estimates, and it is true that better understanding of temperature effects and other kind of impacts is bridging what is prescribed as optimal by CBA analyses and the agressive temperature targets prescribed by the Paris agreement.

Anyhow, implicit recognition of these criticalities brought the modelling community to largely move away for CBA and prescriptive analysis to focus on Cost Effective Analysis, engaging in backcasting exercises. Climate targets are, in this framework, not an objective of the model but a target constraint under which the least cost transition is to be found as an optimal solution. IPCC has summarised this approach by calling for research that would be *policy relevant, not policy prescriptive* IPCC (2014) IPCC (2018). Such a method has the important merit of removing the necessity of estimating damages, thus shifting the core of the assessment to mitigation costs - much easier to estimate since primarily dependent on technological system. Of course, ultimately, the policy choice of how much mitigation is a desirable target for the global community still depends on expectation about future damages, so the problem is - so to speak - avoided but not removed and remain implicit in the climate debate. This is even more true as, while the global community has formally accepted in its vast majority to shoot for a very aggressive mitigation target in the Paris agreement, stated policies are in many case revealing of a different level of ambition, signaling that the debate about the optimal level of mitigation is still alive among policy and decision makers. In this sense, Cost Benefit Analysis or approaches rooted in risk management analysis still compose a relevant part of the literature.

In conclusion, uncertainty has huge implications for research and research methods in the climate-energy-economy nexus area. Moreover, Drouet et al. (2015) show that aversion to costs and damages uncertainty provides a comparable disincentive to action as the inter-temporal preferences discussed in section 1.1, making uncertainty management vital not only as an abstract modelling issue, but also entailing crucial practical consequences in a policy-making perspective.

1.2 Policy instruments for climate change mitigation

I have already stressed in section 1.1 that the technological transformation required to transition the energy system towards clean substitutes must be guided by policy. In particular, the role of the legislator must be that of internalizing the global externality that GHGs emissions constitute by manipulating the market environment via price or quantity mechanism.

The latter distinction is the first and perhaps most relevant categorization of climate and environmental policies. As it is fair to assume, price mechanisms work by manipulating the relative price in the market of polluting goods, either increasing the price via Pigouvian taxes proportionally to their emission intensity or decreasing the price of clean substitutes via incentives. The resulting interaction in the market would then lead to reduced consumption of goods with high polluting content relative to their clean substitutes, in accordance to neoclassical price-quantity equilibrium dynamics. Quantity mechanisms, on the contrary, act by enforcing the maximum quantity of pollution that producers of the final good are allowed to emit: this in turn will cause either a reduction of the total amount of the final good circulating in the market, if it's not possible to reduce the specific content of pollutant it embeds, or a reduction of the specific content of pollutant due to less emitting production methods. In either case, however, price will increase (at least in the short term): in the first scenario, it will be because of lower quantity supplied facing the same aggregate demand; in the second, because the price of the good produced with the new, less polluting methods will embed the increase in cost of production due to the shift. This last statement rely on the assumption that firms produce at the frontier of their production curve and with the best technology available, such that any shift in the ways of production will result in an overall increase in costs. As much as this hypothesis may be fairly standard in neoclassical environmental economics, it may be not the case for real world industries, in particular in low competition sectors, that could face little to no incentives to innovate their production methods. In such cases, incentives to shift to cleaner processes may as well result in ultimately lower cost of production.

In the end, both price and quantity mechanisms ultimately aim to reduce the total pollution emitted by the market, either by decreasing the overall quantity of the polluting good consumed or by changing the specific quantity of pollution embedded in the good. Towards which one of these two poles the corrected market equilibrium will tend depends on two interacting factors: the availability of substitutes (at a certain point in the production chain between the polluting row material and the final good, each step having its own market) and the elasticity of demand for the final good. The more substitutes the polluting material or process has (including efficiency improvements), the lower the cost of converting such process or procuring alternative raw materials. The more elastic the demand for the final good (either because of availability of consumption substitutes or because of low marginal utility derived from the consumption of said good), the more efficient the price signal will be in decreasing demand.

Clearly, this implies the existence of a worst case scenario of low substitutability of the polluting process and very inelastic demand for the final good. In such a market, both price and quantity instruments would ultimately cause a shock to the market the costs of which, at least in the short run, would result in a overall loss of total surplus and/or a transfer from consumers to producers or governments (who collect the tax revenues). Furthermore, such damage to consumers (and especially consumers with low purchasing power) would not be counterbalanced by a meaningful reduction of pollution, making the policy both regressive and ineffective: this is particularly true for price mechanisms, that in such an environment would result in a market equilibrium with virtually the same quantity consumed and higher prices facing consumers; quantity mechanisms here are more "effective" in terms of pollution reduction but equally or more disruptive in terms of total society surplus. An example of such a situation may be found in the oil crises of '73 and '79, when the reduction of oil supply by OPEC caused an extreme increase of prices and consequent disruption in industrial production and vital consumer services. The unintended effect of the crises was indeed a reduction in emission for the following years, but the shock to the system was arguably much costlier than the very modest benefits from emission reduction. The example, however, remains instructive because of the long term effects that the shock had in the energy system in the medium-long run: in the sectors where the substitutes of oil existed, like power production, the west phased out in less than a decade virtually its entire fleet of oil fired plants, a very short time-frame considering the large inertias of the power production sector; where they didn't, it contributed to start a process of research and development for such substitutes, like in the transport sector.

If either the process has relatively cheap substitutes or the demand is very elastic, on the other hand, the market effects following the implementation of the policy would be way less traumatizing and, in general, more effective. A suitable example for this is the ozone layer and CFCs.

In the specific case of climate change, however, final goods with high GHGs emissions (electricity, heating, transport and agricultural goods) tend to be inelastic or very inelastic. The main differences thus lay in the availability of substitutes for the process or the material with which the final good is provided. Particularly for energy and transport sector, though, it is very important to stress that the degree of substitutability is a function of time as it depends on the technological inertias of the system. The latter factor determines the threshold between "short-run" (days) - that relates to dispatch and consumer decisions on the spot market, "medium-run" (months to years) - that relates to production and investment decisions as well as change in behavioural patterns for consumers and "long-run" (many years) - that regards technological development and R&D investments. In general, inelastic market will be rigid in the short-run regardless of the availability of substitutes, but they can be flexible enough to stimulus in the medium-run if said substitutes exist. If that's not the case, only in the long run policies can have a desirable effect by redirecting technical change towards cleaner technologies.

The effect of climate policies in general must then be considered twofold: for "easy" markets, substituting polluting good/processes with non polluting goods/processes in the short-medium term; for "difficult" markets, redirecting technical change *or behavioural patterns for consumers* so that, in the medium-long run, pollution reduction becomes a viable and cheaper option for that market, ultimately increasing substitutability or elasticity of consumption.

It is not possible, however, to state a clear prominence of one type of instrument (price or quantity) over the other following this framework. In order to explore which policy is better suited for which job, we need to introduce some further classifications, splitting climate policies into supply or demand-side instruments and supportive or restrictive tools. The first distinction depends on the level where the policy is adopted, if at the source of the pollutant (i.e extraction and selling of hydrocarbons) or at the final good level. The second depends on the policy targeting the polluting sector/process/final good(s) or its clean(er) substitutes, hindering the former or incentivizing the latter. The possible combination of these two categorization generate a matrix of the climate policy toolkit (Green and Denniss, 2018), resulting from the cross-product of two dimensions: supply or demand side policy on one hand, supportive on restrictive policies on the other. The distinction between price and quantity mechanism complete the picture, so that it is possible to design a restrictive market-based demand-side instrument like a carbon tax, or a supportive market-base supply-side instrument like incentives to renewables.

Historically, these last two examples are in fact the most used and advocated instruments for climate policy, due to a mix of economical, political and technical reasons. Incentives to renewables are politically appealing because they are not labelled by the general public as "taxes" and, while they tend to favour new capacity installation of the subsidised technology, they don't produce a direct price increase for the final consumer. That's because they tend to artificially lower the production costs of renewables to the level of fossil fired plants, while a carbon tax operates with the opposite logic.

On the other hand, carbon taxes, even if they targeting directly consumers increasing final prices, are regarded as the golden standard of climate policies (and environmental policy in general), being a theoretical *first best* solution according to neoclassical economics. In fact, in a market environment populated by profit-maximizing firms who face perfect competition and perfect information, a carbon tax grants efficient reallocation of resources and produces the lowest-cost combination of input choice, end-of-pipe treatment, and output reduction (Stavins, 1997). This would include research and development of substitutes, that - if arbitrarily incentivized via selective direct investments subsidies - can create unnecessary distortions in the market, due for example to political lobbying and non economical idiosyncrasy by governments or the general public. A more mature approach, however, tends to recognize that these two kinds of policy act as complementaries, at the point of mutually reinforcing each others (Kennedy, 2018): directed innovation and supply-side incentives contribute in lowering the cost of the technology during development and scaling-up when the risk of failure are higher, while the carbon tax grants an efficient allocation of resources when the technology is at later stage of development and modifies expectations about future competitiveness of different technologies. Moreover, recycling carbon tax revenues into R&D investments for green technologies can create a positive feedback loop (Marangoni and Tavoni, 2014).

Coming back to the distinction between "easy" and "difficult" sectors, it is possible to conclude that supportive policies are more suited for markets with very little competition from "clean" substitutes in order to stimulate their development, while restrictive policies require a sufficiently mature market to be effective.

However they may interact, it should be noted that both these kind of policies fall within the category of market-based [11] instruments, providing incentives to or hindering certain portions of the market without explicitly enforcing performances. This evidence reflects a well rooted preference for market or quasi-market instruments within both the dominant political economy practice of liberal capitalist democracies and neoclassical economic theory, whose arguments revolve around the idea in the superiority of markets in allocating resources and information (even when admitting the possibility of market failures, a foundational assumption of environmental economics in general).

This position, however, has been recently challenged by Lamperti et al. (2020) who, drawing from a classical critique in Weitzman (1974) about the presumption of superiority of price instruments over quantity regulation [12], compares the effectiveness of price (carbon tax and subsidies) and quantity (command-and-control) instruments

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[11] a relevant exception here is ETS, a cap-and-trade system which falls under the category of quantity based "quasi-market" instruments

[12] where he argues that neither instrument is superior a priori, but depending on the relative shape of the abatement cost and benefit curves

in redirecting technical change in the context of climate mitigation. In the context of a top-down Agent Based Model, Lamperti and colleagues' model suggests that the latter are more effective of the former in redirecting society to a stable and 'clean' equilibrium. This conclusion holds because price instruments suffer from a limited time window of effectiveness whose length depends on past stock of innovation capital invested into dirty inputs, while command and control regulation are always able, if properly designed, to move a society stuck in the bad equilibrium to the clean one. Given that delay in climate change action is a certainty of the present and a concrete possibility for the future, this argument possess a strength that compels a discussion about the viability of large scale command-and-control regulation in climate policy, even if one accepts the aforementioned arguments about their cost inefficiency with respect to market instruments.

On a complementary front, the idea of restrictive supply-side policies - extraction or exploration ban on fossil fuel production - has been recently gaining momentum in the literature. The main arguments supporting this claim are described in detail in the next paragraph, but it's relevant to stress out here that, while these authors are officially agnostic about the market or quantity-based nature of such instruments, most of them suggest that command-and-control regulation would be better suited for the job, due the peculiar characteristic of the fossil fuel market such as high physical and capital concentration of the resources.

The combined suggestions provided by these two trunks of literature thus constitute the theoretical rationale underling the choice of exploring the consequences of extraction ban in detailed energy system Integrated Assessment Models. The nature of the models does not allow to capture many of the sophisticated economical interactions discussed here. They do, however, provide a novel insight on the implication for such policies in the energy system and validate with a semi-empirical method some of the arguments exposed below.

1.3 Supply side policy: the road less taken

The first direct reference to restrictive supply side policy can be traced to Sinn (2008). Sinn argues that demand side policies have two fundamentals flows: one the one hand, an international carbon-leakage effect due to the depressing effect of international fossil fuel prices in case of coalitional demand-side policies; on the other, an inter-temporal effect of increase in short-term supply of fossils due to expectations of strong future demand side policies, that he called *the green paradox effect*.

The rationale for the first mechanism is straightforward: if a country or a coalition implements a sufficiently strong demand-side policy, its consumption of fossil fuels will inevitably decrease. This reduction will cause, *ceteris paribus*, a depressing effect on international fuel prices because the same amount of fossil supplied will be met by a lower global demand. In turn, lower fossil prices will result in a rebound effect outside the coalition, as they will face lower prices and no disincentive from demand-side policies.

The core of the Green Paradox argument lays on the mutating cost-opportunity expectations for an exhaustable resource subject to a restrictive policies. In a fossil fuels' producer perspective, it is rational to produce only as much as necessary to satisfy a certain amount of the demand if the expectation is one of increasing consumption with time, both because it keeps prices high in the present and it allows for the marginal quantity of fossil fuel extracted to be sold in a future environment of higher demand and lower supply (due to resource exhaustion). If, however, producers foresee a decline in future demand they may change their cost-opportunity estimates and increase present production to extract as much rent as possible from the fossil fuel reserves while they are still valuable.

In this sense, expectations about future and strong demand side policies can result in an overall increase of consumption and emissions in the present, even if a weak carbon tax or cap and trade system are in place.

Neither of these phenomena can occur, Sinn argues, if restrictive supply side policies targeting directly fossil fuel production are put in place, either stand alone or complementing existing demand side policy: in the first case, because they counteract the depressing effect of price responsible for international the rebound effect; as for the green paradox effect, because a command-and-control regulation, unlike a carbon tax, is infinitely bounding at its margin (i.e the marginal cost of producing an extra gallon of oil above the allowed threshold is, ideally, infinite).

More recently, Lazarus et al. (2015) sketched a review of existing and possible supply side projects categorizing them into market, quasi-market and command-and-control regulations, while Lazarus and van Asselt (2018) resume Sinn's arguments and raise further points in favour of the application of supply side policy.

First of all, they highlight that supply side policy widens the policy portfolio thus, in principle, flattening the abatement cost curve for fossil fuel producing countries. Secondly, they can provide a clearer signal to the financial system and other governments leading to lower investments on fossil fuels' upstream and midstream sectors. This is especially important since it mitigates the scale of *carbon lock-in* effect, i.e the hindering effect on climate action that investments on carbon intensive infrastructure with long life-cycles has because it generates *stranded assets.* Third, being more direct and observable in its effect than a carbon tax, supply-side action can increase moral pressure and public support, because it targets companies directly (and according to many, morally Ayling and Gunningham (2017)) responsible for climate pollution. Finally, they remind drawing from Green and Denniss (2018) that supply side regulation has seen many successful applications in other contexts such as the tobacco industry.

Shortly after, Asheim et al. (2019) reinforces Lazarus and colleagues' conclusions. He organizes its arguments into four points:

1. if coupled with a demand side-policy, it attenuates the free-rider effect, as supply-side action should countervail carbon leakages by keeping international market prices high. This argument is a reframing of the green paradox effect.

2. it fosters green R&D. Higher fossil fuel prices encourage R&D investment in green technologies raising expectations about future lower clean energy prices.
3. it provides a back-up for possible demand-side policy failures. It restricts fossil fuel production reducing carbon emissions, and in the case of success of the demand-side policy it comes for "free", because the extraction bans become non-binding in a low demand environment.
4. signaling an environment of future restricted supply, it can avoid excessive planned investments on the fossil fuel upstream sector, reducing future stranded assets.
5. unlike demand-side policies, supply-side policies increase fossil fuels prices and the income per output, therefore gaining producers support.

Even if they concern different areas, most of these considerations rely directly or indirectly on high market prices as the main difference between policies targeting the demand side and a supply side approach.

While many of these papers are explicitly agnostic about the specific kind of policy instrument to be used in the context of supply side policies between market instruments (such as ending public investments on fossil fuel industry) and quasi-market or command and control instruments (such as quotas and extraction or exploration ban), most mention the latter option as the better suited for the task, both because the high concentration of the upstream sector makes it possible to effectively apply extraction bans and because not in all regions the public support is vital to the survival of the fossil fuel industry.

1.4 Research questions

This work aims to respond the call for further exploration of supply side policy summarised in the previous section. To do so, we use several global Integrated

Assessment Models engaging in a multi-model exercise lead by CMCC. Our direct contribution to the project, reported in this thesis, was carried out with the WITCH model. Using a detailed energy-economy models with global scope and regional disaggregation allow us to explore, in a first-of-its-kind assessment, the implications of supply side policies in the energy system and the international fuels markets.

In particular, drawing from the theoretical literature, we identify some critical point to analyze:

- the effect of global-scale extraction bans on international fuel prices. The structure of the model allow us to directly investigate this dimension, as it contains a representation of global fossil fuel markets.
- the effect of fossil fuel scarcity on the energy system. In particular, we investigate if and how much supply side policies can substitute or complement carbon pricing scenarios aiming for a Paris compatible target (ie well below 2C). Containing a detailed representation of the energy system, the WITCH model is well suited for the task.
- the effect of fragmentation in the enforcement of the supply side treaty on international fossil prices. In order to do so, we designed a scenario in which regions enter in the supply side treaty at different speeds, following an exogenous narrative we designed.
- the effect of supply side policies in changing the international fuel market landscape, in terms of producers revenues and energy security.

Chapter 2

Methods

In this section we discuss the methods. First of all, we briefly describe the WITCH model, with a focus on the current representation of fossil fuel extraction and investments. Then, we describe the modification to the extraction algorithm for gas and coal that was necessary to implement the scenarios.

Afterwards, we describe the scenarios we designed in order to explore supply side policies, with a particular attention on methodological coherency in the design phase. Finally, we focus on the development of the narrative for SUP, a scenario in which the supply side treaty is joined globally but with different timing and speed for different regions.

2.1 The WITCH Model

The WITCH model is a state of the art integrated assessment model maintained and developed by RFF-CMCC EIEE that aims to assess climate change mitigation and adaptation policy. WITCH is a perfect-foresight general equilibrium optimization model, based on a mixed bottom-up and top-down approach: the economy is modelled as a Cobb-Douglas function that nests Energy, Labour and Capital. The energy supply is described as a nested CEST production function in which technologies are substitutable with different elasticities of substitution. Single technologies are then modelled bottom up to carefully model costs and constraints. WITCH also allows for R&D development, both learning by doing and learning by researching, in key technological areas such as efficiency and renewables. The model is multi-regional and allows for non-cooperative coalition. Each coalition maximize its own intertemporal discounted utility as the logarithm of consumption per capita.

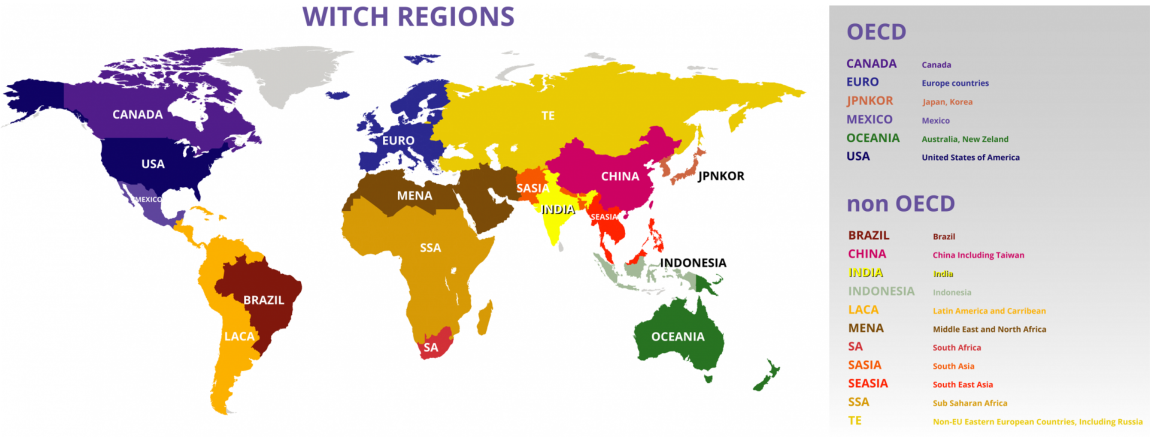

Figure 2.1. Regions in the WITCH model

WITCH thus solve as many internally optimized NLP models as many coalitions are active (up to 17 regions, Figure 2.1). That means that global aggregate variables such as fuel and carbon markets cannot be solved within a single iteration, as the production/consumption of each regions depend on the other region solutions. In order to reach a global solution, an iterative approach is then necessary and market balance of carbon and fuel prices is granted via iterations thanks to an ADMM algorithm

(Boyd et al., 2010).

For extensive documentation about the model nature, see `https://www.witchmodel.org/documentation/`.

Fossil fuel extraction and trade in WITCH

In the main version of WITCH, the models for fossil fuels extraction and market differ: while oil is fully integrated within the main solver and full optimization of extraction and infrastructure is allowed, coal and gas extraction is managed by a pre-solve (before each iteration of the main solver) heuristic algorithm that, given global demand, assign price and regional productions according to calibrated global and regional production curves.

Oil extraction

Oil production must, in all regions and at all times, be lower than the available infrastructural capacity:

$$OIL_{prod}(t,n,g) < OIL_{cap}(t,n,g) \tag{2.1}$$

Where g refers to the grade of oil: higher grades have higher base unit costs of extractive capacity and higher CO2 emissions coefficients. The higher costs are intended to reflect both increasingly difficult geologies and increasingly difficulty of discovery.

The production capacity is modelled as a cumulative-built, depreciating capital stock:

$$OIL_{cap}(t+1,n,g) = OIL_{cap}(t+1,n,g) \times (1-\Delta) + \Delta CAP(t+1,n,g) \tag{2.2}$$

New capacity requires proportional investments, whose costs is governed by three elements:

- a specific investment cost that represents a cost floor (specific to each category).
- a short term cost component that becomes large if investments exceed a certain threshold to mimic adjustment costs and reduce incentive to over-invest in oil extraction capacity
- a long term cost component that is inversely related to remaining oil resources for each category, to reflect resource depletion effects and smooth the transition from a lower (cheaper) to a higher (more expensive) category of oil

The actual regional production (the sum of production of all oil grades) is then determined by the ADMM clearing algorithm, that grants global balance between supply and demand and determines the market price for the resource. The oil market is modelled as a perfectly competitive global pool, without strategic behaviour from producers nor bilateral trade. Trade emerges as the difference between regional demand and production. The second component of the cost equation here described, however, grants that low cost producers will not flood the market with their product, depleting their resources and depressing prices, implicitly mimic their strategic behaviour.

Gas and coal extraction

For gas and coal production, the algorithm is based on calibrated global and regional supply curves from the ROSE project (Figure 2.2). Gas and coal extraction works under the assumption of perfect market competition, and the cost of the infrastructure is embedded within the supply curves.

The algorithm is heuristic and located outside the main loop. It works as follow:

- read global price corresponding to global cumulative production, for each period:

$$FUEL\_PRICE(f,t) = fun(\sum_{n,t} Q\_FUEL(f,t,n)) \tag{2.3}$$

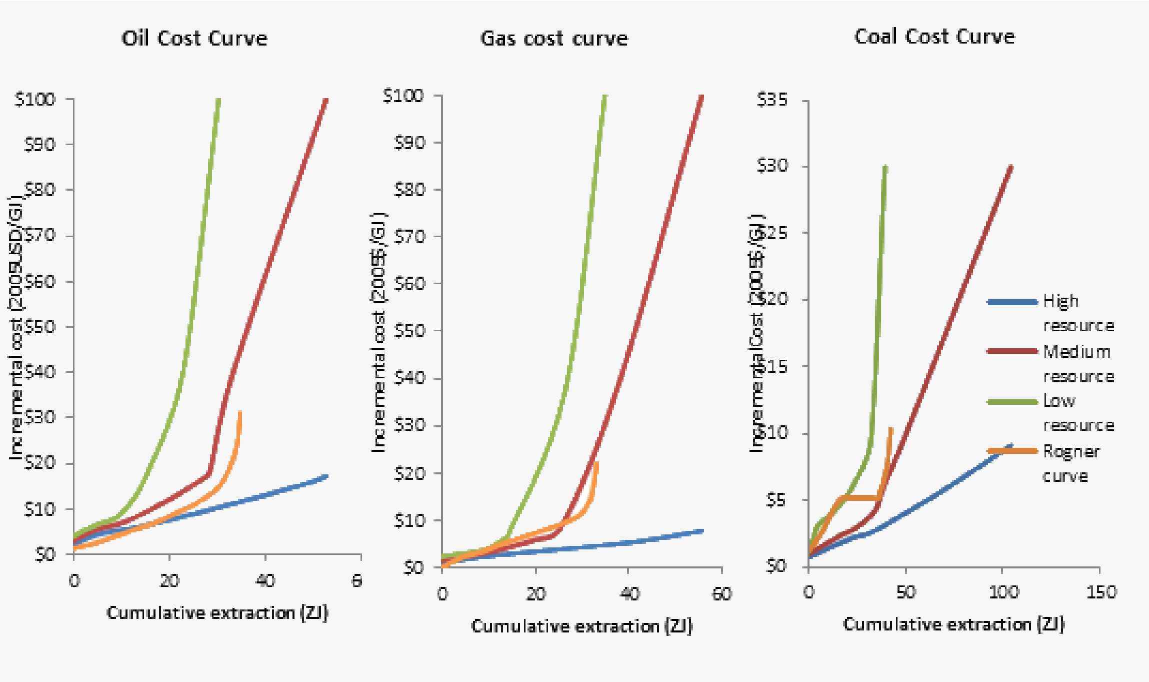

Figure 2.2. Fossil fuel global supply curves from RoSe project and Rogner

Where *fun* represents the interpolation of the global supply curves.

- read from the regional production curves cumulative regional production level corresponding to the price

$$cum\_prodpp(f,t,n) = fun\_n^{-1}(FUEL\_PRICE(f,t)) \qquad (2.4)$$

Where fun_n represents the regional supply curves.

- compute production levels as difference between consecutive cumulative production and send to solver

$$Q\_OUT(f,t+1,n) = cum\_prodpp(f,t+1,n) - cum\_prodpp(f,t,n) \qquad (2.5)$$

- assign regional mark-ups to fuel prices in order to mimic different local market environments (e.g subsidies)

This means that, at each iteration, the main solver (that optimizes each region utility with perfect foresight) endogenously decides demand, while it receives production as a fixed value. Of course, the amount of fuel consumed influence the total price and thus its competitivity. The consistency between global supply and demand, however, is granted by the iterative nature of the WITCH model, that converges when the residual through iterations of total investments and total primary energy supply is below a certain tolerance threshold. As the nature of the algorithm does not allow for imbalances between global supply and demand, there is no need for market clearance with the ADMM iterative algorithm. As with oil, trade emerges as imbalance between regional demand and supply levels.

2.2 Software and hardware

The WITCH model is written in GAMS, a powerful high-level algebraic language coupled with state of the art optimization algorithms. Input analysis and data trasformation to interface data sources (IEA, IRENA, WorldBank, SSP projections ecc.) with the model is performed in the R software, a free and open source tool for data analysis and visualization. WITCH is solved by the Conopt NLP solver, an optimization algorithm included in the GAMS distribution.

Given the complexity of the model, the computational burden of running the scenarios was entrusted to the ZEUS supercomputer, based in Lecce and owned and operated by the CMCC foundation. Zeus is based on 348 Lenovo SD530 dual processor nodes (for a total of 12.528 cores) all interconnected by means of an Infiniband EDR network. The new system has a computing power (theoretical peak performance) of 1.202 TFlops. The HPC storage infrastructure connected to Zeus consists of two Lenovo DSS-G260 storage systems, with identical configuration, which offers, overall, a usable capacity of 4 PetaBytes.

In order to perform the runs, I was granted access to the supercomputer as well as all the other physical and virtual resources of CMCC, which I joined as a Visiting Student for the duration of this work.

All data visualization was performed in R, using *dplyr* package for data analysis and *ggplot2* for graphs and figures.

2.3 Algorithm for extraction ban in WITCH model

As described in Section 2.1, Oil extraction sector in WITCH is fully integrated within the main model, while gas and coal production levels are computed outside the main solver.

The nature of the model (which implies a parallel solution of multi-regional non cooperative sub-coalitions) and of the standard algorithm for coal and gas did not allow for a simple implementation of the production ban by constraining the upper level of production for each region.

For this reason, a modification of the algorithm was necessary at two levels. On one hand, a different reading in the fossil availability curve had to be implemented in order to take into account that some regions may reduce their maximum production, thus forcing the substitution with higher cost resource. On the other hand, if the combined effect of the production cut for all region combined is such that the global demand cannot be met by overall allowed production, then a market balance algorithm is needed to grant convergence between global supply and demand.

The first component is computed before the solver performs the main optimization, thanks to a modified reading from the supply curves as described below. The second emerges from the integration of coal and gas market into the main ADMM algorithm that grants convergence for oil and carbon markets.

Reading from the supply curves

Below we describe in detail the modified version of the heuristic algorithm that reads into the supply curves described in Section 2.1. All the operations described below happen, at a given iteration, before both the main optimization and the ADMM algorithm.

- STEP 1 - read demand as if no cut were to occur to initialize variables.

  At each iteration, this step of the algorithm receives as inputs:

  - From the main optimization, the previous iteration solution for demand
  - From ADMM, the previous iteration guess for fuel price, accounting for scarcity

  From the cumulative value, the pure component of extraction cost *as if no production cut were applied* is computed by reading price into the global supply curve.

  A series of parameters have then to be initialized for the first iteration: the reference level of production with respect to which the level of the ban is calculated, the regional cumulative production and the maximum cumulative production compatible with the ban.

  In order to do so, as a first guess production level, cumulative production without any ban is computed reading into the regional inverse supply curves quantities corresponding to the first guess price (which, in the first iteration, comes from a previous solution chosen as starting point - usually and in this case the BAU scenario). This allows the initialization of reference ban level and regional cumulative production.

  As for the maximum cumulative production, at the first iteration it is computed, for each time step, referring to its previous year maximum cumulative production. This is necessary to initialize correctly the algorithm, but in successive iterations the values of allowed cumulative production refer to previous year's actual cumulative production level. This models expiring production quotas, not allowing WITCH to search for a solution in which production is saved for later years. This modelling choice is justified by the fossil fuels infrastructure obsolescence and divestment that, while not modelled explicitly for coal and gas in WITCH, would probably make unrealistic a comeback in fossil fuel extraction after a sharp decline due to a "reverse" lock-in effect.

- STEP 2 - loop the allocation mechanism to account for production cuts

  Once the path of cumulative maximum production available is computed for each region and period, it is necessary to allocate global and regional productions compatible with the production cuts. To do so, a while loop is implemented to read the global price for the fuel, corresponding to global cumulative demand summed with *allocation*, a parameter that quantifies the amount of non economical resources that have to be extracted due to low cost resources being unavailable for production. This price is of course higher than *price_ nocut* given the monotocally increasing shape of cumulative production curves as calibrated in WITCH.

  $$price\_sup = fun(\sum_{n,t} Q\_FUEL(f,t,n) + allocation(f,t,n)) \tag{2.6}$$

  From this value of extraction cost, we compute the corresponding cumulative regional production level as the minimum between cumprod_max and the cumulative production corresponding to that price level.

  $$\begin{aligned} cum\_prodpp(f,t,n) = max(&cumprod\_max(f,t,n), \\ &fun\_n^{-1}(FUEL\_PRICE(f,t))) \end{aligned} \tag{2.7}$$

  Then *allocation* is updated as the difference between cumulative demand and supply, computed as regional sum of the just calculated regional cumulative production values.

  $$allocation(f,t,n) = \sum_{n,t} Q\_FUEL(f,t,n) - \sum_{n} cum\_prodpp(f,t,n) \tag{2.8}$$

The loop is repeated for a sufficiently high number of iteration, at the end of which one of two things is going to happen: either all demand has been allocated respecting production cuts, or the global production level are incompatible to that demand value. In the first case, price will be higher due to higher extraction costs, but no imbalance is left and the ADMM algorithm will not have effect on prices for that fuel. However, the main solver will read an higher price, which will cause a stimulus to reduce demand for that fuel in later iterations. In the second case, ADMM will mark-up the prices, sending a stronger signal for the solver to reduce demand and meet supply.

- STEP 3 - send regional quantity production to main solver and re-compute prices if a residual imbalance exists

  The pre-solve algorithm has thus produced the regional quantities and global price. These variables are sent as fixed to the main model, which will adjust demand accordingly to the new price and supply levels. After the solver has produced a globally optimal solution for all regions, the ADMM algorithm (alternating direction method of multipliers) is called to modify the price according to the residual market imbalance: if demand exceeds supply (as it is the case in initial iteration for production cuts), the price will increase proportionally to the amount of the imbalance, its velocity of decrease with respect to the last iteration and a dynamically adjusted parameter that allow to express an equivalence between the imbalance (a quantity) and price of the fuel. In order to grant better convergence, a moving-average of the last iterations of the price in the main loop was introduced to avoid oscillations and help the ADMM algorithm to converge.

This process is repeated iteration after iteration of the main model loop, until the price value of the imbalance between supply and demand is below the tolerance level of 5% of total consumption (in bUS$):

$$\frac{FPRICE(f,t) \times \sum_n (Q\_FUEL(f,t,n) - Q\_OUT(f,t,n))}{\sum_n CONS(t,n)} < 0.05 \tag{2.9}$$

This method allows for a good coupling of global demand and supply and an adequate interaction between the extraction module and the main solver (Figure 2.3): the performance is good for gas, while for coal a small residual imbalance in the transition years persists. This is due the fact that, being prices for gas higher, the same imbalance for coal is weighted less with respect to global consumption. However, while visible, these imbalance have hardly a role in changing the overall picture of the scenarios.

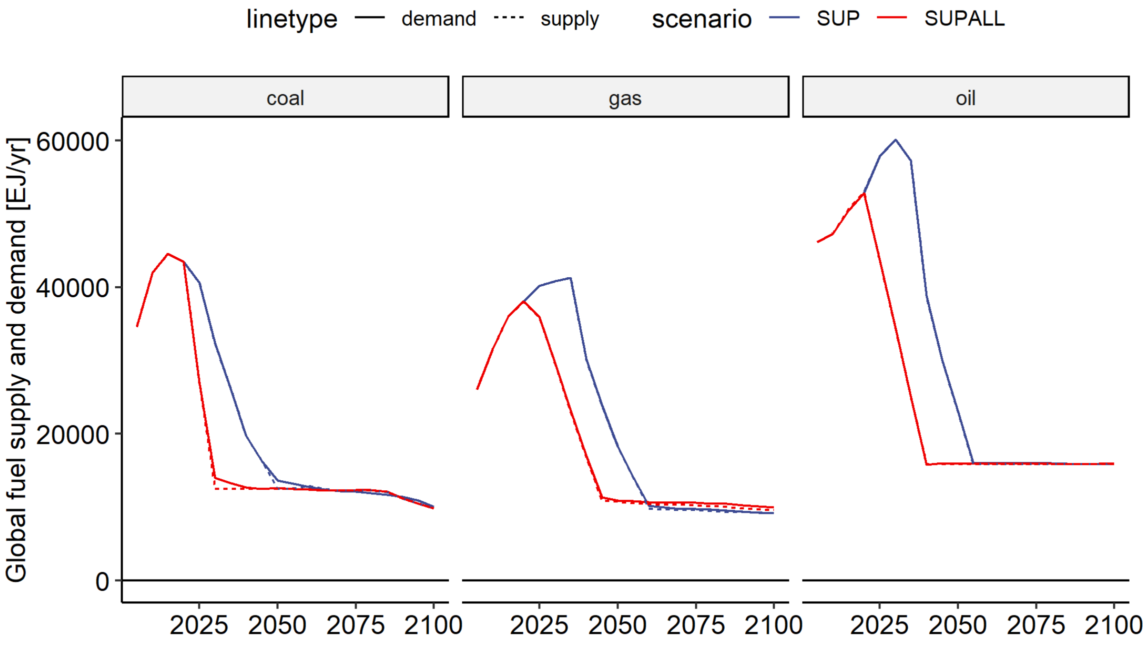

Figure 2.3. Supply and demand balances for supply side scenarios

2.4 Scenarios architecture

In order to analyze the effect of supply side policies and their interaction with demand side policies, we develop a framework composed of six scenarios summarised in Table 2.1.

Table 2.1. Scenarios names and definition.

Reference scenario	REF
Supply-side scenario - Narrative	SUP
Supply-side scenario - All front-runners	SUPALL
Supply-side scenario - Coal only	SUPCOAL
Demand-side scenario	DMD
Combined scenario	SUP+DMD

reference and literature scenarios

Reference scenario includes the implementation of the NDCs and assume a linear extrapolation of the policies adopted after 2030 (the natural deadline of the NDCs). It simulates a world of current commitment in which low and fragmented carbon tax are adopted throughout the century, as well as standards and target for single technologies. Roelfsema et al. (2020). The reference scenario is based on the SSP2 (middle-of-the-road scenario) Riahi et al. (2017). 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 as the NDC policies. In regions with implicit NDC carbon price of zero in 2030, we assume a minimum carbon price of 1 $tCO2 in 2030. For land use, a carbon price ceiling of $200tCO2 is applied.

The demand scenario (DMD) is a pathway consistent with Paris target of well below 2C and a total carbon budget below $1000GtCO2$ in 2100. To reach the target, an homogeneous global carbon tax starts in 2025 and increases exponentially after a ramp-up period (Figure 2.4).

These scenarios are well documented in literature for the WITCH model and

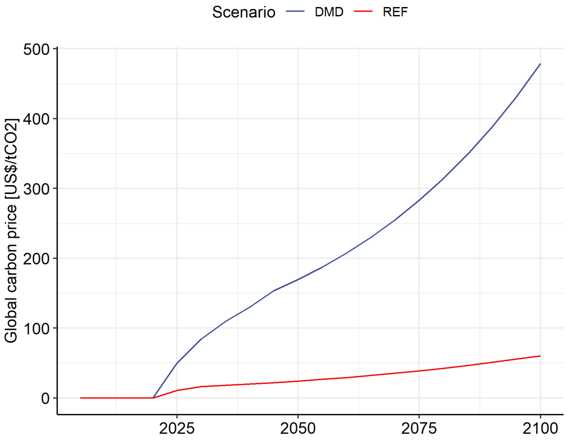

Figure 2.4. Global average carbon tax in DMD and REF scenarios.

Integrated Assessment Models in general (IPCC, 2018; Roelfsema et al., 2020) and serve therefore as a landmark for comparison for the novel scenarios.

Supply side scenarios

Remaining scenarios model a direct cut on production for all or some fossil fuels. SUP, SUPALL and SUPCOAL are implemented on top REF scenario, inheriting the NDC policies and carbon tax.

Production cuts are modelled imposing a 70% reduction of the production level with respect to 2020 levels for each country that participates the ban. Regions are forced to meet the *target* level after a certain year, or *ban year*, and the upper constraint on production is kept constant for all following periods. In order to simulate a gradual transition up to full enforcement of the bans, the target level is reached after a 20yr period of linear decrease of allowed production, starting from 2020 levels (Figure 2.5).

The *ban year* is a function of both the fossil fuel and the region implementing the ban, while the target level and the velocity of phase out are constant with both. Regions are grouped into three categories, defining different willingness to reduce production levels: frontrunners, followers and laggard. The cartesian product of group and fuel defines a matrix which is completely characterized by its ban year, as shown in

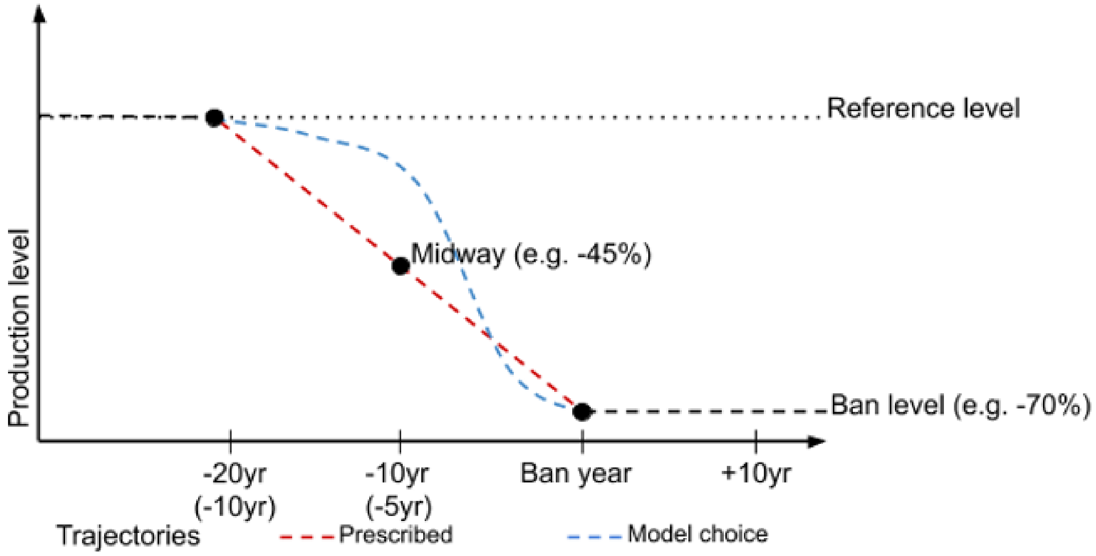

Figure 2.5. Structure of the ban trajectory. In the WITCH model, the ban is linearly prescribed in the transition phase.

Table 2.2. The same country/region can fall into different categories for different fuels, in order to account that some regions may have stronger socio-economical-political reasons to reduce production of a given fossil fuel but strongly oppose the ban of another, for example if they are large exporters. Each country will thus be assigned with a certain position for each fossil fuels. This framework allows to find an acceptable compromise between the need of taking into account obvious regional differences - both in term of ability and willingness of phasing out a certain fuel - and the necessity of building a simple enough framework that can be effectively compared between scenarios and between models.

Table 2.2. Ban year matrix.

	Coal	Gas	Oil
Frontrunners	2035	2050	2045
Followers	2045	2055	2050
Laggards	2055	2065	2060

To assign countries into a certain position, a simple framework described in detail in Section 2.5 has been developed, taking into account both quantitative and qualitative factors such as trade position, propensity to climate action in general and fossil fuel dependency. The results is the narrative shown in Table 2.3, that is implemented exogenously in the WITCH model and constitutes the backbone of SUP scenario. The idea behind this narrative is the global participation in a supply side treaty, for which is recognized that different countries have the necessity of different speeds to transition away from the fuel production, according to their economical, energetic and political dependency on that fuel. As a result, the narrative wants to simulate a possible and likely result of a global negotiation within the context of a global supply side treaty. Given the high uncertainty of such a method, a counterfactual scenario SUPALL has been developed where all regions act as frontrunners for all fossil fuels.

Last of all, SUPCOAL scenario implements only a coal ban extraction on top the NDCs, timed with the narratives. The rationale for this scenario is multiple: on the one side, it tries to answer a growing demand in the public opinion - both from advocacy and research - to phase-out coal as quickly as possible as a first response climate strategy. Moreover, a selective ban on coal could show higher political feasibility than a complete extraction ban for a variety of reason: more evident co-benefits in short term health effects, already being a decreasing industry in large parts of the world and less geopolitical importance due to its relative abundance and widespread distribution. On the other hand, it allows to evaluate potential risks in terms of substitution and rebound effects when banning a single fuel without a strong carbon policy in place, constituting in this sense a second counterfactual for SUP.

Methodological note on SUP and SUPALL

From a methodological standpoint, both scenarios (SUP and SUPALL) kind of mix a prescriptive and descriptive approach in the attempt of keeping the temporal and computational cost affordable: a purely prescriptive point of view would have implied the necessity of recurring to a Cost Effective Analysis - with respect to a certain target level of CO2 or forcing - to determine the global optimal timing of participation to the treaty for each region; on the other hand, a purely descriptive approach would try to capture - within a non cooperative Cost Benefit Analysis framework - when and if conditions exist for regions to cut production of a fossil fuel, weighting the cost of phase-out (both in terms of missed revenues from fossil fuel sale and in increase of energy system cost) with potential benefit (avoided climate impacts on the one hand, exploitation of substitution and trade effect on the other). However, both approach would have been very challenging from a modelling point of view and outside of the scope of this work, which aims to provide a first of its kind quantitative evaluation of massive scale supply side policies. Moreover, using a scenario type approach (meaning mixing a narrative within a numerical modelling framework), while losing in terms of robustness and comparability of results, it allows to capture more effectively and *transparently* real world complexity and provides a easier starting base for a discussion, to some degree avoiding the exactness-certainty trap that is intrinsic in optimization modelling.

However,if a spectrum between those two extremes is imaginable, then SUPALL scenario covers more the normative end of it, modeling a uniform and cooperative environment in which the international community is able to phase-out fossil fuels homogeneously and sharply. SUP on the other hand is developed with a more descriptive mindset and tries to capture some of the real world complexity that would go into a treaty that touches at its core one of the greatest concerns of State actors, that is to say fuel independence and security.

That being said, the downside of completely exogenizing the logic of participation to the supply side treaty is, of course, the risk of obtaining results too much dependent on semi-arbitrary decisions in the form of expert elicitation, like speed, timing and regional participation. SUPALL scenarios thus also serve the scope of avoiding this trap and provide a counterfactual to test the robustness of the results to the hypotheses that build the narrative. Moreover, allowing for different speed and timing of phasing out production allow to search for inter-regional other than inter-fuel rebound effect, in the form of green paradox or trade effect.

Table 2.3. Region position in production bans. FR are frontrunners, FO are followers, LA are laggards

	COAL	OIL	GAS
USA	FR	LA	LA
Canada	FO	LA	LA
China	LA	FO	FO
India	FO	LA	LA
Brazil	FR	FO	FR
Latin and Central America (LACA)	FO	FO	FO
Mexico	FO	FO	FO
Japan and Korea (JPNKOR)	FR	FR	FO
Indonesia	FO	FO	FO
South Africa (SA)	LA	LA	LA
South East Asia (SEASIA)	FO	LA	LA
South Asia (SASIA)	FO	LA	LA
Sub Saharan Africa (SSA)	LA	LA	LA
Middle east and north Africa (MENA)	FO	LA	LA
Russia, Turkey and ex-Soviet Union (TE)	FO	LA	LA
Oceania	FO	FO	FO
Europe (EURO)	FR	FR	FR

Mixing supply and demand policies

SUP+DMD meets a carbon budget of 1000 GtCO2 coupling the production bans as in SUP scenario with a global uniform carbon price starting from 2025, allowing to explore complementarities between supply and demand side policy when shooting for a Paris scenario.

A second methodological note

Some points have to be made about the comparability in this scenario framework. First of all, directly comparing SUP and DMD scenario searching for substitution between the two kind of policies would require in theory that they shoot for the same carbon budget. However, due to the structure of the WITCH model - the top-down of electric and non electric substitutability above all - it is very challenging to obtain convergence if the residual supply of fossil fuels is too low, making it probably impossible to shoot for a Paris scenario with extraction ban only. Moreover, while the carbon budget for the two scenario is not equal, the cost of policy in terms of GDP loss are. As a consequence, SUP and DMD can be compared, while they produce different effect in terms of overall emissions, as they imply a similar effort in terms of global costs.

Second of all, the comparison of DMD and SUPDMD scenario searching for complementarities require a reflection on the nature and modelling of the carbon tax on the one hand and the extraction ban of the others. The latters are, in fact, decided exogenously, while the former is fitted iteratively within the model optimization to meet the correct carbon budget. The consequence is that the model can choose the level of the carbon tax to reach the budget - even if not the shape or the slope of the exponential - but is unable to modify the ban narrative. A "fairer" comparison would have required allowing some kind of degree of freedom for the production ban as well in order to highlight the "optimal" (given model bias) mix of the two policies. However, for this last point, the same considerations previously made on the value of a narrative approach stand.

Third and last, coupling a fragmented supply side narrative with a global uniform carbon tax can sound problematic in terms of internal narrative coherency. While this is partially true, there are justifications to this choice. First and foremost, while a supply side literature in detailed IAMs is non existent, there is huge literature and hundred of scenarios that implement a Paris consistent carbon budget with a global uniform carbon tax. While the likelihood of such an harmonic and cooperative behaviour is debatable *per se*, using the same framework allows higher direct comparability of the SUPDMD scenario within the existing literature. Second of all, while its true that the supply side narrative follow a non uniform storyline, the idea behind the scenario is anyways a global treaty, in which, whilst with different timing, all countries agree to partecipate the ban. In this sense, the implementation of a such a treaty would still require a high level of cooperation between countries. Given this factor, while SUPALL scenario could have been chosen for joint implementation with DMD, we chose to privilege the higher richness of interaction (see already mentioned green paradox and interfuel substitution effect) that SUP allows to explore over the higher level of narrative consistency that a SUPALL+DMD scenario would have offered. Lastly, SUP actually covers somehow the storyline of fragmented supply policies within a differentiated demand policy effort, given that it is implemented of top of REF that already contains fragmented climate policies as announced into the NDCs by countries participating the Paris agreement.

2.5 Developing the narrative

As already mentioned, the supply side narrative was developed in order to respond two needs: on one hand, to explore the effects of dishomogeneity of extraction bans on fuel market and the energy system; on the other, to offer a rationale of the different speeds of participation without explicitly addressing the modelling of endogenous coalition formation. In order to address the second point, we mapped the different dimensions that could influence the interest or opposition of a country/region in joining the treaty. Each of these dimension was assigned an indicator, normalized to its maximum and minimum levels. The normalized indicators were then summed with equal weights, and according to the overall level of indicators the regions were assigned to frontrunners, follower or laggards groups. While this numeric framework served as a basis, the ultimate decision of how to allocate regions in different groups was left to the researchers' choice, collecting inputs from all modelling groups and including other modelling needs in the picture. In this perspective, a particular attention was given to provide significant production shares to different groups, and in particular to avoid that all regions would be laggards for certain fuels.

The dimensions taken into considerations were divided into two two categories: dimensions relating to adhesion (or oppose) to climate policy in general, and supply side policies in particular. As extraction ban are modelled here as a climate policy, the propensity to climate action in general was given a particular attention to estimate the willingness of regions to participate the treaty.

As for the first set of dimensions, the following were considered:

- Current commitment: countries with higher ambitions in their NDCs are supposed to be more committed to climate mitigation and more likely to participate to stronger climate action in the future. The indicator providing a metric of commitment of the NDCs was taken from Paroussos et al. (2019)
- Equity: wealthier countries have more historical responsibility in the form of cumulative emissions, and can tolerate better the costs of mitigation.
- Relevance: countries with higher emission share will face more international pressure to start mitigation policies.
- Impacts: countries facing higher projected climate change impacts will tend to back-up mitigation efforts, while regions with low (or, according to some estimates, negative) damages from climate change will have less incentive to do so.

The positioning in the climate supply treaty per each fuel was instead evaluated considering these dimensions:

- Trade position: big exporters tend to oppose participation of a climate treaty.
- Cost of barrel and proven reserves: in general, countries with high reserves will tend to oppose climate policy; high cost producers, however, may sponsor a supply side treaty, because it raises fossil prices and fixes production quotas.
- Substitution effect: countries with low endowment in a certain fossil fuel, but big producers of others may sponsor an early participation for the former, exploiting the substitution effect in the energy system, that would lead to an increase in price of the latter.

The resulting narrative shown in Table 2.3 and Figure 2.6 implies a dis-homogeneity in the distribution of fossil fuel share of production and consumption between groups. Unsurprisingly, Table 2.4 and Figure 2.6 show that, especially for oil and gas, the

		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

Table 2.4. Shares of supply and demand among groups in REF scenario, selected years

vast majority of big producers falls among laggards, with frontrunners accounting for less than 10% of total production for both fuels. The coverage of demand is, instead, less penalizing for early participants, with frontrunners for oil accounting for 20% of global demand. Coal sees higher early participation in the treaty, with more than 50% of global production covered between frontrunners and followers. This is a sensible behaviour, since coal importance in the energy mix is expected to reduce even in an environment on modest climate policies. Furthermore, coal industry is less powerful in most relevant countries than oil and gas and less geopolitically relevant in international terms.

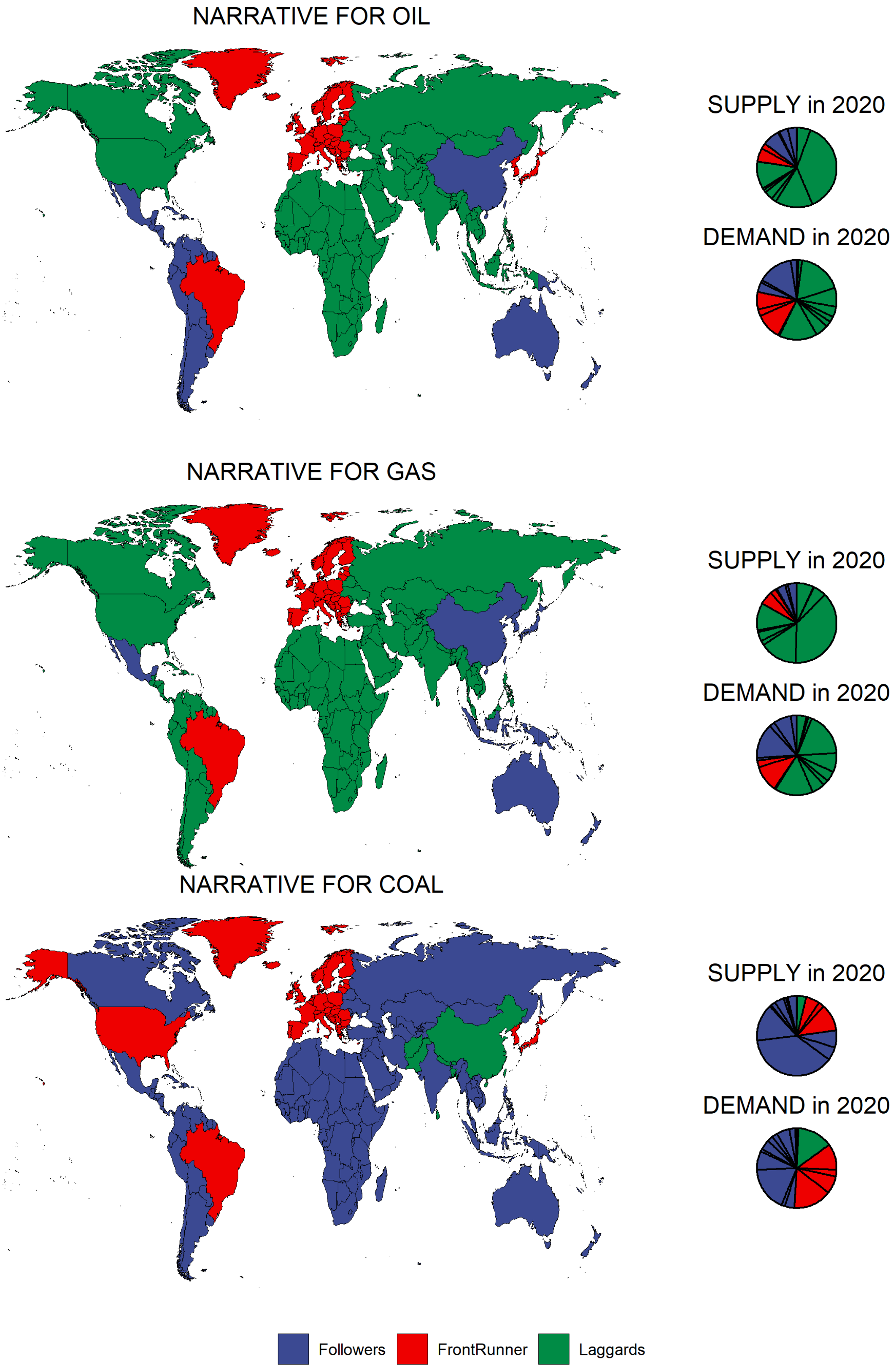

Figure 2.6. Region position in production bans and production and consumption shares in 2020, by group

Chapter 3

Results and discussion

In this section we present and discuss the results. First of all, we discuss the implications on emissions trajectory and the energy system of supply side policies. Then, we study their effect on international prices, before turning the analysis to general considerations about policy cost. Finally, we analyze the energy security implications of a supply side treaty and its effect on trade revenues.

Key findings are summarise below:

- Supply side policy can substitute carbon pricing before mid-century in shooting to a very ambitious climate target. After that, however, they fail to reach zero emissions, diverging from Paris consistent scenarios.

- The effect on market price is relevant, causing price spikes of more than 3 times the current levels, but only a large enough coalition can meaningfully effect the global market.

- Supply side policies are costlier and less efficient than global uniform carbon pricing.

- Supply side policies increase producers revenues with respect to demand side policies.

3.1 Emissions and energy

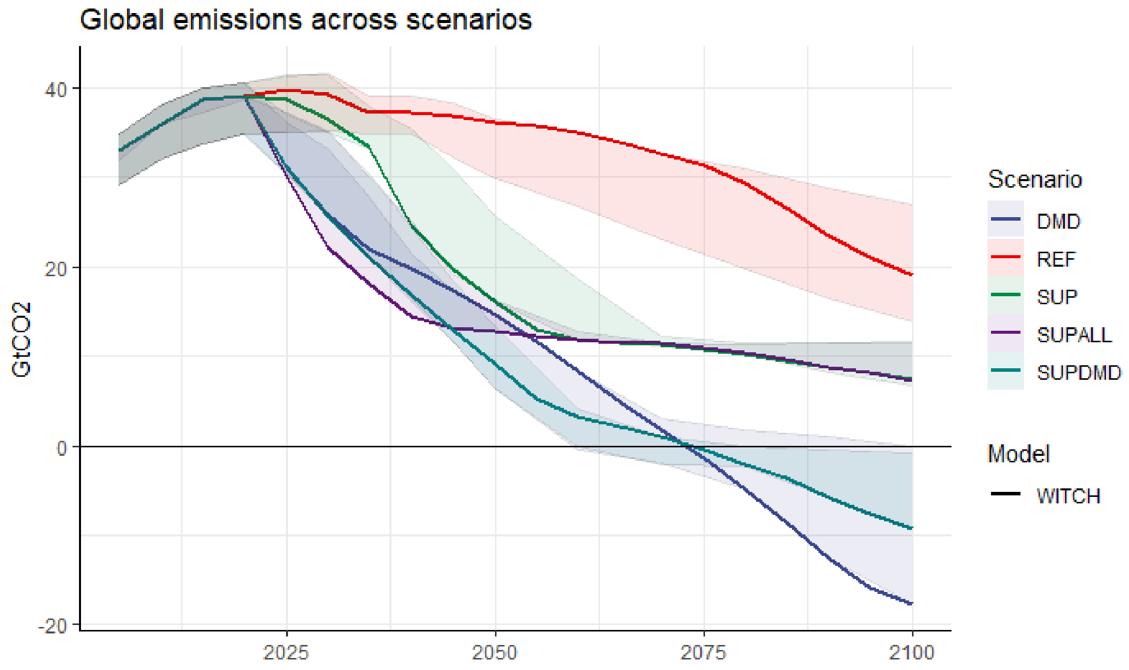

Figure 3.1. Global CO2 emissions among scenarios in WITCH. Shaded area refers to other models' results participating the study

Figure 3.1 show the emissions trajectories for the scenarios. First of all, it is important to stress that REF is not a business as usual or no policy scenario: having embedded in itself the NDCs projected throught the century, it does contain some kind of climate policy in itself. These commitment levels lead to a significant decline in CO2 emissions, with a peak around 2025 and a slow and constant decline afterwards, leading to a overall carbon budget of 2995 GtCO2 in 2100. In the range of current policy scenarios available in the literature (IEA, 2020; Roelfsema et al., 2020), it falls in the optimistic range of the spectrum, the general consensus being that stated policies may lead to somewhere between a flat emission world and a slowly decreasing one. As we can see from Figure 3.3, a REF scenario such as the one designed here implies by itselt a huge growth of intermittent renewables in the energy system. DMD scenario, on the other hand, show a classical (IPCC, 2014) trajectory of a 2C scenario: steep emission reduction followed by net zero at same point in the second half of the century followed by negative emissions late to suck up residual atmosperic CO2 and restore the overshot budget. This result is very consistent between integrated assessment models, even though the underlying energy system and the amount of negative emissions used vary between them. WITCH in particular tend to rely significantly on BECCS and DACs in late century, which comes with a relatively late net zero year (around 2075).

With these two frame of reference in mind, we can now characterize the emission trajectory for a SUP scenario: we will start by comparing SUP and SUPALL scenario to DMD scenario, searching for substitutability between carbon pricing and supply side policy. Then, we will confront DMD and SUPDMD searching for complementarities between the two.

3.1.1 Carbon pricing and extraction ban as substitutes

The supply side treaty lead to a significant divergence from the reference scenario, consistently reducing emissions thorough the century. The peak phase is smoother and delayed compared to a DMD scenario, due to regionally differentiated enforcing of the production ban. When most regions start banning for most fuel, the rate of decarbonization is coherent with a 2C scenario until 2060. If the partecipation in the global supply treaty is homogeneus (SUPALL), the speed and timing of emissions reduction is in line with Paris consistent pathways (DMD and SUPDMD).

In the second half of the century emissions flatten around 15GtCO2, diverging significantly from the trends of deep mitigation scenarios and leading to a carbon budget of 1803,8 GtCO2 for SUP and 1511,7 GtCO2 for SUPALL.

It can be stated that up until 2050 supply side scenarios show a good substitutability with carbon pricing policies, but after 2060 they produce very different effects on the energy system.

The reason for this behaviour lies within the response of the energy system and the mitigation portfolio to the two kind of policies.

To find an answer on that, first of all is necessary to compare global fossil fuel consumption within scenario, rooting out the possibility that the exogenous level of the production ban is too relaxed, producing the residual emissions we just discussed. In fact, fossil fuel extraction patterns are fairly similar in SUP and SUPALL scenario compared to DMD. As Figure 3.2 shows, the trend and depth of reduction in primary energy demand are consistent with a 2C carbon tax policy, if not more pronounced for supply side scenarios. For Coal, the reduction is more pronunciated with the application of a carbon tax, that sees a steady decline also after 2050 while supply side policy scenarios stabilize at the 70% target level. For Oil, supply policies grant faster and steeper reduction in the near term, anticipating oil phase-out and moving the transport sector away from ICE vehicles. In the late century, however, the downward trend for DMD scenario continues, leading to level of consumption below the supply site target. For gas, however, we see the greatest difference in pathways: being it the cleanest of fossil fuels in terms of cO2 emissions and fundamental for some hard to decarbonize sector such as heavy industry, this fuel remain relevant also in a deep mitigation scenario (DMD). After a decline to around 50% of 2020 consumption, production levels start rising again to stabilize at around the current consumption levels. This result may be debatable, as the model does not include relevant factors such as infrastructure inertia (for the upstream and midstream sectors) and lock-in effects. Nonetheless, it signals that natural gas (coupled with CCS) could play a very relevant role for the future of energy systems also in deep mitigation scenarios. In supply-side scenarios (SUP, SUPALL and SUPDMD), however, the maximum level of production is bounded and this leads to consistently lower level of consumption in each time period, with the exception of a small green paradox effect for SUP scenario in early years. Indeed, scenario comparison for fossil fuels consumption levels would seem to suggest that residual fuel extraction allowed in the supply side treaty is in line or more stringent with 2C consistent scenarios for gas and oil, while coal stabilzes at higher levels of production compared to a steady decline in Paris consistent pathways. This latter point may contribute to the relatively high amount of residual emissions at which SUP and SUPALL stabilize. It does not explain, however, the reason of the emission pathways divergence.

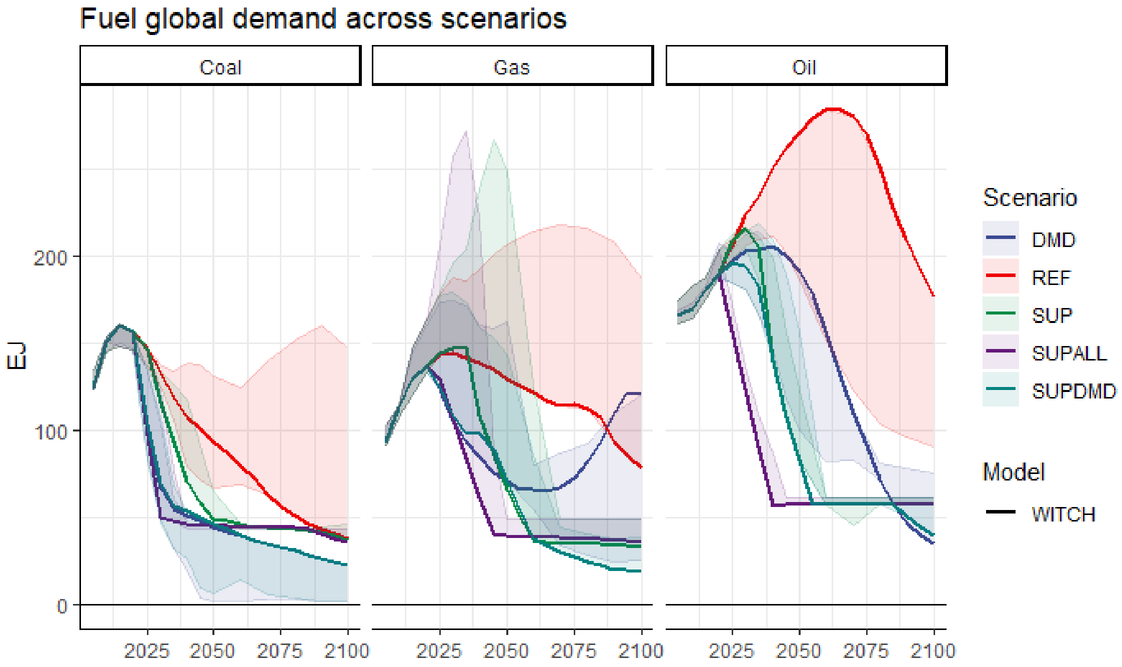

Figure 3.2. Global demand across fuels and scenarios. Shaded area refers to other models' results participating the study

As a side note, please note that in REF gas consumption peaks in 2025 and decline during the century. This is because, in order to make a solution for the supply treaty scenario possible, we assumed a future relaxation in substitutability between the electric and non electric sector, simulating technological innovation on electrification of hard-to-decarbonize sectors such as heavy industry. This is a debatable assumption on future technology, and other runs of the WITCH model show a pattern similar to oil's one, with a peak around 2050. Moreover, we don't capture the overall costs (or benefits) of this transition. The nature of the modelling of non electric sector in WITCH, however, is rigid and does not allow for substitutes in all sectors. Thus, this relaxation on the assumptions about future elasticity between electric and non electric sectors is fundamental to allow for a solution.

The lack of substitutability between strong supply side policy and demand side instruments is then to be searched mainly within the energy system: Figure 3.3,

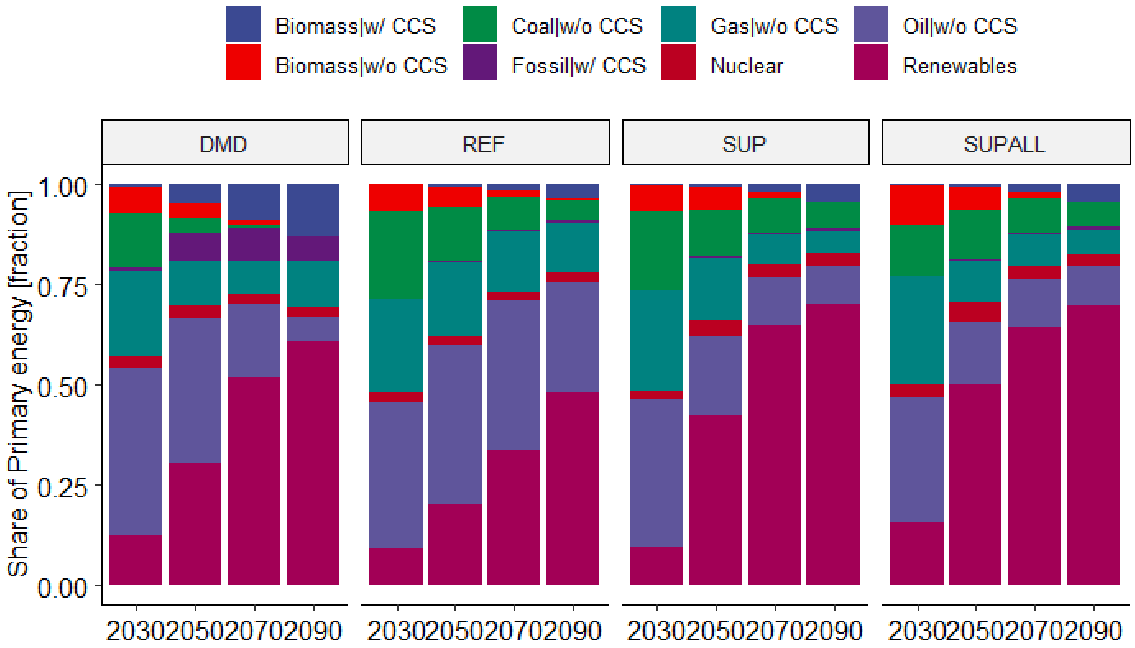

Figure 3.3. The energy sector in main scenarios, share of total. Renewables refer to wind, solar, hydro and geothermal; Biomass is the sum of traditional and modern biomasses

Figure 3.5 and Table 3.1 show the shape of primary energy shares and levels, including the electrification ratio of final consumption.

Starting from REF scenario, we can see from Figure 3.3 that current policies application already implies a great increase in the penetration of renewables, touching 20% of total TPES in 2050 and almost 50% in 2090. However, fossil fuels keep playing a fundamental role in the energy system, covering together around 40% of TPES in 2090: this is particularly true for oil (for industry and transportation) and gas (for heating and industry), but also coal keep a secondary but significant role in the electricity mix even in late century despite it's relative decline. Traditional biomasses disappear from the picture in the late-century thanks to GDPc development in now under-developed areas of the world. The TPES steadily grows to accomodate the increasing energy demand (due to population and GDPc growth) up to 909 EJ/yr in 2100. Coherently with the high penetration of renewables, the energy system electrification is constantly increasing, at a slower pace until 2050 - where the share is

35% - and faster after mid-century, touching 65% in 2100.

A global uniform carbon tax coherent with a 2C scenario (DMD) leads to higher penetration of renewables and modern biomasses in favor of a depletion of the shares of oil and coal, which almost completely disappear from the picture. A very important role is played by fossil CCS, useful to meet the flexibility constraint on the power system and provide dispatchable electric energy. The same can be said for biomasses coupled with CCS, or BECCS. This technology is fundamental in the late century because it allows for a net negative carbon cycle, effectively suckin up CO2 from the atmosphere and allowing to offset the remaining emissions to meet the budget. The net negative portfolio is complemented by DAC (Figure 5), whose deployment is necessary because of land use constraints of BECCS caused by competition with agriculture.

Oil and gas, still play a role to meet non electric demand from hard-to-decarbonize sectors while coal without CCS is completely phased out from the energy system. The necessity of moving away as much as possible from these sectors imply an higher and faster rate of electrification, up to 76% in 2100. Interestingly, total primary energy follow a non regular pattern: up to the 2050s, energy requirements are significantly reduced compared to REF thanks to investments in energy efficiency (587 EJ/yr against 732 EJ/yr, 20% reduction to REF); in 2100, however, TPES is higher for DMD at 1004 EJ/yr. This results is caused by the nature of DAC technologies: they do not produce energy, but require it as an input, leading to a significant increase in overall energy demand.

We are now ready to analyze the effects on supply side policies on the energy system (Figure 3.4): first of all, renewables penetration in a SUP scenario is consistently higher than both REF and DMD in terms of share. Looking at absolute values, the level of renewables deployment are slightly lower than a DMD scenario. This a strong and significant result, since it proves that a ban of extraction and the following increase in market prices (Figure 3.9) can provide a similar incentive to decarbonization of

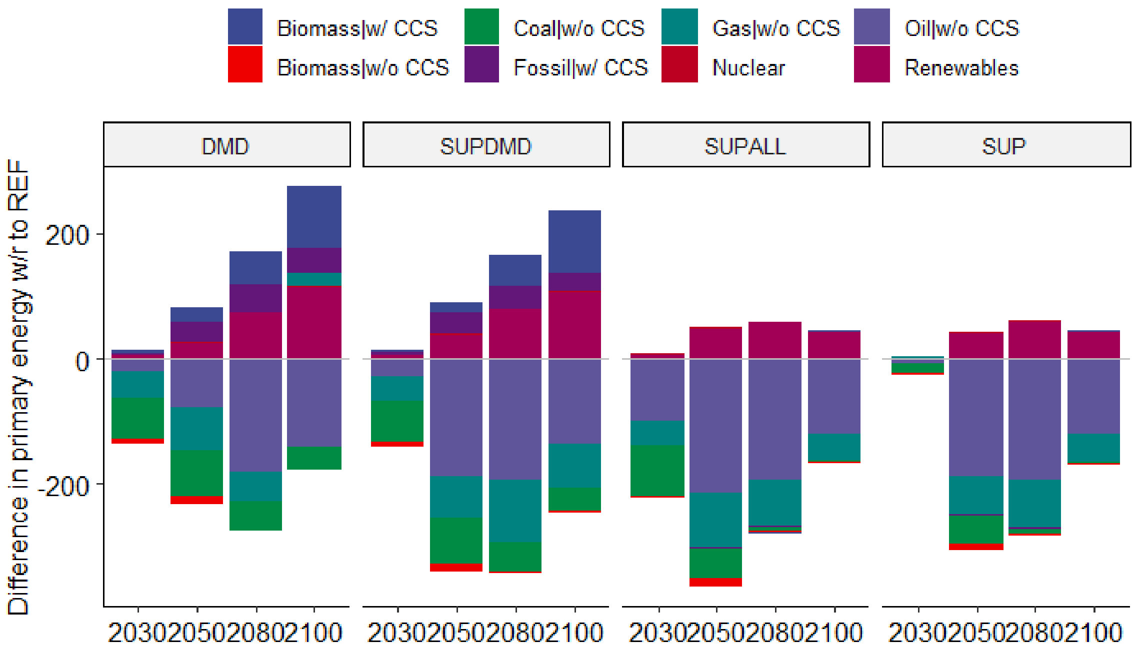

Figure 3.4. Difference between REF and scenarios. Negative values are reductions.

the power production system as a gradual carbon tax to increase investments in renewables. The same can be said for nuclear penetration, which slightly increase in absolute terms. As for energy efficiency, primary energy requirements decrease compared to REF right starting from the near future. The bulk of the reduction starts around mid-century, where TPES reach lower levels than 2030s for SUP. With respect to DMD, energy efficiency investments are delayed to due to fragmentations of the ban, but when most of the regions partecipate the treaty the effect of a supply side policy is stronger than a carbon tax, with a 15% reduction of total primary energy in 2100. In SUPALL, thanks to global early partecipation, the effect on energy efficiency are comparable to a DMD scenario already since 2030. As for electrification of the energy sector, SUP provides a stronger signal for electrification than DMD before mid-century, but the 2100 values stabilize at a slightly lower level (72% against 76% for DMD). Figure 3.5 clearly shows the different trends of energy efficiency between REF, DMD and SUP, and how much a supply side treaty causes a push in energy efficiency when it enters into action. As for fossil fuel, coal, oil and gas consumption is, of course, reduced by at least 70% with respect to 2020 level of consumption. Comparing the trends to DMD, the story is different for different fuels: for oil, SUP grants faster reduction of demand but result in higher share of total demand late century; for gas, the contrary holds true, while for coal the reduction is slower and shallower. SUP and SUPALL show very similar behaviours in the energy sector with the exception of the 2030s, where for SUP the fragmentation in the enforcement of the treaty for different region produce a delay in cutting emissions and phasing-out fossil fuels in the energy system.

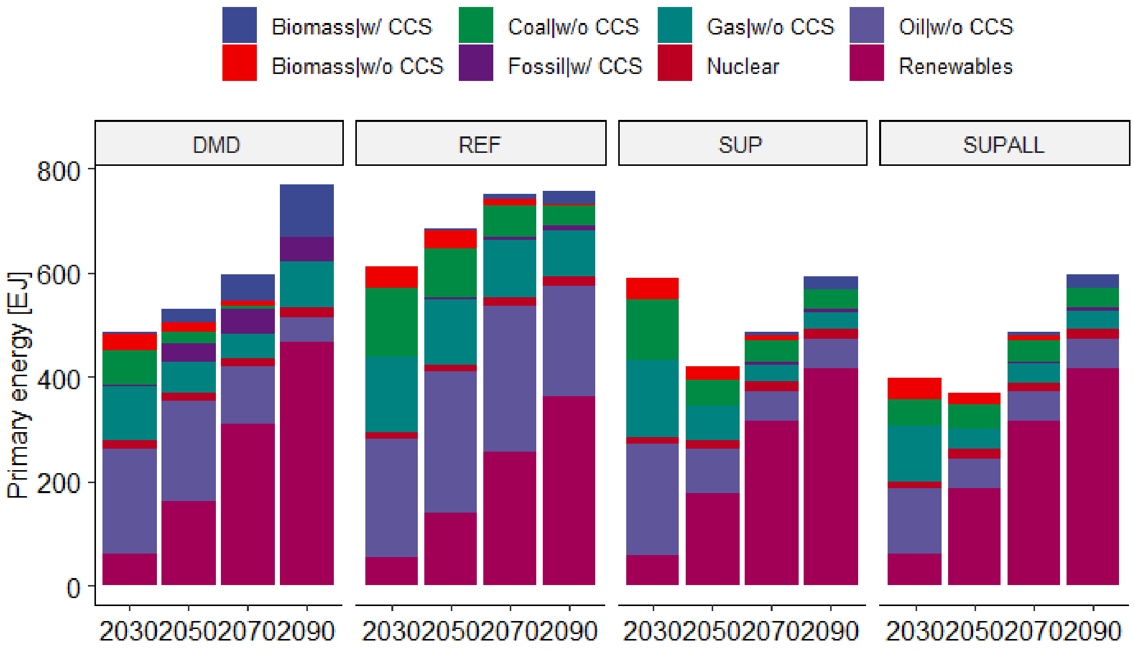

Figure 3.5. The energy sector in main scenarios, absolute values. Renewables refer to wind, solar, hydro and geothermal; Biomass is the sum of traditional and modern biomasses

So far, a global supply treaty seem to provide a similar if not stronger signal for decarbonization than a global carbon tax aiming at 2C, anticipating it in some aspects such as renewables penetration and oil phase out. In some others such as coal penetration, however, SUP fall shorts of DMD in completely phasing out the most polluting fossil fuel. This is indeed caused by the fact that the ban allow for a residual fossil production. On the other hand, fossil CCS also plays an imporant factor: while its deployment is relevant in covering emissions from residuals fossil fuel use in a DMD scenario, in SUP the level of deployment of CCS is very low and similar to a REF policy landscape (See Figure 3.8). This statement is also true for BECCS and DACs, the two negative emissions technologies modelled in WITCH. This is quite straightforward, since banning fossil fuel at its source does not provide, per se, any incentive in deploying costly technologies to remove CO2 from the exhausts of power production combustion or directly from the atmosphere. To put it in another way, while low carbon technologies in the energy sector such as renewables (toghether with efficiency and electrification) directly substitute fossil fuel in their main function of providing final energy, the same does not hold true for CCS and CDR, which are thus virtually unaffected by a fossil fuel ban. Such techniques can thus only be deployed if the carbon emitted is correctly priced, and its removal subsidized.

The implications are however very important: the inability for a supply side treaty (as designed in this study, focused only on fossil fuel banning) of stimulating negative emissions technologies or CCS puts a serious limit in its ability to target ambitious climate scenarios if it's the only kind of policy in place. Of course, there are possible changes in the research protocol that we can expect to result in an emission curve for SUP closer to the net zero late in the century: on the one hand, decreasing the level of fossil fuel production allowed after the enforcement of the ban; on the other, enforcing CCS on the burning of the residual extractable fossil fuels in the sector in which it is possible. As for the first option, further decreasing available production would be problematic for hard-to-decarbonize sectors that lack foreseeable substitutes. Changing level of ban for different fuels, however, it's a possibility that could be explored, decreasing levels of residual coal extraction to almost zero and allowing for an higher production of gas. Regarding the second option, such a policy could be enforced with a low cost of information for the power production sector, but it would be much more difficult to do so for non electric sectors such as industrial and heating. Given that the second ones constitute by fare the largest share of fossil consumption in the second part of the century, the applicability of such a policy would be questionable.

In conclusion, we show that well designed supply moratoria policy can indeed substitute a carbon tax aiming for a 2C effort up until around mid-century (SUPALL), or at the very least bridge current ambition with a 2C scenario (SUP), when the need for CCS and negative emissions technologies such as BECCS cause a failure for a supply side treaty focused only on fossil fuel production bans in reaching ambitious climate target.

3.1.2 Carbon pricing and extraction ban as complementaries

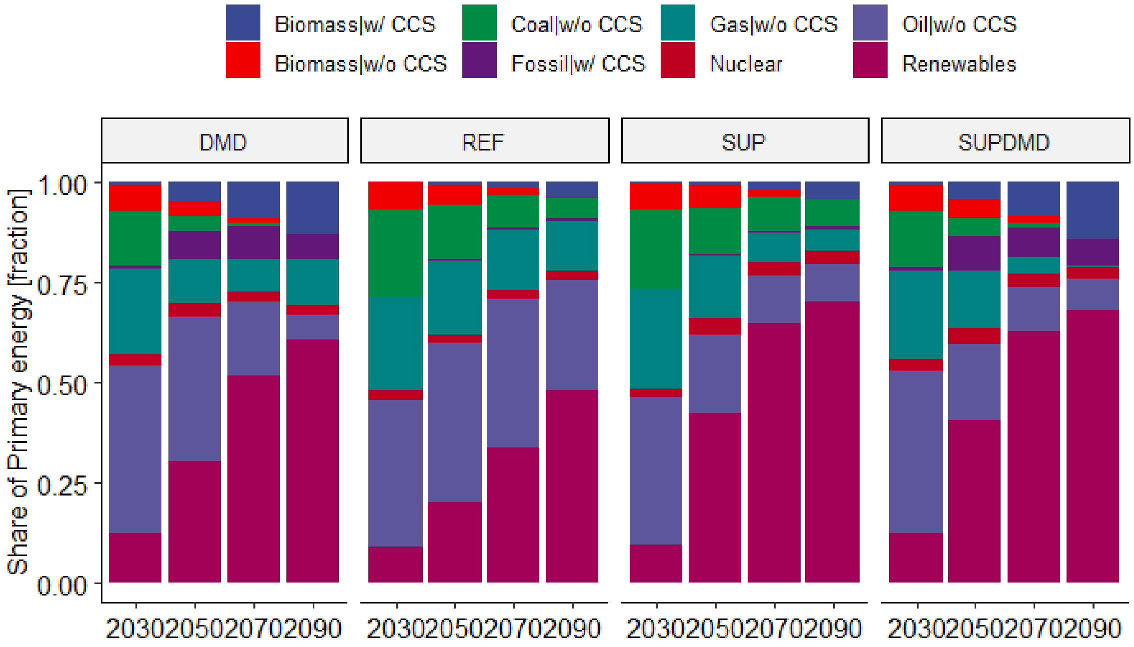

Figure 3.6. The energy sector in main scenarios, absolute values. Renewables refer to wind, solar, hydro and geothermal; Biomass is the sum of traditional and modern biomasses

We are now ready to focus our analysis on the confrontation between a 2C target scenario with and without the implementation of the supply side treaty, searching the effects on the energy system of a supply side treaty if coupled with a strong global carbon tax. Figures 3.6 and 3.7 show primary energy shares and values for

		Primary Energy, Total	Final Energy, Total	Efficiency	Final energy, electric	Final Energy, non electric
		EJ/yr	EJ/yr	tfc/pes	% total	% total
current	2020	590	404	0.68	22	78
REF	2030	641	437	0.68	25	75
	2050	732	493	0.67	35	65
	2100	909	630	0.69	65	35
SUP	2030	622	427	0.68	25	75
	2050	529	382	0.72	48	52
	2100	850	602	0.71	72	28
SUPDMD	2030	517	376	0.72	25	75
	2050	532	375	0.7	49	51
	2100	898	618	0.69	83	17
DMD	2030	520	380	0.73	24	76
	2050	587	413	0.7	42	58
	2100	1004	689	0.69	76	24

Table 3.1. Total primary energy, final consumption and eletrification in main scenarios

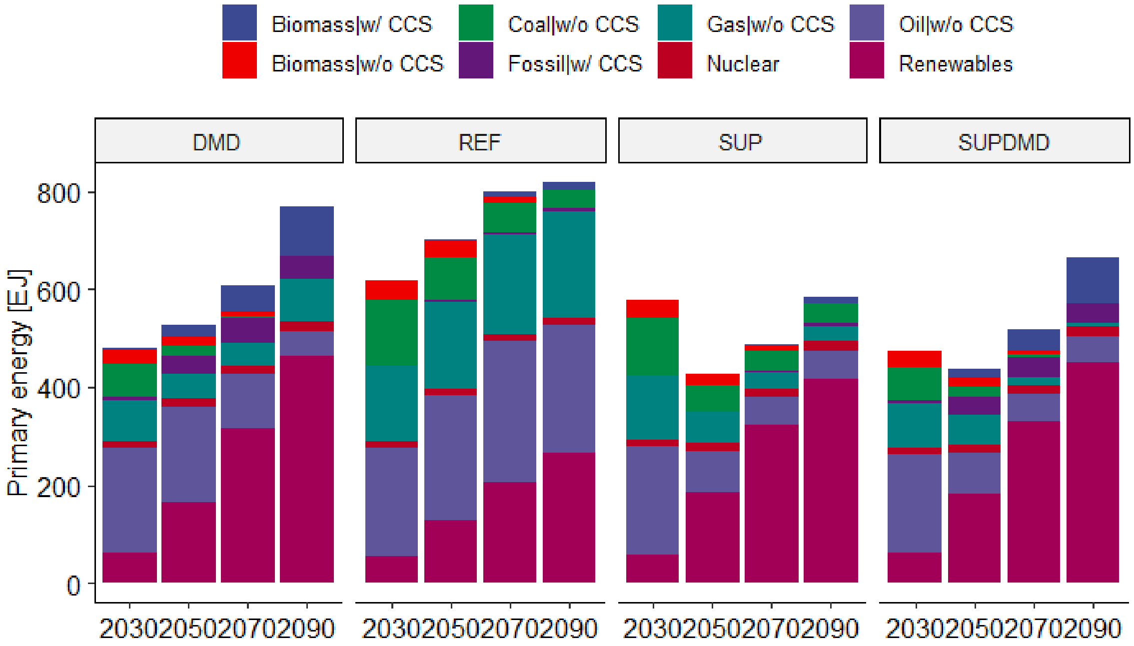

Figure 3.7. The energy sector in main scenarios, absolute values. Renewables refer to wind, solar, hydro and geothermal; Biomass is the sum of traditional and modern biomasses

SUPDMD, and Table 3.1 contains information about the values for final consumption and electrification.

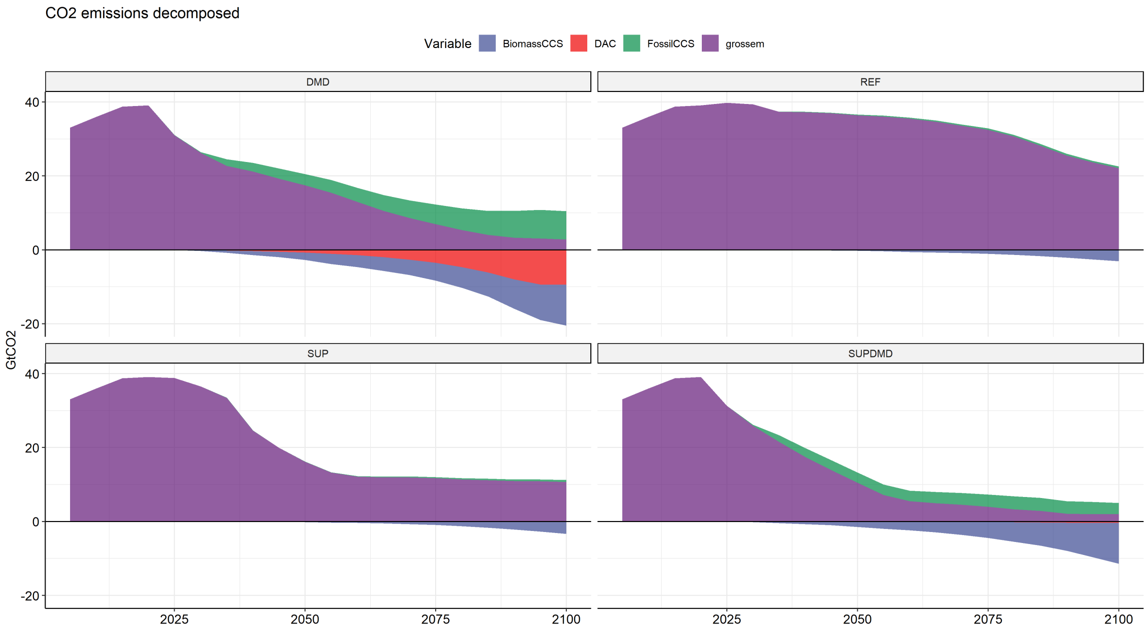

Figure 3.8. Emissions decomposed by sources and sinks

The main effect of a supply side treaty within a the context of a 2C pathway is evident from Figure 3.1: SUPDMD anticipates decarbonization compared to DMD, reducing reliance on carbon removal on a global scale. This reflects on the carbon budget as a reduction of the overshoot, a desirable feature because it reduces the stress on the geophysical system and uncertainty linked to the climate transient responses.

Figure 3.8 shows in more detail how the interaction between supply and demand side policies influences the optimal pathway for a 2C scenario, decomposing the net emissions of Figure 3.1 into sources and sinks: the violet area shows gross emissions from energy, industry and land use, the green area emissions captured and stored by CCS while red while blues contributes belong to DACS and BECCS.

First of all, we can notice that gross emissions at the source (i.e. including the portion captured at the chimneys with CCS) are very similar in DMD and SUP scenarios in the end of the century, both stable at around 10 GtC02. This confirms the conclusions of subsection 3.1.1.

Secondly, it shows very clearly the already highlighted fundamental importance of CCS and CDR in a deep mitigation scenarios. Even thought it should be noted that the WITCH model is on the high end of Integrated Assessment Models usage of these technologies, the massive scale of deployment of at least one of these technologies is a constant in virtually every stringent target pathway: in general, the rate of deployment of negative emissions technologies is a function of the modelling of their capital costs compared to the marginal abatement cost of traditional mitigation measures. Moreover, all models keep into account the existence of hard mitigation sector like industry, aviation or shipping, for which no viable substitutes exist in the present to fossil fuels. While the total burden in terms of emissions of this impossible to substitute sectors is somewhat variable depending on the modelling approach and assumptions, it is in any case a relevant component. This derives from the physical necessity of sucking carbon from the atmosphere to reach net zero if not negative emissions, useful to recover from the overshoot of the carbon budget before the end of the century.

This conclusion is not, however, without worrying consequences both from an intertemporal optimization perspective (Low and SchÃ¤fer, 2020): a first argument states that model reliance on CCS and negative emissions above what absolutely necessary constitutes an "expedient" for models and modellers to postpone decarbonization, allowing for a gentler reduction of emissions in the near term [1]; the second point, somehow related, argues that over-reliance on technologies that do not exist in scale is a dangerous hazard and possible failures in their deployment would jeopardize the reaching of the desired target, where of course the width of the miss would be proportional to the amount of CDR planned and then proved unavailable (Realmonte et al., 2019). Another critical point related to risk-assessment and failure is the availability and security of geological storage, which of course is once again as relevant as the total CO2 captured (as more CO2 captured implies recurring to riskier and riskier geological site and higher challenges in transportation of the carbon dioxide from site of capture to site of stocking).

Following these arguments, the general agreement about CCS and in particular carbon dioxide removal is that, while almost certainly necessary to a significant extent, *the less the better*. In this sense, the interaction of a carbon pricing and the supply side treaty in SUPDMD shows a very interesting result: not only it reduces the need for CDR because of steeper decarbonization before 2050, almost halving total emissions sucked from the atmosphere in 2100 and almost completely eliminating DACS deployment, but it also halves the gross emissions from 10 GtCO2 in DMD to around 5GtCO2 in 2100, which reduces the need for geological storage and the intensity of policy failure in case of technology availability.

This reduction in gross emissions produced by fossil fuels burning (either capture at the source or recaptured via CDR) also means that supply side policies and

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[1] such a critique seem however to ignore the fact, hard to demonstrate but very easy to agree on, that the rate of emission reduction required by scenarios involving CCS and CDR is already at the limit of techno-socio-economic feasibility

carbon prices interact in a way that mutually reinforce each other and reduces total dependence on fossil fuel burning from the energy system. Looking back at Figure 3.2 this holds true for gas in particular, which levels of consumption not only are far below DMD ones in SUPDMD, but also below SUP. As a matter of fact, the model does not produce at the upper bound of the constraint on production for gas (despite it being clearly binding).

The reason of such behaviour lies in the double effect on prices (see section 3.2) of supply and demand side policy joint: while the optimal carbon tax is reduced, the combined effect of prices increase due to the ban result in higher overall prices for the fuels. Consequently, gas with CCS (which further increase generation costs) is a comparatively less competitive option in SUPDMD than DMD to an extent that makes other substitutes such as efficiency and electrification more cost-effective, while of course gas without CCS is not a viable option because it would incur in the costs of carbon pricing [2]. The net result is consumption levels lower than the most stringent one between the two policy taken singularly, showing a non trivial interaction. This does not happen for oil and coal for two different reasons: for the first CCS is not an option modelled [3]; for the second, the residual level of production allowed in the extraction bans is higher than the consumption levels caused by the carbon tax alone. This means that the extraction ban is not a binding upper bound for coal and it has no effect on prices in SUPDMD, thus showing no such interaction. To conclude, this kind of mutual reinforcement occurs if a fuel is used by technologies that can fit with CCS and if the extraction ban levels are lower than the consumption in a DMD only scenario.

We are now ready to turn our analysis to the energy sector to explore other interactions between supply and demand side policies, shown in Figure 3.7. Primary energy requirements in SUPDMD are consistently reduced with respect to a DMD

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[2] costs that, unlike in a DMD scenario, cannot be balanced by the subsidies to DACs due to reduced need of negative emissions

[3] residual emissions are in any case linked mainly to transport and industry for which carbon capture is infeasible

scenario, stabilizing to values close to SUP. In the 2030s, when the supply side treaty has not yet fully entered into force, the presence of a globally harmonized carbon tax grants early improvements in efficiency and clean substitute penetration. At the end of the century BECCS requirements increase TPES with respect to SUP, but still at lower levels than DMD. Electrification (Table 3.1) in SUPDMD is consistently higher than both scenarios in which the policies are implemented as stand alone, due to lower gas consumption in SUPDMD pushing for electrification of non electric sector. As for the energy mix, renewables penetration show a similar trend in both 2C scenarios, reaching slighly lower absolute values but higher share of TPES in SUPDMD compared to DMD. The amount of BECCS and fossil CCS deployed is nearly identical for the two scenarios, but avoided CCS emissions by fossil CCS in Figure 3.8 show a different composition of CCS capacity in the two scenario: as this share of emissions is more than doubled in a demand only scenario, this implies higher penetration of coal with CCS, while in SUPDMD is gas to consitute the main part of the fleet equipped with carbon capture and storage. As for BECCS, we already highlighted how the difference in negative emissions between the two scenario is due to DAC deployment, which is comparatively more costly between the two technologies. Fossil without CCS is where the most differences are found: oil consumption is halved in 2050 in SUPDMD compared to DMD, and gas without CCS completely disappear after 2050 in SUPDMD while seeing a resurgence in DMD, also due to higher energy requirements for Direct Air Capture. The earlier reduction in oil consumption is the main driver of anticipated decarbonization in SUPDMD, due to the extraction ban forcing a costlier early transition of the transport fleet to electric or biofuels. Overall, coupling a supply side treaty with extraction bans reduces the net reliance on fossil fuels both around mid-century (in particular oil) and later (mainly gas), pushing for electrification and TPES reduction as main substitutes for these energy sources.

It should be noted that the relevant differences here highlighted and the positive complementarities between a supply side treaty and carbon pricing largely lay on the structure of the WITCH model, which foresee a significant overshoot and a lot of net negative emissions in the late century. Given that such possibility is granted by CCS, DACS and BECCS, this means that those technologies are - also thanks to the focus of WITCH on endogenous technology improvements via learning by doing or researching - comparatively cheaper to deploy late in the century (where their cost is partly mitigated by the discount rate) than standard mitigation measures such as efficiency or clean substitutes. Increasing costs of CDR technologies would probably result in earlier mitigation using these latter kind of measures, thus increasing the similarity between DMD and SUPDMD scenarios.

This consideration, however, doesn't eliminate the main point made so far: extraction ban together with a carbon pricing policy reduces the risk of failures, here analyzed in the form of reduction in potential over-reliance on dangerous and immature technologies. Clearly, the less this reliance is considered optimal even in a carbon pricing-only landscape, the lower the probability of failure. Supply side policies would then become increasingly redundant, but the cost increase of deploying extraction ban together with carbon pricing would at the same time decrease. In this sense, supply side policies as complement of carbon pricing are well designed as a risk management tool, as they increase the actual cost of policy only if their introduction produces a large effect on the energy transition. If not, they are both redundant and increasingly cheap, provided the extraction ban is designed properly in terms of speed and depth for each fossil fuel. Of course, at least in the stylized economy world of the model, the overall cost of policy with a extraction ban will be always higher than a carbon pricing policy only, as long as, at least for a fuel and in some years, the upper limit on production is binding. In fact, the superimposed trend of reduction here designed for the supply side treaty will be always inefficient with respect to a Pigouvian tax. That the magnitude of this cost difference, however, will tend to be lower the more the energy system transformation trends with an optimal carbon tax is similar to said extraction ban pathways. Such condition is more likely to be verified in case of low reliance of negative emissions technologies.

3.2 International prices

3.2.1 Fossil fuel market prices

Figure 3.9. Fuel prices in the international market, in semi-logarithmic scale (y axis). The values refer to the energy content, to make the resources directly comparable

Figure 3.9 shows international market prices of fossil fuels in the main scenarios. These values simulate spot market prices, thus representing market value before the application of the carbon tax. Thus, they are not representative of the prices consumer or utilities will face to buy the good. First of all, the reference scenario shows a gradual and slow increase in global prices for all three fuels due to progressive depletion of lower cost natural resources. This growth is more pronounced for oil, both because the global demand is forecast to increase significantly for oil in REF (peaking after mid-century) and because of relative scarcity of cheap reserves. Coal and gas, on the other hand, have more abundant cheap reserves and both it's consumption levels peak in 2025. More importantly, a 2 C scenario with demand side policies only consistently shows a reduction in spot price with respect to the reference. This behaviour occurs because of the decrease in demand for all fossils due to the mark-up in final prices caused by the carbon tax.

When a supply side treaty is implemented, either as stand alone or together with the carbon tax, the underlying dynamic completely changes: prices spike due to reduction in supply, causing in turn a reduction in demand. The trend for prices in the presence of a supply side policy is consistent through fuels and scenarios: prices spike around the time in which laggards start enforcing the ban at a level of several times 2020 levels, and after that they slowly decrease. In general, the earlier the participation (SUP vs SUPALL) the higher the peak in price, where of course in SUPALL the timing of the peak is also shifted to earlier years (because all regions are frontrunners). Late in the century when all the ban are in place, however, the two trends tend to unify, as the final enforcment level is the same in both scenarios.

SUPDMD shows instead a more various picture, each fuel responding in a different manner to the interaction with the carbon tax (which, to remember, is slightly lower in its optimal value in SUPDMD compared to DMD). Coal is simply unaffected by the ban, showing the same price in both DMD as SUPDMD. This is unsurprising, since the same happens with consumption (see section 3.1) and the same explanation holds true for prices: for coal, the upper bound provided by supply side treaty is not binding, as the reduction due to the carbon tax alone is already higher. Gas prices, on the other hand, keep increasing even after mid century after a brief plateau. It is possible to make sense of this trend by understanding the underlying modelling dynamics: price of fuels, not differently than a "fuel tax", reflects the shadow cost of the energy system transition due to the ban being in place for the fuel. This implies that the final price level tends to be higher if its substitute technologies have high costs: in the case of gas, it has been shown that in a carbon tax environment the fuel consumption increases again after the 2070s, meaning it's competitive with respect to the alternatives in particular in the non electric sector, whose total demand increase for DACS requirements. Thus, its value in the energy system is high in those final years and phasing it out requires higher disincentive in the form of price increase. Oil, finally, suffer a more accentuated reduction in price after its 2055 peak compared to SUP and SUPALL, so enunciated that by the end of the century its price is lower than both REF and DMD. On one hand, that's because - unlike gas - oil consumption monotonically decreases after peaking in 2040s already in a DMD scenario. On the other, the difference in behaviour lies in the difference in modelling those two fossil fuels within the WITCH model (see chapter 2): unlike coal and gas, oil enjoys a full representation of the extraction section and its infrastructure investments. The combined effect of the ban and the carbon tax causes a collapse in such investments way earlier in SUPDMD than DMD, with a peak in 2020 for the former and 2035 for the latter and a much steeper fall SUPDMD, that in 2035 has a near floor investment level on the oil upstream sector of 159 bUS$ against the peak of 545 bUS$ in DMD. Such early divestment causes later in the century the collapse of the industry because of combined low demand and supply.

In this sense, it is clear that the better modelling of the oil extraction sector allows to capture a dynamic whose development is precluded in the case of gas: it is difficult to make hypotheses to on what extent the same trend would have occurred for the gas industry and infrastructure, also given the differences in the international market structure of the two fuels (see chapter 1 for a brief description). The possibility exists, however, that such dynamic would occur if properly modelled, thus revealing a limitation of simple representation of oil and gas upstream and midstream sectors.

3.2.2 A focus on the role of the narrative in price-quantity dynamics

Figures Figure 3.10 and A.2 show in detail the interaction between prices increase and quantity consumed by regions, aggregated by their membership to a certain group in the narrative. The first graph shows REF and SUP scenarios, while the second compares DMD and SUPSMD. Coloured vertical lines represent the period in which each group *starts* banning the fuel. This representation allows to capture the dynamic existing in the context of a fragmented supply side treaty between supply reduction, price increase and demand reduction.

About the division in groups, is worth to remind that the distribution of consumption and production quotas other then shear number of participants is very different across groups (Table 3.2.2 for 2020 shares): frontrunners account for few percentage points of global production (expecially for oil and gas) but are more relevant as consumers; followers are similar in consumption shares but more relevant producers, while laggards include all major producers, the majority of world regions and the relative majority of global consumption. However, followers contains the regiond with higher forecast future economic and energy growth, e.g. China and India, while frontrunner relevance in total demand shares is expected to be reduced. Being global demand and supply balanced, the difference between shares of supply and demand also identifies the average trade position of the regions belonging to each group: frontrunners and followers tend to be net importers for oil and gas, while laggards are the net exporters of these two fuels. With a bit of semplification, then, one can say that followers are the big consumers of the XXI century and net importers while laggards are big producers and net exporters. Frontrunners, on the contrary, are increasingly marginal in quantitative term both as producers and consumers throughout the XXI century, but have the comparatively lower abatement cost curves.

This unequal distribution of production and consumption shares has implications on the effects of the unraveling supply side treaty in the transition years: roughly

		Frontrunners			Followers			Laggards		
		Oil	Gas	Coal	Oil	Gas	Coal	Oil	Gas	Coal
2020	Demand	20.4	11.3	24.2	21.7	16.2	28.4	57.7	72.4	47.3
	Supply	7.8	5.9	17.4	14.7	11.0	34.5	77.3	83.0	47.9

Table 3.2. Shares of 2020 production and consumption by group, in %

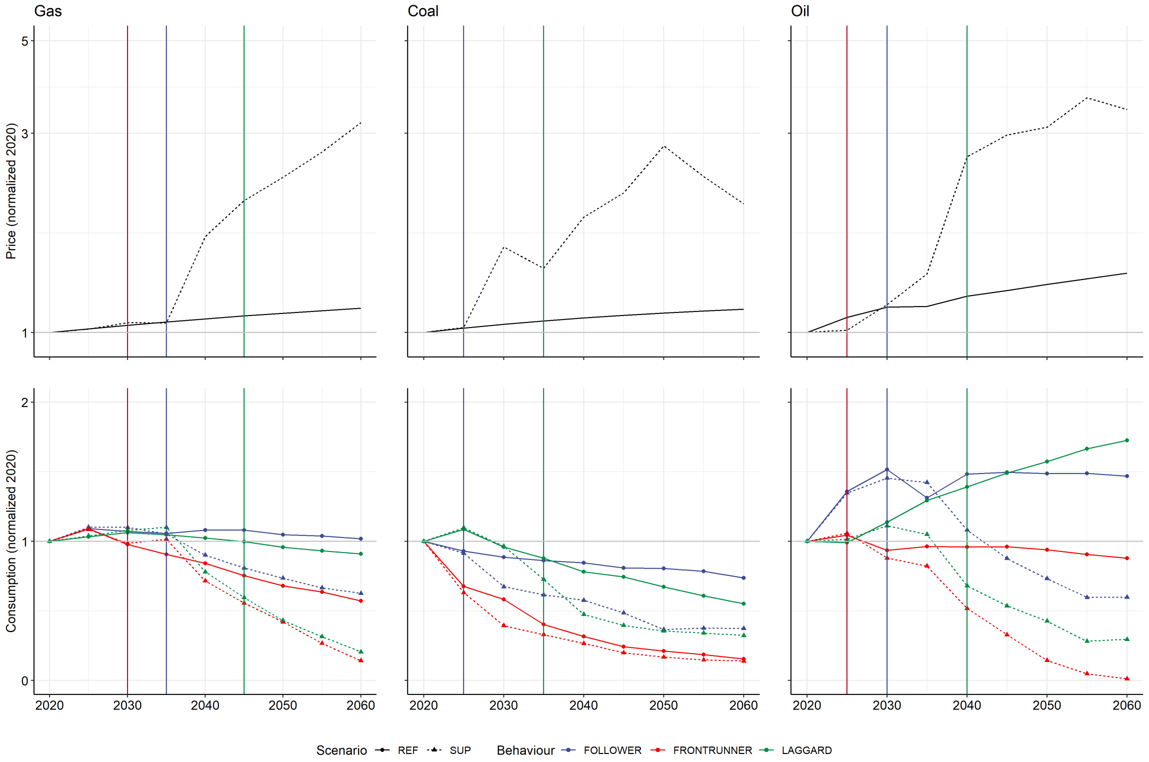

Figure 3.10. Prices and quantities, normalized 2020, aggregated by group in the narrative (Frontrunners, followers, laggards). Vertical lines represent starting year of ban for each group (color consistent); coal frontrunners line is not showed as coincident with followers. Price scale is semi-logarithmic. REF and SUP scenarios showed

speaking, the amount of increase in global prices is a function of the share of production of the group(s) banning the fuel, while the magnitude of demand reduction following prices increase is a function of the consumption shares and the marginal abatement costs of the region(s) (i.e. the available of low cost substitutes/presence of stranded assets in the energy system).

Results of these interactions can be observed in Figure 3.10. In general, as expected, the start of the ban is followed by a price increase which, in turn, causes a reduction in demand. Such interaction is actually a two-fold mechanism: one the hand, the short-term effect of a price increase is to reduce demand according to standard microeconomic theory; on the other, expectations of future high prices in the long term cause, in a perfect-foresight model, a divestment effect on the infrastructure dependent on the fuel. As a matter of fact, this divestment can be preceded by a *green paradox* effect (chapter 1). Given the high inertias of the energy system, however, "short-term" can very well mean a time frame of 30 years or so, as the natural lifetime of big power plants is often more than 50 years. So, at least for the period considered in this analysis (i.e 2060, up until the treaty enters completely into force for all fuels), the spot market price effect is more relevant than the divestment effect, that is predominant late in the century. This hypothesis is also confirmed by (and provide further explanation to) the inverse V shape of prices in supply side scenario, as already seen in Figure 3.9.

For both these dynamics to be effective, however, the amount of fuel banned must be sufficient to cause a global scarcity effect: this is evident in the case of frontrunners for oil and gas, whose extraction ban has little to no contribution to the increase in global prices. On the contrary, a slight green paradox effect for oil - lower prices, higher quantity - and substitution effect for gas - same price, higher quantities - is noticeable before followers take action. Coal ban, on the contrary, produce a significant effect from the first period as the critical mass of the banning coalition is sufficient from the start, accounting for more than 50% of global production.

When followers start enforcing the ban, however, the treaty reaches enough participation to stimulate a price increase also for oil and gas. After that point (2030 for Oil and 2035 for Gas) global demand start decreasing for all groups: as the demand depend on the international price of fuels, the reduction happens regardless of the fact that the countries are participating the supply side treaty.

The aforementioned result is very relevant in policy-making perspective, marking a significant difference from carbon pricing policies. The latter, infact, have positive effect in terms of emission reduction only within the country/coalition that implements them. Outside of it, they can very well produce a detrimental effect, due to decrease in international market price and carbon leakages (chapter 1).

On the contrary, results show that if the coalition is large enough in terms of production shares a supply side treaty, even if the partecipation is coalitional, causes a global effect on demand reduction of fossil fuels, fostering the energy transition even in countries without climate policy at all. The amount of the reduction cannot be precisely assumed, as the price increase and divestment effects (due to even higher prices expectation in the future, following laggard entering the treaty) are difficult to disentangle. Qualitatively, however, this "positive spill-over" of supply side policies can be traced from the differentiated narrative here developed, and the analysis of capacity factors suggests that before mid century the spot price effect predominates due to high inertias in the energy system.

The other side of the coin, however, can be noted returning to the previous considerations about the lack of consequences of frontrunners' action. If it's true that unilateral carbon pricing policies can have negative spill-overs outside of the coalition, it's also the case that - if strong enough - the external increase is overcompensated by the internal reduction in emission. This means that, while less efficient compared to an harmonized policy, a coalitional demand side policy tend to produce an overall positive effect in terms of emission reductions, regardless of how small the coalition is. In fact, even though decreasing coalition size reduces the percentage reduction of global emissions (thus decreasing the positive effect), at the same time decreases the impact on international fuel prices and thus rebound effects. On the contrary, if they don't hit a minimum threshold of participation, extraction ban prove to be completely ineffective and highly detrimental for the countries that enforce them in a economic and - more importantly - energy security perspective.

In this last perspective, early participation to a global supply treaty or unilateral implementation of such policies make sense only considering complex dynamics of leading-by-example, i.e. in the expectation that other will follow. In the specific context of the narrative here developed, the early participation of frontrunners can also be justified [4] by promise of future gains from keeping market shares in the distant future, production quotas that would otherwise be dwarfed by biggest producers. The fact remain, however, that in a policy relevance perspective, where countries are almost never sure of the intentions of the international community and face enormous challenges in acquiring reliable information about future behaviour of other actors [5], this poses a enormous threat to unilateral implementation of extraction ban policies (stand alone, or coupled with a unilateral carbon pricing).

A realistic implementation of such policies must then be included in an ample international framework to gain effectiveness and viability just as much as a carbon-pricing based climate policy. In this sense, restrictive supply side policies do not seem to provide a complete escape to the free-rider dilemma that daunts climate issues, even though they are able to produce a global effect even if implemented by a non-global coalition.

3.2.3 Carbon prices

While the effect on fossil fuel market prices is preponderant, supply side policies interact also with carbon pricing: on one hand, less emissions with the same carbon tax means lower tax revenues; on the other, the combined effect of supply and demand

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[4] narratively, as the exogenous nature of the scenario does not pose any problems of strategic interaction for coalition formation and stability

[5] See Keohane (1984) for a unrelated but brilliant exposition of cooperation enabling and hindering factors in the international arena in a game-theoretic perspective

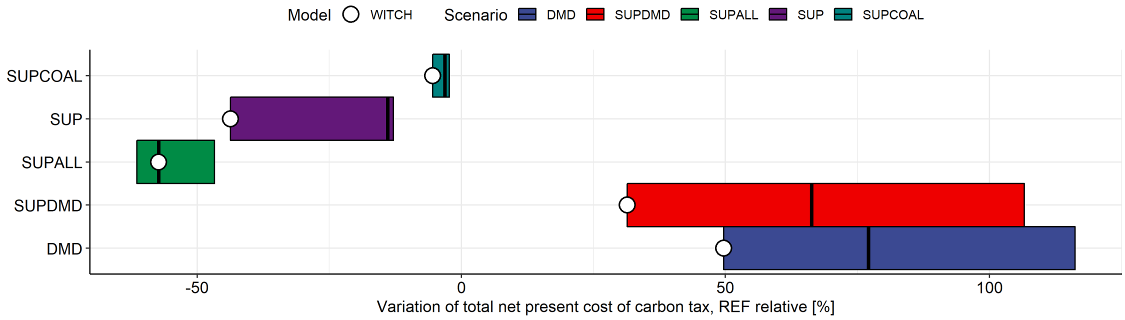

Figure 3.11. Total net present cost of the carbon tax from 2020 to 2100, discounted at 3%, REF relative. Range represents models participating the study.

side policies can allow to reach the same budget with a lower carbon tax levels. To summarise both phenomena, Figure 3.11 shows the range across participating model, with the results for WITCH highlighted, of the net present cost of the carbon tax from 2020 to 2100, discounted at 3%. The carbon cost is obtained as the product of the global average carbon price times global emissions. If the net emissions are negative, this cost becomes negative because it enters society in the form of payment of the carbon dioxide removal industry (BECCS and DACs).

Before analyzing the results, it is worth remembering that Reference scenario has a certain level of carbon tax implemented, because it embeds a continuation of the regional NDCs. As a consequence, SUPCOAL, SUP and SUPALL share the same carbon price, as all these scenarios are modelled on top of REF.

Confronting REF against supply side only scenarios, the latter show a reduction in the overall carbon tax burden on society: given that the carbon tax is identical among these scenarios, it is due to a reduction in the total emissions. For SUPALL the reduction is much more accentuated both because the sharper emission reduction relative to SUP and because of the discount rate, that values more reduction of cost near the present.

The most relevant interaction, however, appears confronting SUPDMD and DMD. In the joint supply and demand action scenario, in fact, the anticipated decarbonization causes a reduction in the optimal level of the carbon tax necessary to reach the carbon budget of 1000 GtCO2 by 8%, relative to DMD. This, combined with lower negative emissions late in the century, results in an overall reduction in size of the "carbon economy". Given the concerns on the overall financial feasibility of large carbon tax revenues and costs, this is overall a desirable feature.

3.3 Costs and distributional considerations

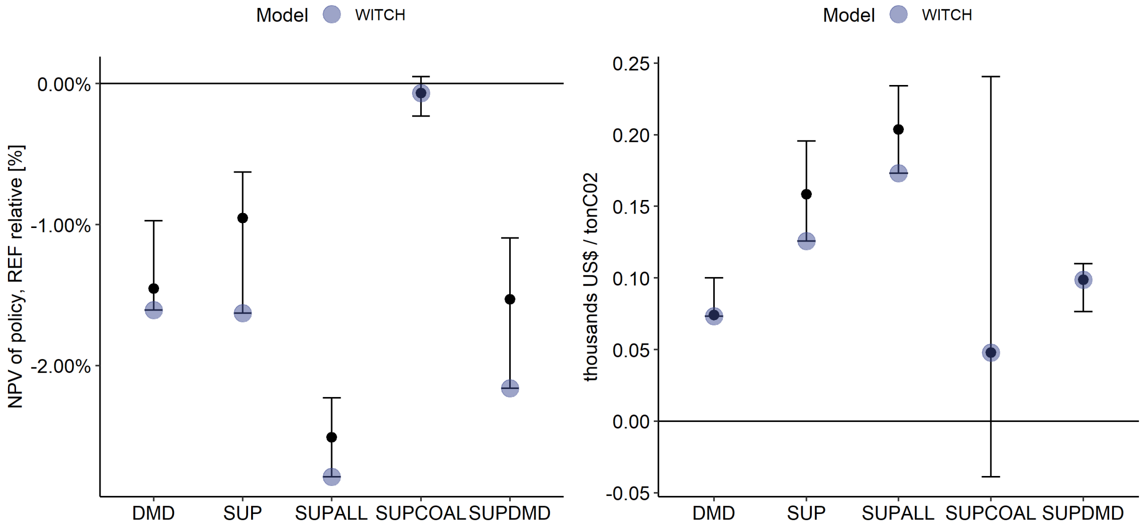

Figure 3.12. Net Present Value of policy by scenario relative to REF (right figure) and cost efficiency of the policy in 1000$ over ton of CO2 mitigated, REF relative. NPV is computed with a 3% discount rate. Bars represents model range.

Figure 3.12 shows the percentage change in Net Present Value of the policy with respect to Reference Scenario (left figure). Unsurprisingly, all policies account for a significant increase in total GDP loss with respect to the Reference scenario, as they imply a much higher level of efforts in terms of emission reductions and transition of the energy system (see Section 3.1 and Figure 3.1). SUPCOAL makes the exception, causing a negligible incremental effort compared to the Reference scenario. SUPALL is the costlier policy, accounting for an extra 2.78% of discounted GDP loss against REF, while DMD and SUP entail nearly the same costs of 1.6%. Joining a carbon pricing policy with a supply side treaty in SUPDMD lead to a total incremental cost of around 2.16% wrt REF. The results of the other models partecipating the study (whose results are shown in the range bars) show good harmony with WITCH results, which is always the costlier model with the exception of SUPCOAL.

Confronting costs of policies, however, does not allow to highlight the dimension of the mitigation effort in the picture: the right graph of Figure 3.12 shows a metric of the cost-efficiency of the policies as the extra-economic effort implied by the policy wrt REF over the emission reductions wrt REF.

In formulas:

$$costefficiency = \frac{NPV_{REF} - NPV}{emissions_{REF} - emissions} \tag{3.1}$$

This simple metric shows quite clearly that, overall, stand alone supply side policies (SUP and SUPALL) are less efficient than carbon pricing based policies (DMD). Coupled together (SUPDMD) the value lies somewhere in between the stand alone scenarios, while banning only coal provides emission reductions at a lower cost than the alternative (even if the confidence from the multi-model assessment here is low).

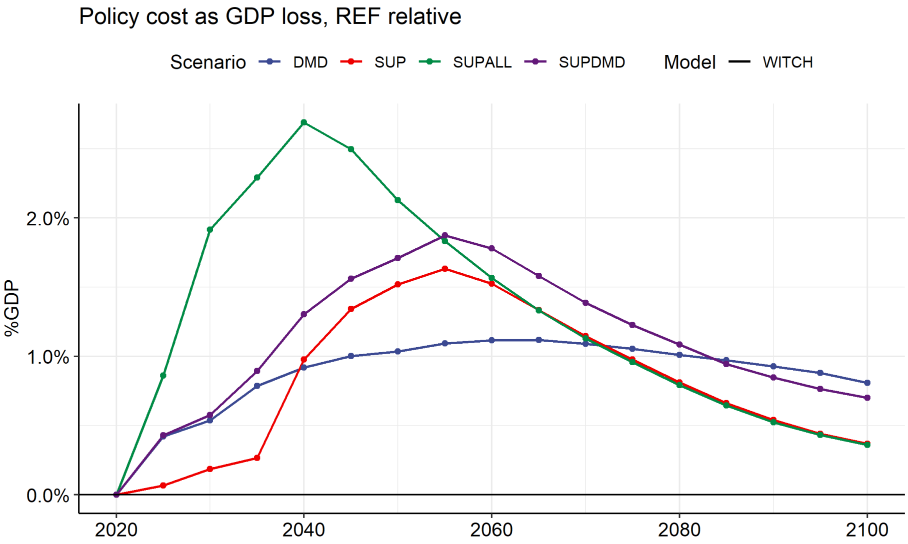

Figure 3.13. Policy cost as % of GDP loss wrt to REF, WITCH model

Figure 3.13 complements this information by showing GDP loss as a function of time: the higher cost of supply side policies is mainly bared by the world economy in the transition phase, peaking around the time when the laggards enforce the treaty for oil and gas (2050s to 2060s) and declining afterwards. Demand-side policy cost, on the contrary, follows a smoother path, stabilizing at around 1% of GDP loss wrt REF for most of the century. After 2080, however, the cost of supply side policies decreases below a DMD scenario: this is because of higher negative emissions required by an optimal 1.5% consistent pathway (DMD) compared to the other scenarios (see subsection 3.1.2 and Figure5 for a detailed analysis of negative emissions).

The difference in the trends of GDP loss between pure demand-side policies (DMD) and scenarios that implement supply side policies (SUP, SUPALL and SUPDMD) is to be searched in the timing of the relative policy instruments: the carbon tax, as implemented in DMD scenario, is exponentially increasing during the century; the fossil production bans, on the contrary, provoke prices (see Figure 3.9) to spike and then decline when the ban is completely enforced. For this reason, fuel prices (including the cost of the carbon tax) are higher in a DMD scenario towards the end of the century, when the economy has mostly phased-out fossil fuels, while they reach the maximum in supply side policies around mid-century, when the energy system is still more fossil dependent. In this sense, supply side policies provide a greater shock to the system in the middle term, while proportionally reducing their burden to the economy in the late century.

Moreover, the fact that supply side policies prove to be less cost efficient than carbon pricing is not a surprising result: in fact, given the underlying neoclassical economy of WITCH model, one would expect carbon pricing emerging as a first best solution against command-and-control policies.

3.3.1 A considerations on supply side policies' caused gdp losses

Classic economics do, furthermore, helps in making another consideration: while SUP and SUPALL imply the same levels of cost late in the century, given that the depth of the ban is equal for both scenarios (70% for each fuel), earlier and coordinated supply side action (SUPALL) results in higher both higher cumulative losses and earlier time of the peak of the effort. This seems to suggest that, in case of production reduction for fossil fuels, coordination does not automatically imply an efficiency increase. Such remark is supported by Figure 3, that show a considerably higher cost per ton of mitigated emission for SUPALL with respect to SUP. This marks a distance with carbon price policies, who are widely recognized to be more efficient if uniform across countries and regions.

Such difference resides, once again, in the very nature of the two policies: while a carbon tax enforce levels of regional mitigation that reside at the margin of the abatement curve, a supply side treaty such that the one we designed in this experiment is a command-and-control style approach.

If a region has a very steep abatement cost curve (because for example it has a large amount of carbon lock-in in in the energy system) it will mitigate less under a global uniform carbon tax environment compared to another for which mitigation is relatively cheap.

In the case of a global production ban in which *each country* caps *its own* production, instead, such an efficient allocation is granted neither on the production side - where more costly resources may be exploited first because of the ban of other region(s) more competitive extraction sites, nor on the demand side [6], both because the forceful reduction of supply limits mitigation options and because of the shape of prices increase following a production ban (see above).

Of these two sources of inefficiency, the first one can be address by designing a quota system in which production is assigned to least cost producers. Such a system would, however, exacerbate the issue of energy security and market concentration (See section 3.4) and would eliminate one of the key point towards the negotiation of a supply side treaty. Moreover, this mechanism is dwarfed by the scarcity effect, by far

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[6] meaning here the energy/industrial system

the largest driver of the huge price increases discussed in section 3.2. Addressing that issue would then result in little to no effect to the overall picture at the cost of the aforementioned concerns on energy security.

3.3.2 Regional costs

Figure 3.14 explores the regional effects of the scenarios by the REF relative Net Present Value of policy, discounted at 3%, for each of the 17 WITCH regions. This figures include only *policy cost* and not the effect of climate damages due to temperature increase: the two main determinants of GDP loss shown here are thus the additional energy system cost (see section 3.1) and the difference in trade patterns and value for fossil fuels (described in section 3.4). If climate damages were to be kept into account, the difference in cost between deep mitigation scenarios and the NDC continuations (REF), would reduce and possibly reverse, as lower impacts from climate change due to lower emissions would overtake the increase in mitigation costs.

Anyhow, the regional disaggregation shows some key characteristic of climate policies in general and offers precious insights on production ban in particular. The general consideration is the high regional heterogeneity of an ambitious climate policy, regardless the policy instrument: this asymmetry is largely robust to the scenario we designed - meaning that regions that pay the larger share of costs of climate action tend to do so for all type of policies and mitigation targets. So, unsurprisingly, big producers like MENA region or the former soviet union (TE) tend to lose a relevant share of their GDP from the reduction in fossil fuel exports.

OECD countries (Oceania, Europe, US) face lower costs of mitigation at less than 1% of the GDP NPV, while developing economies range from 2% to 4% of relative loss with respect to REF. Such behaviour has actually two reasons: on one hand, western economies and energy system are less decarbonized today and suffer less of carbon lock-in and stranded assets that increase the cost of higher climate ambition for countries like China or India; on the other, our reference scenario already contain

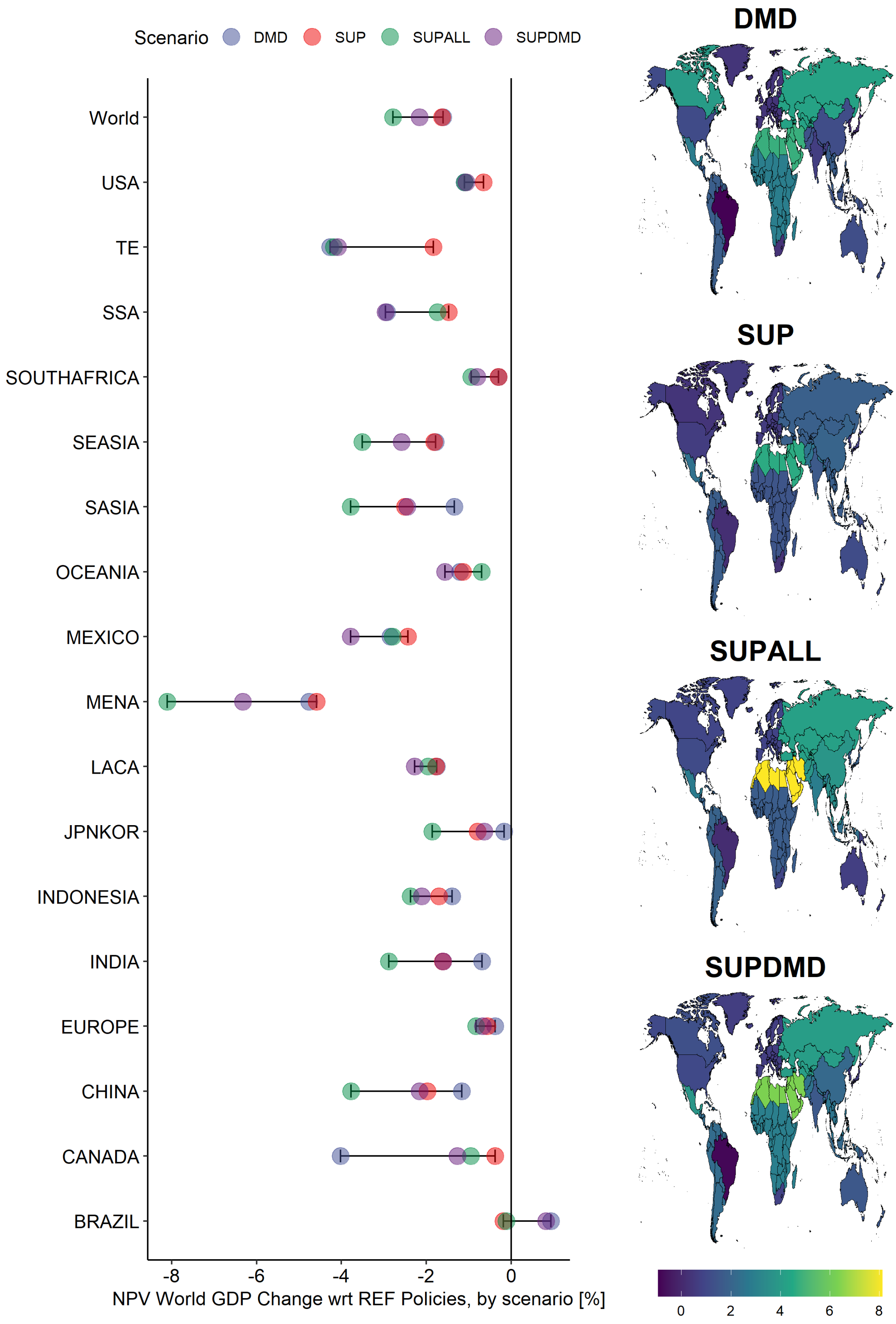

Figure 3.14. Regional GDP loss due to climate policy, % of GDP

an extrapolation of the current *and stated* climate effort by all regions. This means that the baseline (to which the percentage loss refers to) already entails some climate action: in case of the OECD countries, this means starting from a reference point that already implies a fairly ambitous amount of mitigation.

Moreover, OECD countries meet a much lower scissor of uncertainty when looking at the difference in costs between different scenarios. Developing and producing countries, instead, face large differences in costs among policies. We briefly analyze the trends for a few of them:

- **MENA** regions see the higher losses in general, mainly due to revenue losses from fossil fuel exports. Interestingly, however, the SUP scenario implies a similar level of losses than DMD, despite the fact that the supply side treaty reduces the volume of exports in the late century with respect to an unregulated low-demand scenario (see section 3.4). The reason is that, while volumes decrease, price increase, keeping constant or increasing the revenues stream. The same cannot be said, however, for SUPALL scenario, for which the losses surpass 8% of the reference NPV. This is because in SUP producing countries (who are laggards in the narrative) can free-ride in the time lag between the start of the treaty and the moment in which they actually have to enforce the ban, temporarily increasing their market share, while in SUPALL the ban is coordinated.
- **Russia** (TE) shows a similar trend, but supply side policies are overall more competitive, both because Russia is a higher cost producer of oil and because gas - its main export - proportionally increase more its value in supply side scenarios. The net effect is significant reduction of GDP loss in SUP with respect to a standard DMD scenario.
- Big developing economies and importing countries (**China** and **India**) overall lose more from supply side policies than with carbon pricing only. Once again, this is due both to the greater shock to the energy system that the spike trend in

prices seen in SUP and SUPALL produces, and to the higher cost of importing fossil fuels in general.

- High cost producers like **sub-saharian Africa** (SSA) tend instead to gain from the increase in fossil fuel prices and market share late in the century due to a supply side treaty (SUP and SUPALL), losing less than in a DMD scenario. This result, however, is not valid for joint supply and demand side action (SUPDMD).

A regional analysis, in the end, provides a complex picture, suggesting that some regions would have economical interests in signing a supply side treaty - as long as they are able to negotiate a favorable position in terms of entry time, while others would prefer to stick with a classical demand side approach. In general, however, a coordinated global action on the supply side (SUPALL) would see most of the regions worst off with respect to any other alternative, with very few exceptions (Canada and Oceania).

3.4 Energy security and trade

3.4.1 trade

Figure A.3 complements the picture on the regional effects of each scenario by computing the Net Present Value of each fossil fuel's trade, over the size of the region's economy [7]. In this sense, it is a proxy for fossil fuels revenues enjoyed by producing companies/countries. Being relative to the wealth of the region, it is also a measure of the exposure of a certain country/region to the international markets. This figure can thus give information both on a producer support perspective and in a energy sovereignty framework: in the first point of view, for exporting countries, the higher the better; in the second perspective, the more the trade value balance is close to zero

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[7] Please note that in the WITCH model the GDP is measured at Purchasing Power Parity. While nominal GDP would be more suitable for this indicator, there is no convenient way to switch to the second metric for future trends.

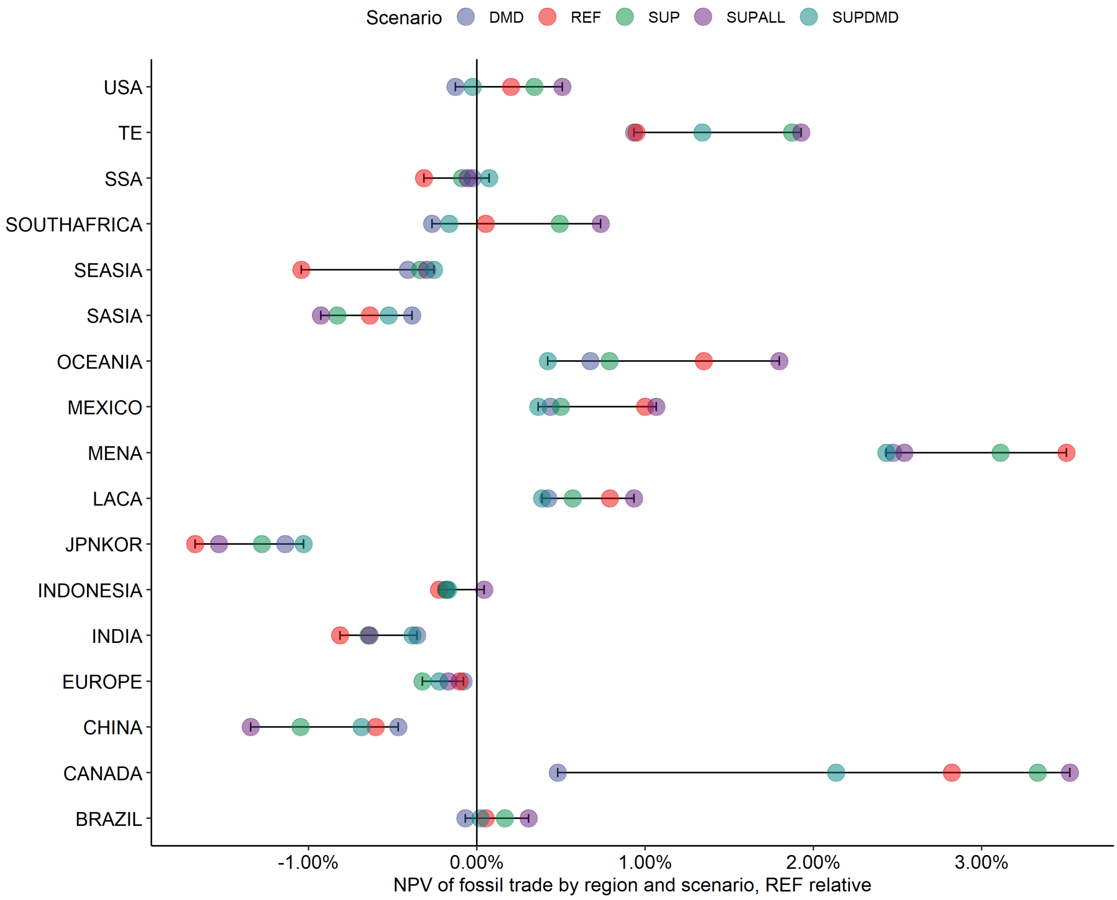

Figure 3.15. Regional Net Present Value of trade for all fossils fuel, over NPV GDP PPP

the lower the international exposure of the region. This is true both for importers and exporters, the former because they may face interruptions to supply due to unforeseen developments, the latter because countries highly reliant on exports tend to be more fragile to fluctuation in the fuel prices.

We first focus on the producer support aspect, because it is one of the points stressed out in the literature in favour of supply side policies Asheim et al. (2019) (see Appendix A). As it was the case for overall policy cost, the difference among supply side scenario (SUP, SUPALL), the NDC Reference scenario and the 1.5 C scenarios (DMD, SUPDMD) depends considerably across regions.

First of all, different scenarios imply a large variation on the indicator for most region, as they effect both prices and quantities of fossil fuels traded and the overall GDP (due to different policy cost). Given that the policy cost is relatively similar across policies and it accounts for only a few percentage points of GDP, however, the largely predominant effect is the change in trade dynamics and the international prices of fuels. However large the difference among policies may be, however, it tends not to change the general position of the region in the international market: net exporters remains exporters and viceversa. Brazil and the US make a relevant exception: the US, in particular, improve their trade position with supply side policies w/r to REF, while they would lose market share in DMD and SUPDMD scenarios.

As for big exporters, in general, stand alone supply side policies provide a more lucrative alternative than global carbon pricing (DMD). If this is true also with respect to the current ambition scenario (REF), however, depends on the characteristics of the reserves: low cost producers of oil and gas (MENA) face a reduction in revenues from fossil fuels from REF to SUP. Moreover, if they are not able to negotiate a favorable position in the treaty (SUPALL), the reduction in total gains from fossil exports is comparable to a DMD or SUPDMD scenario.

Higher cost producers (TE and CANADA), on the contrary, gain considerably from a supply side treaty w/r to REF, be it stand-alone (SUP and SUPALL) or coupled with carbon pricing (SUPDMD). This is because, in a context of decreasing demand due to climate policy, fixed quotas grant better retaining of production shares which would otherwise be eroded by cheaper fields. Such statement is demonstrated by the fact that early entry in the supply side treaty (SUPALL) does not undermine the fossil revenues throught the century.

As for big coal exporters (OCEANIA, SOUTH AFRICA and CANADA), supply side policies tend to have positive effect, in particular if coordinated (SUPALL): this suggests that the price increase is the main determinant for the otherwise least valuable and most abuntant fossil resource.

For most importers (CHINA and INDIA), however, supply side treaty are overall detrimental for the balance of trade: due to higher prices, the overall cost of fossil fuels imported increase despite the decrease in demand (with the exception of Japan and Korea).

The overall picture is thus the following: in general, supply side policies increase the value of fuels, thus widening the scissor of the balance of trade between importing and exporting countries. The consequence is, in general, an increase in vulnerability of the international system with respect to both REF and DMD scenarios. The reader has to take into consideration, however, that *all these scenarios*, implying at least the currently stated amount of climate policies, show a consistent trend of reduction in the global (and regional) relevance of fossil trade as a share of GDP (see Appendix A additional figures).

This means that while supply side policies may cause an increase in sovereignty-related risks *relatively to REF*, the value of trade over GDP PPP ratio will anyways be lower than today's levels, with the subsequent reduction in geopolotical risks associated.

As for the single regions, high cost producers tend to gain more from the implementation of a global treaty, while floor cost producers of oil and gas are ultimately penalized from fixed production quotas, unless they are able to "free-ride" during the implementation phase of the treaty.

3.4.2 energy security

As much as the balance of trade account can shine some light on energy sovereignty considerations, it cannot exhaust the energy security dimension discussion.

A complete treatment of the issue would require a multi-dimensional analysis, analyzing both regional and global indicators. For the sake of simplicity, however, we propose here a simple global indicator, the Herfindahl–Hirschman Index. This metric is a measure of market concentration, is computed as the sum of the square of market shares and has been used in the literature Cherp et al. (2016) to explore the energy security dimension.

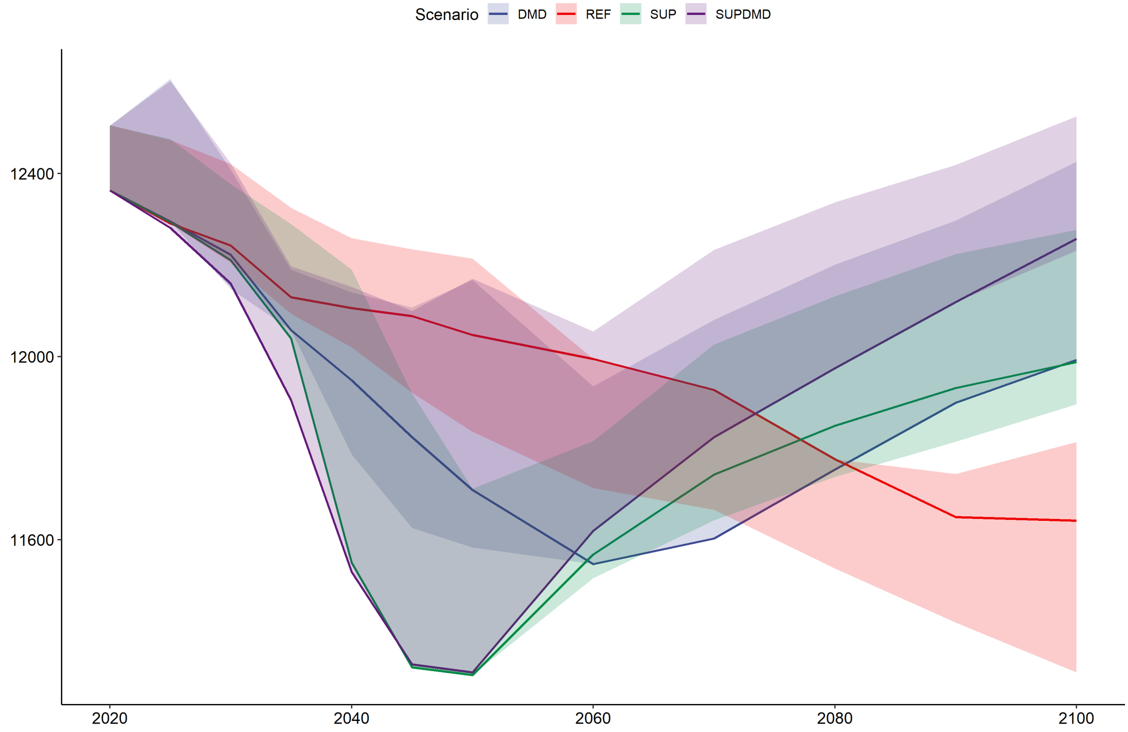

Figure 3.16. Global energy diversity index, computed as the HH index of primary energy shares

In particular, Figure 3.16 shows the HHI computed for primary energy shares. In this fashion, the index can be read as a global energy diversity indicator, where lower values indicate higher diversity [8].

Once again, it is worth noticing that the REF scenario implies a steady improvement of the energy diversity in the mix, as a relevant increase in penetration of renewable energy is foreseen (see section 3.1).

Secondly, more ambitious climate policies show a very clear (and robust across models) inverse v-shape trend throught the century, with energy diversity sharply decreasing until mid-century and then starting to increase again, eventually overcoming the values of reference scenario. This behaviour find an immediate explanation in the energy system response to ambitious climate policies: during the transition phase, renewables and zero carbon technologies enter aggressively the mix, thus increasing their relative share and the overall TPES diversity. After mid-century, fossil sources are either taxed to very high levels or capped by the extraction bans. The only feasible way to cover the projected increase in energy demand then become zero carbon energy systems, which gain the vast majority of the energy mix. As a consequence, energy diversity starts decreasing.

Confronting supply policies (SUP) and carbon pricing (DMD), the former show a sharper transition: this is due both to higher levels of energy efficiency investments and the lack of CCS deployment in SUP, that subtracts an option to the mitigation toolkit. Since joined supply and demand side policies (SUPDMD) show a trend way more similar to SUP than DMD, it can be deduced that the predominant effect is the first one.

In conclusion, both supply side and demand side policies cause an increase in energy diversity before mid-century and an increase afterwards. The range of variation is, however, fairly small: the average share of an energy source varies from around 35% in 2020 to a minimum of 30% in SUP and SUPDMD scenarios in 2050. In this sense, climate policies in general don't pose neither particular threats nor provide extreme benefits in terms of diversity of the energy mix. This last statement, however, stands

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[8] the value for the index reads as the square of the average share of TPES (in percentage) for a energy sources

at the global level, but some regions particularly dependent on fossil fuels may benefit from renewables based diversification; viceversa, regions with high endowment of renewable energy potential may suffer from excessive reliance on a single intermittent source.

Moreover, there is a conceptual difference between over-reliance on renewable energy and fossil-based sources: the first one pose essentially technical challenges (balancing load and supply), while the second ones imply supply risks, especially for importing countries. While both can result in service disruptions that damage the economic output and the general welfare of the country, the former issue can be resolved with technical means[9] (storage means, demand management), the latter is economical and geopolitical, and consequently more delicate.

In this sense, it is useful to use the HH index to explore market concentration in fossil fuels production (Figure 3.17): of course, lower market concentrations are vital in terms of energy security, because they reduce the market power of the single actor and they allow for an easier substitution of supplier if needed.

While this is undoubtedly a meaningful indicator, the information it provides must be read with some cautions. First of all, the WITCH model is aggregated in 17 regions, which means that the levels of concentration will be overestimated. The regional detail, however, should be sufficient to capture the trends, especially considering that the regional division rarely aggregates more than one relevant producer (with the exception of the MENA region. However, most of producing countries within MENA belong to OPEC, so they can be decently modelled as a unicum). Second of all, the same value for the indicator reads very differently for different fuels: as coal is abundant, its reserves geographically distributed and its transportation easy, market concentration has very little implications in terms of long term energy security. In fact, even if the actual production is concentrated into few key regions, the *potential* producers are many and distributed into different regions. Gas and oil, instead, are

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[9] most of which are modelled in WHICH

way more susceptible to geopolitical risk, as they are more concentrated geographically, way scarcer and in average costlier to extract.

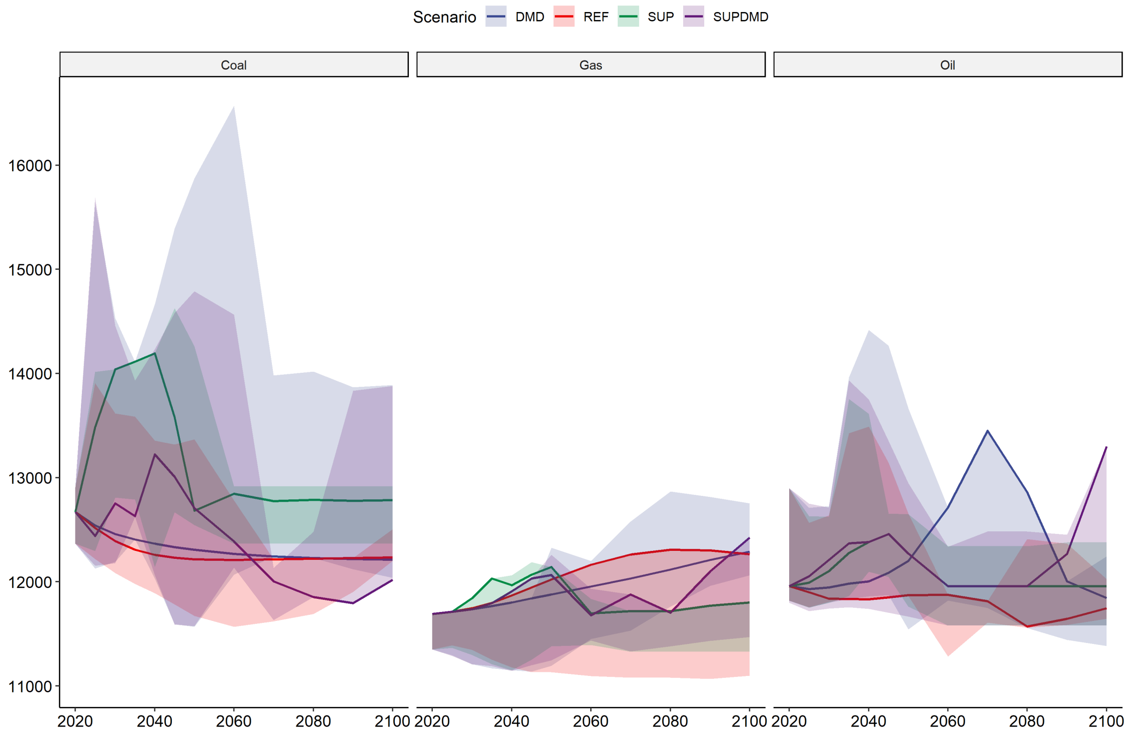

Figure 3.17. The market concentration index for each fuel, computed as the HH index of the regional shares of production

In this framework, different trends can emerge as shown by Figure 3.17. In general, Reference scenario foresees different trends: for oil and coal, the concentration index steadily decreases through the century. For gas, on the contrary, it increases. The shaded area referring to the other participants model's behaviour, however, reflects large future uncertainty, especially for gas.

In supply side policies, market concentration increases in the transition phase, when front-runners and laggards are banning their own production but laggards are still allowed to freely extract resources. After the treaty enter into full force, however, the value stabilizes at 2020 level by design of the extraction bans. As a consequence, inter-model uncertainty reduces significantly.

The steadiness of the market quotas in case of the implementation of a supply side treaty stabilizes the long term value of the indicator, given that extraction is fixed at today's share of production (SUPALL is not showed here as it would be just a flat line). Clearly, this imply that SUP will be detrimental in terms of energy security with respect to REF in case of coal and oil (that show a decreasing pace in REF) and improve for gas. If we compare oil behaviour between scenarios containing a treaty (SUP and SUPDMD) and the carbon pricing policy (DMD), however, we can see that supply side policies, while contributing to climate mitigation, can act as a useful stabilizer to the international market, avoiding spikes in market concentration as in DMD.

Such a spike occurs because, in a low demand environment, low cost producers gain market share in a perfectly competitive setting. Of course, the main caveat here is that WITCH does not model strategic interaction between producers, that today and in the past were fundamental to explain the trends in price and production shares for oil. However, the existence of international cartels in the oil market is a relatively recent introduction, and the underlying rationale behind it is the forecast of future increasing demand: in such an enviroment, big producers have the best interest in acting like a capacitor to the system, absorbing shocks and stabilizing price to reasonably high levels in the long term, because the future expectation for the resource rent are high. In a scenario of falling demand such as a Paris consistent pathway, however, this expectation does not hold and low cost producers may actually decide to act like competitive actors, flooding the market with their product, decreasing international prices and gaining market share in the present as they expect that the value of the resource will decrease in the future.

In this sense, a supply side policy may be appealing to both producers and consumers alike: the first ones, because they would face a more stable oil market under different climate policy ambition, and the bargaining power of low cost producers would decrease. For the second ones, because their natural resources would retain a long run higher value due to prices increasing.

3.5 Banning coal extraction: overview and implications

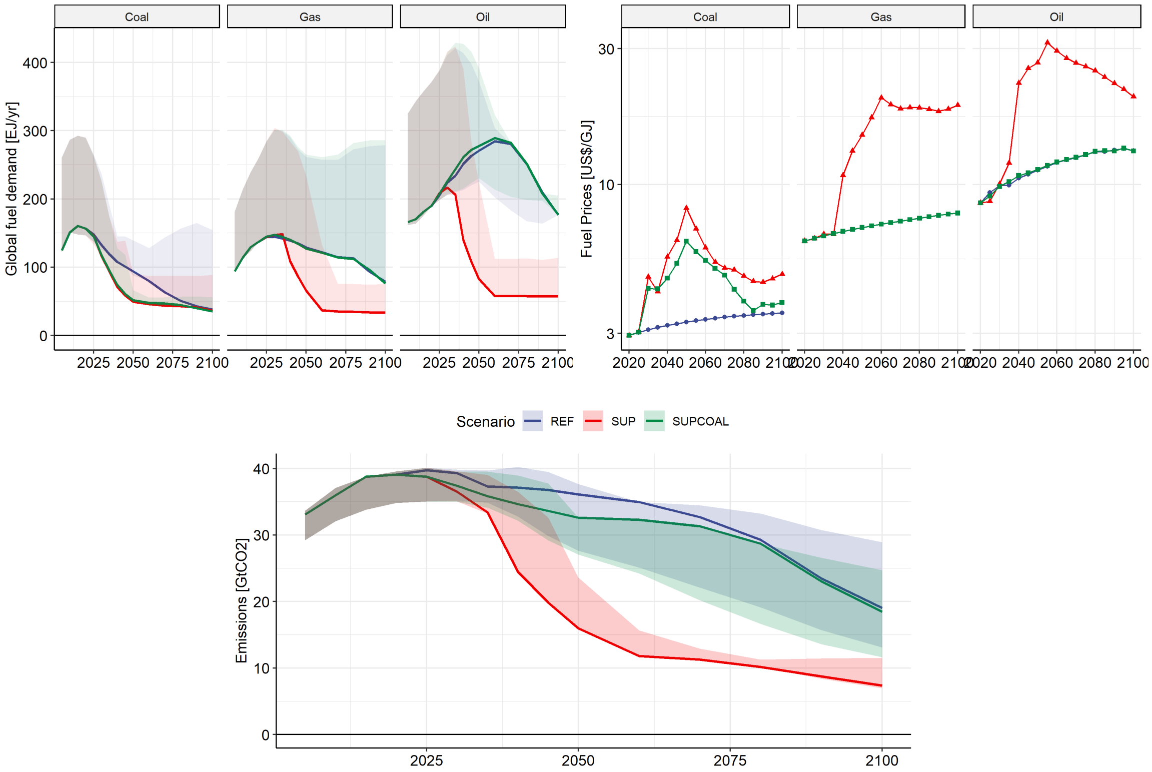

Figure 3.18. Emissions, fossil fuel consumption and international fuel prices for SUPCOAL scenario.

In section section 3.3, we showed that banning only coal (SUPCOAL) is by far the cheapest option among all the scenarios we analyzed, both in absolute costs and per ton of CO2 avoided. We didn't discuss, however, the overall effects of this scenario. Figure 3.18 provides a quick overview, comparing SUPCOAL to the reference scenario and the supply side scenario. Results for emissions clearly show that, while banning coal extraction reduces emissions, the net effect is not sufficient to modify the overall trend of the REF policy: CO2 emissions essentially follow the same trend of slowly decline thorough the century. This is true because, while the supply side treaty causes a faster phase-out of coal, the underlying trend in REF is already one of steady decline of the coal industry (see right panel of Figure 3.18).

	Ban level	Carbon budget	Policy cost
SUP_30	30%	2329	0.9 %
SUP_40	40%	2227	1.0 %
SUP_50	50%	2095	1.1 %
SUP_60	60%	1961	1.3 %
SUP	70%	1803	1.6 %
SUP_80	80%	UNFEASIBLE	UNFEASIBLE
SUP_90	90%	UNFEASIBLE	UNFEASIBLE
SUP_100	100%	UNFEASIBLE	UNFEASIBLE

Table 3.3. Sensitivity results for different extraction ban maximum levels.

The effect on international market prices of coal are, of course, very similar between SUP and SUPCOAL for coal: the latter, however, sees a lower increase of price, because in that case the combined scarcity of all fossil fuels increases the value of the unit of coal and thus the shadow cost of banning it.

As for the effect on prices and quantity of the other fuels, results show that the substitution effect between fuel is virtually non existent in the gas of gas and very limited for oil. This means that even the low and fragmented carbon price of REF combined with decrease in cost of renewables is enough to make clean power generation cheaper than new fossil fuel plants. The small increase in oil consumption is instead to be attributed to non electric sector, in which, as already mentioned, the substitutability with clean option is lower.

3.6 Sensitivity analysis

In order to assess the effect of the design choices in the scenario implementation, we performed two different kind of robustness and sensitivity analyses: SUPALL scenario serves the purpose of testing how much results are robust to the assumptions made in developing the narrative. This scenario has been widely described in the discussion of results.

Besides timing, the depth of the ban is another key design choice for the supply side treaty. In order to evaluate the sensitivity of results over this parameter, we run

Figure 3.19. Decarbonization effort measured as carbon budget against policy cost for all feasible sensitivity scenarios.

a series of SUP scenarios, all implementing the timing of the narrative but differing in the depth of the fossil fuel production cut, as in Table 3.3. When producing a feasible solution, we reported the carbon budget between 2011 and 2100 as a metric of mitigation effort and the total cost of policy, computed as the relative ratio of Net Present Values of GDP between the scenario and REF. These variables are also shown in Figure 3.19.

Two considerations are important here: first of all, stronger ban levels than the 70 % used for the standard SUP scenario produce infeasibility. This proves the point made in section 3.1 about the impossibility for supply side policy alone to produce complete decarbonization of the energy system, at least given our understanding of the likely developments in the technology portfolio for the energy sector. Of course, this threshold is model dependent and thus must be treated with caution. However, the fact remains that complete decarbonization is impossible without deploying CCS or CDR technologies.

Secondly, Figure 3.19 shows that supply side scenarios with different depths loosely follow a linear trend in the mitigation effort/policy cost space. This is overall a desirable feature of the policy, as costs increase linearly with the mitigation effort. Furthermore, given the highly non linear behaviour of international market prices of fossil fuels, such a finding is non trivial.

Chapter 4

Conclusions

In this thesis, we have explored the viability of supply side policies in the form of fossil fuels' extraction bans. We confronted them with a Reference scenario containing projections on today's stated efforts and a Paris consistent scenario shooting for a Carbon Budget of 1000 GtCO2 in 2100 via a global uniform tax. Of the four novel scenario we designed, one considered joint supply and demand side action shooting for the same carbon budget, while the others deployed only supply side policies on top of the ones modelled in the Reference scenario. In order to cope with the complexity involved in a global supply side treaty we developed a narrative regulating the entry time of different regions, with the objective of mimicking a possible negotiation in which actors with more market power gain better positions in the treaty.

The results of this analysis indicate that the effect of fossil fuel scarcity on the energy system is similar to the carbon tax in phasing-out dirty inputs and deploying clean substitutes (renewables, nuclear, efficiency). The carbon tax, however, is the only instrument capable of boosting the deployment of ”non conventional” technologies such as Carbon Capture and Storage and Carbon Dioxide Removal that are fundamental for reaching net zero or net negative emissions. For this reason, extraction bans alone fail to reach aggressive mitigation targets compatible with 2C of warming in 2100.

Acting directly on the international prices of fuels, however, supply side policy enjoy an interesting property: if the coalition implementing the ban is big enough to meaningfully effect the market dynamics, then the reduction in fossil fuel consumption due to the increase in prices will be equally felt by countries internal and external of the coalition. This marks a significant difference with carbon pricing that, if implemented unilaterally, has negative spillover effects on the regions outside the coalitions (both economically and in terms of emission reduction). It must be noted, however, that small coalitions do not seem to produce a significant effect on international markets: in this sense, the coordination dilemma and the need for international cooperation does not disappear with supply side policies.

In terms of costs, however, supply side policy seem more expensive and less efficient than its demand side counterpart. A first explanation for this resides in the lower technology portfolio that supply side policies engage; on the other hand, the shape of price increase due to the ban makes the vast majority of the costs concentrated around mid-century, where the discounted value of the future is higher than at the end of the century.

These costs, however, distribute differently within and among regions: banning fuel extraction keep market prices very high and increases the total revenues extracted through the century by fossil fuels producers (especially those with high cost of extraction per barrel), despite the reduction in volume traded. In this sense, they would favour producing countries and fossil fuel producers.

If a uniform and coordinated supply side treaty is considered, the above considerations essentially stay valid, with faster decarbonization and higher costs. Banning only coal is beneficial and relatively cheap, but cannot change the overall emissions trend of the Reference scenario. If supply and demand side policies are put in place together, the interaction depend on the relative effort implied by the two: if the extraction ban are more binding, they increase prices and anticipate decarbonization, helping to reduce reliance on carbon dioxide removal late in the century. Otherwise, they effect the production shares but don't have a relevant effect on climate policy and costs for society.

The above results seem to suggest that supply policies can substitute carbon pricing before mid-century and complement demand side policies after 2050 in order to reach net zero emissions.

4.1 Limitations and future work

The main model caveat of our analysis is the representation of coal and gas: while the algorithm developed allowed for a representation of the production cuts, it is not completely integrated within the main optimizer and does not directly model upstream infrastructure cost, unlike oil. Secondly, the possibility of strategic behaviour by fossil fuels producers is lacking: such behaviour would occur for regions that have not yet entered the treaty and may possibly be relevant.

In terms of scenario design, while we did capture some price dynamics caused by the regional dis-homogeneity of the supply side narrative, we did not explicitly modelled coalitional supply side policies, possibly coupled with regional carbon pricing. A different experimental design would have allowed to explore in more detailed how the size, composition and characteristics of climate coalition effect the ability to reduce global emissions, employing carbon pricing, extraction ban or the two instruments together. As this is one of the pointy frequently raised in the literature about supply side policies, such a project constitutes the more promising possibility for a follow-up work on this thesis and the multi-model exercise it was part of.

Appendix A

Additional figures

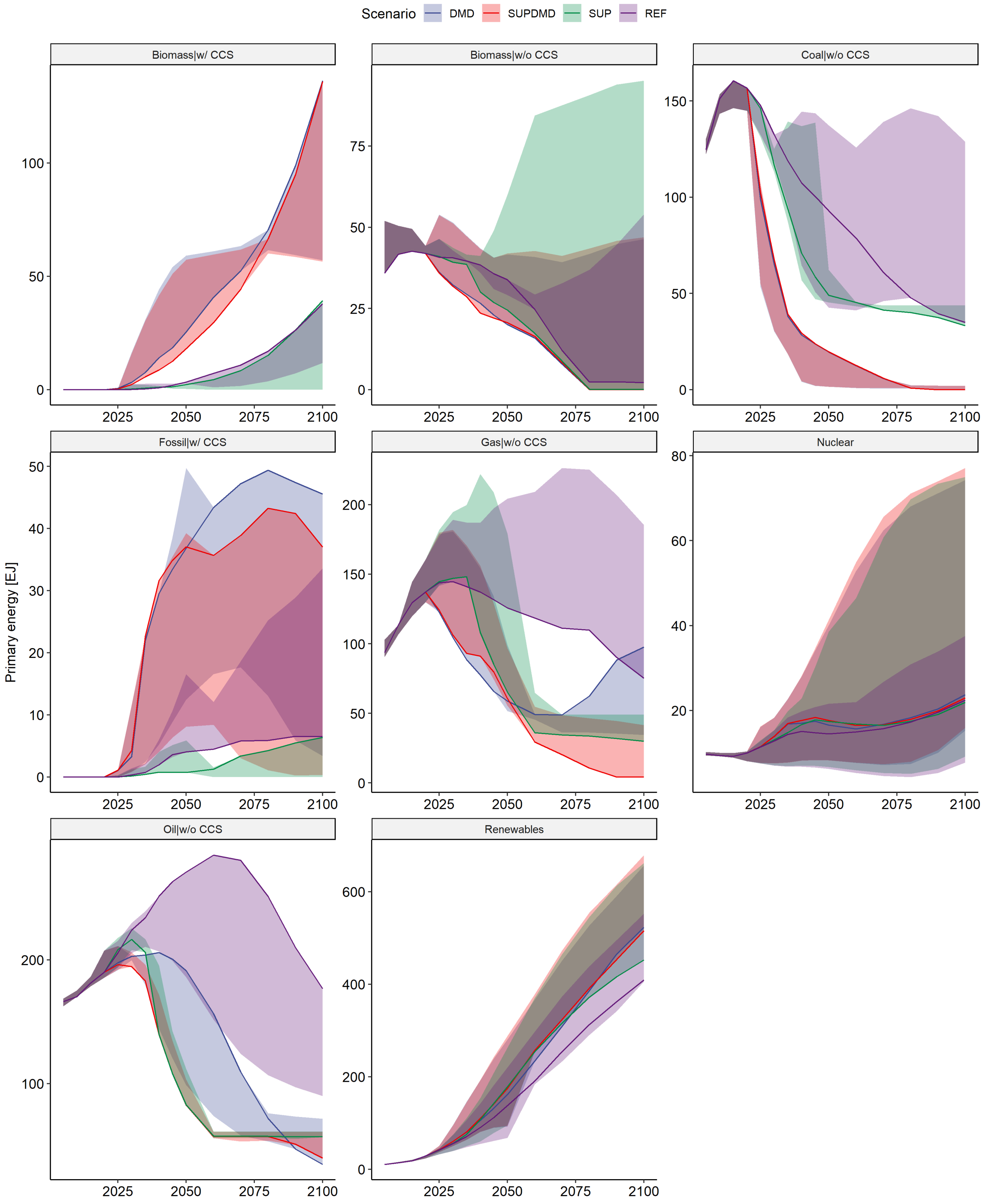

Figure A.1. Global primary energy trends. Shaded area refers to model range

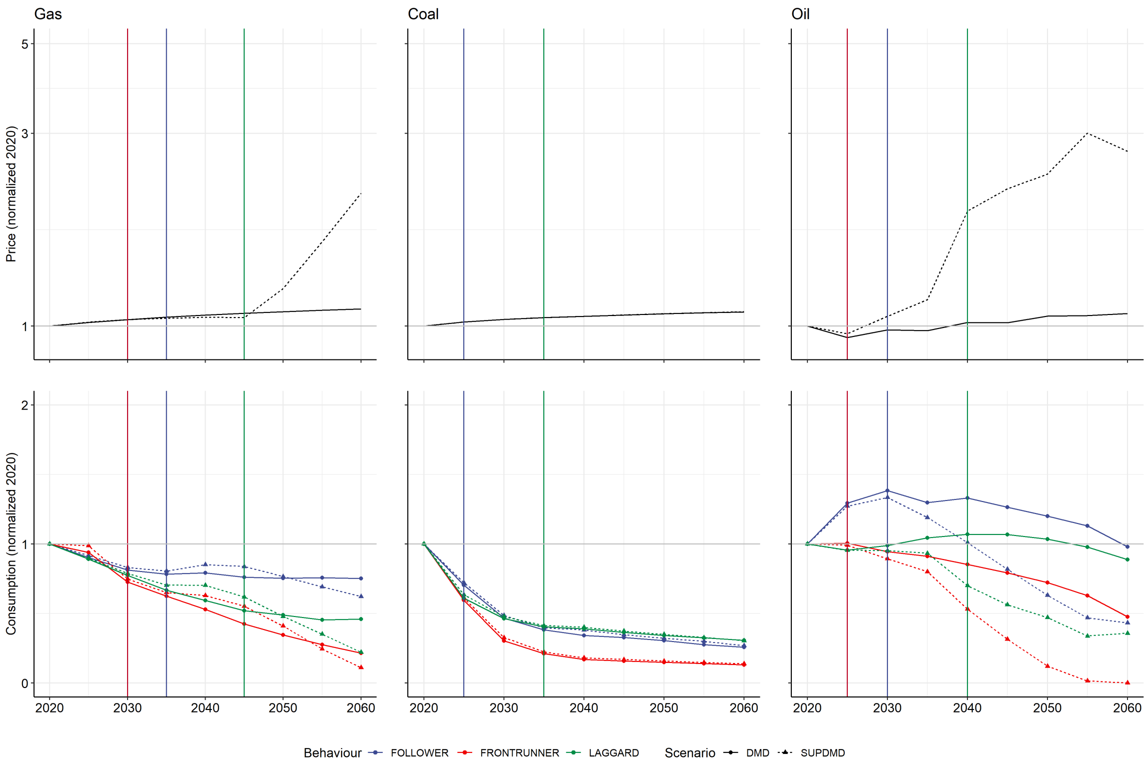

Figure A.2. Prices and quantities, normalized 2020, aggregated by group in the narrative (Frontrunners, followers, laggards). Vertical lines represent starting year of ban for each group (color consistent); coal frontrunners line is not showed as coincident with followers. Price scale is semi-logarithmic. DMD and SUPDMD scenarios showed

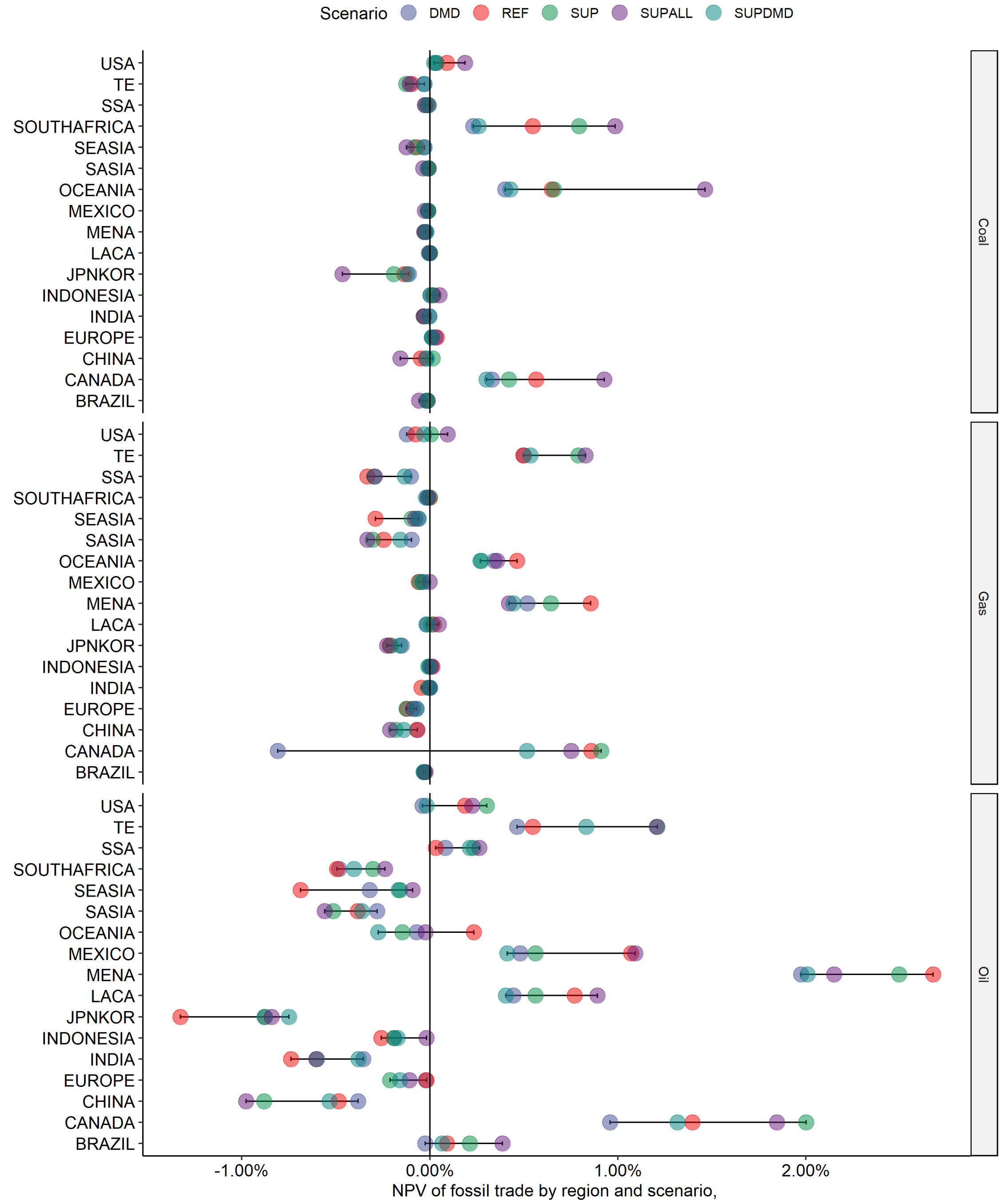

Figure A.3. Regional Net Present Value of trade for each fossils fuel, over NPV GDP PPP

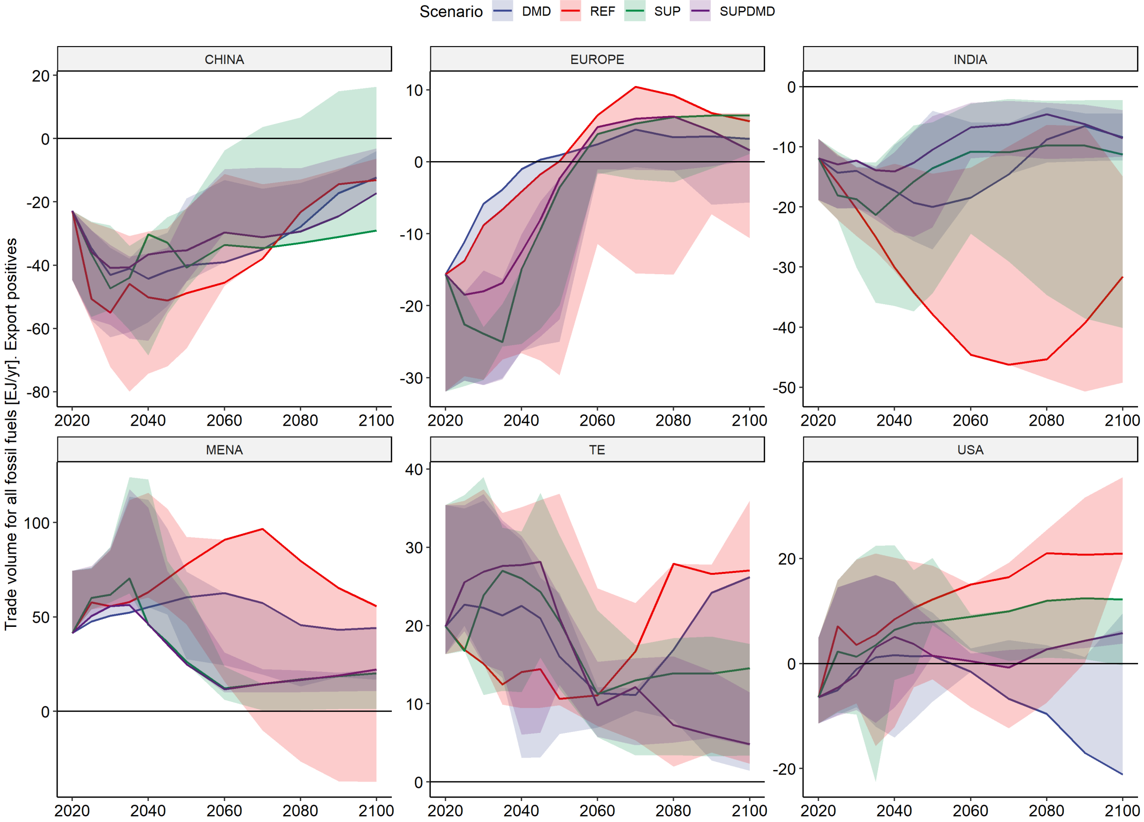

Figure A.4. Total volume of fossil fuels traded in selected regions. Shaded area refers to model range.

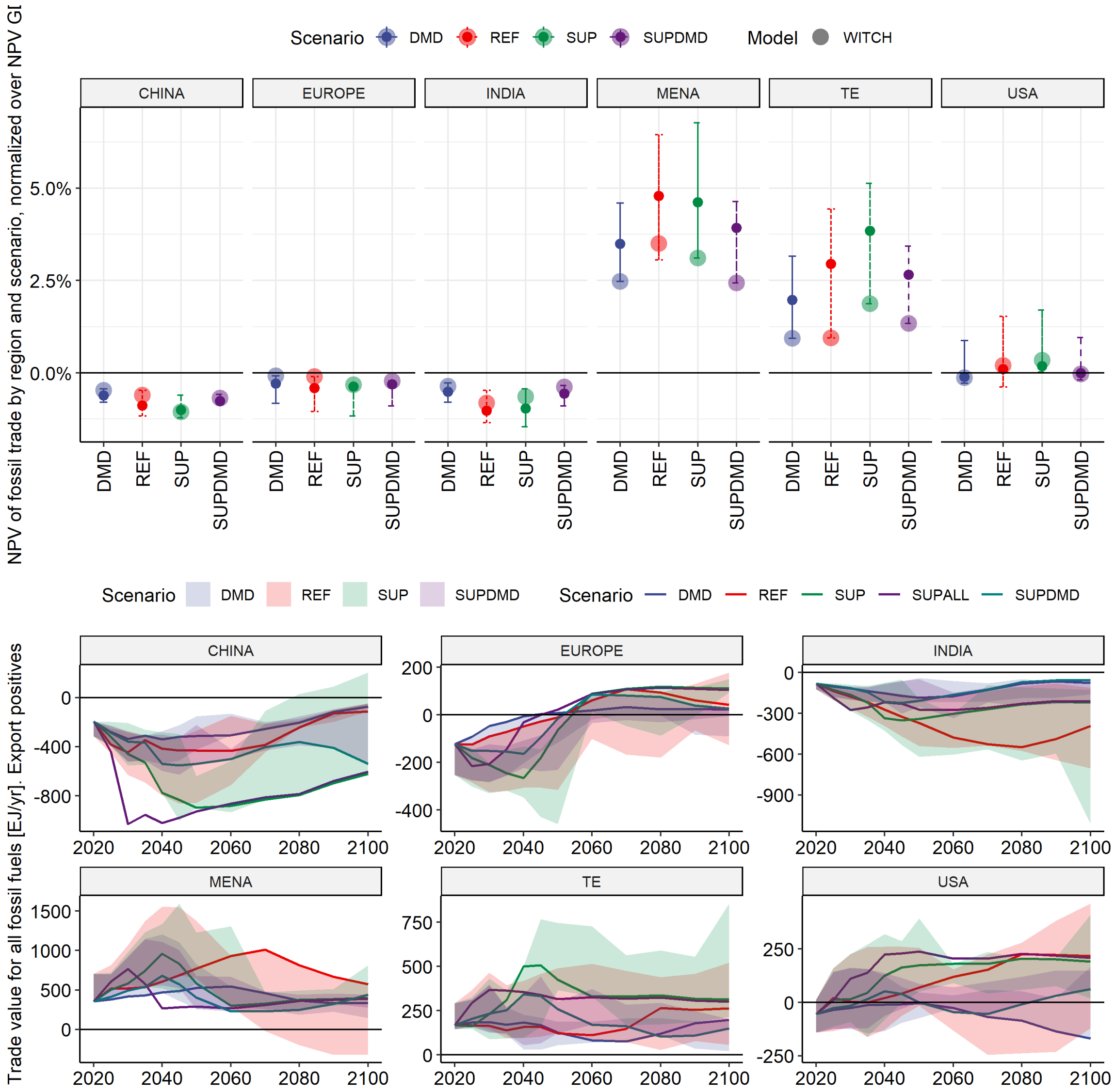

Figure A.5. Value of fossil fuels traded, across time and NPV, for different regions. Shaded area refers to model range.

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