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Long-term climate policy implications of phasing out fossil fuel subsidies

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Abstract

It is often argued that fossil fuel subsidies hamper the transition towards a sustainable energy supply as they incentivize wasteful consumption. We assess implications of a subsidy phase-out for the mitigation of climate change and the low-carbon transformation of the energy system, using the global energy–economy model REMIND. We compare our results with those obtained by the International Energy Agency (based on the World Energy Model) and by the Organization for Economic Co-Operation and Development (OECD-Model ENV-Linkages), providing the long-term perspective of an intertemporal optimization model. The results are analyzed in the two dimensions of subsidy phase-out and climate policy scenarios. We confirm short-term benefits of phasing-out fossil fuel subsidies as found in prior studies. However, these benefits are only sustained to a small extent in the long term, if dedicated climate policies are weak or nonexistent. Most remarkably we find that a removal of fossil fuel subsidies, if not complemented by other policies, can slow down a global transition towards a renewable based energy system. The reason is that world market prices for fossil fuels may drop due to a removal of subsidies. Thus, low carbon alternatives would encounter comparative disadvantages.

Keywords: Fossil fuel subsidies, Climate change, Sustainable energy transformation

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1 Introduction

In 2009, G20 leaders committed to "rationalize and phase-out over the medium term inefficient fossil fuel subsidies that encourage wasteful consumption" (G20, 2011). Despite this commitment, subsidies to fossil fuels continue to grow reaching about 523 billion USD in 2011 (WEO, 2012). Motivations for these governmental expenditures range from energy security concerns to supporting domestic production and job markets, alleviating energy poverty, and redistributing wealth (Porter, 2020, Koplow et al., 2010, WEO, 2010, del Granado et al., 2012 and OECD, 2012). However, by distorting markets and discouraging the production and use of clean energies, fossil fuel subsidies do not only cause economic inefficiencies but they may also hamper a transition towards a sustainable provision of energy.

In this paper, we aim to answer two questions: (1) To what extent can a phase-out of fossil fuel subsidies pave the road towards the stabilization of greenhouse gas emissions? (2) To what extent can a phase-out of fossil fuel subsidies trigger a transition of the energy system towards a clean and sustainable provision of energy? We answer these questions by analyzing scenarios that span two policy dimensions – a varying degree of phasing out fossil fuel subsidies in combination with varying degrees of climate stabilization policies.

Due to the difficulty in identifying, collecting, and measuring fossil fuel subsidy data, attempts to quantify global benefits from phasing out fossil fuel subsidies were made only recently. A milestone is the database published by the International Energy Agency (2013), which includes data for consumer subsidies in 37 countries for coal, natural gas, oil, and electricity. This large data set can be used to study scenarios for the phase-out of fossil fuel subsidies with the help of integrated assessment models. Currently, two models have provided an analysis of such scenarios. The first model is the OECD's world general equilibrium model ENV-Linkages that has provided the background analysis for the G20 initiative on removing fossil fuel subsidies (Burniaux and Chateau, 2011). Related to that, Burniaux et al. (2011) take a closer look into terms-of-trade implications. The second model is the World Energy Model (International Energy Agency, 2012) on which the analysis in the World Energy Outlook 2010 and 2011 is based (WEO, 2010 and WEO, 2011).

There are large and partly intrinsic uncertainties inherent in modelling the global energy–economy system and its inter-linkages with the climate system. These circumstances strongly suggest to compare results across a variety of models instead of looking at single model results, only. Thereby, the confidence into the robustness of result can be strengthened. This is even more important as this class of models cannot be validated (Oreskes et al., 1994). Using the integrated assessment model REMIND, we study the impacts of phasing out fossil fuel subsidies in light of an intertemporal energy–economy model with perfect foresight (Leimbach et al., 2010, Luderer et al., 2012a, Luderer et al., 2012b and Bauer et al., 2012).

The structure of this paper is as follows. In Section 2 we compare the model frameworks of REMIND, ENV-Linkages, and the World Energy Model and we describe our scenario set-up for studying the impact of phasing out fossil fuel subsidies. Section 3 discusses and compares results with those obtained by the two other models. The focus is on short- and long-term implications for the mitigation of climate change and a low-carbon transition of the energy system. Finally, we conclude, linking the results of our study to current policy initiatives.

2 Comparison of modelling frameworks and scenario set-up

2.1 REMIND compared to ENV-linkages and the World Energy Model

The global energy–economy system with linkages to the climate system is a complex system involving large uncertainties. These uncertainties do not only lie in historical data, interpretations of past and present developments, or limited knowledge of the best level of spatial and sectoral coverage. But uncertainties also concern fundamental laws governing the development of the socio-economic system. Therefore, and due to computational limitations, modelling teams have to make a multitude of choices and assumptions when modelling the global energy–economy system, refer e.g. to van Vuuren (2009) for a concise overview about challenges and different modelling approaches.

Here we provide an analysis of the effects of phasing out fossil fuel subsidies based on the REMIND model[1]. This model uses a different modelling approach than ENV-Linkages and the World Energy Model, refer to Table 1 as a basis for the comparison. A key difference is the assumption of myopic behaviour in the World Energy Model and in ENV-Linkages, whereas REMIND features perfect foresight. Furthermore, model objectives are distinguished in the following: ENV-Linkages is set-up to maximize producer profits and consumer welfare in a recursive-dynamic mode. The World Energy Model follows a least-cost approach to satisfy energy service demand. REMIND's objective is to maximize intertemporal welfare at the global level. It should also be pointed out that only in REMIND prices develop endogenously, determined by short- and long-term scarcities.

[1] For the documentation of REMIND refer to Luderer et al. (2013).

Table 1: Comparison of ENV-Linkages, the World Energy Model, and REMIND. See also Appendix A.1 for further details.

Feature	ENV-linkages	World Energy Model	REMIND
Time horizon	2001–2050	2010–2035	2005–2100
Regional coverage	12 regions	25 regions	11 regions
Sectoral coverage	25 economic sectors	15 economic sectors	10 final energy types
Type of model	Recursive-dynamic computable general equilibrium, myopic agents, some trend projections	Simulation of energy markets, no foresight apart from trend projections	Inter-temporal optimization, perfect foresight
Model objective	Static maximization of producer profit and consumer welfare	Least-cost approach to meet energy service demand	Dynamic max. of global welfare, Pareto-optimum among regions
Population	UN 2006/2008, medium project	UN 2010, medium projections	UN 2010, medium projections
Global GDP growth	3.5% (2005–2050)	3.5% (2010–2035)	3.9% (2010–2035), 3.5% (2005–2050)
Final energy demand	Based on existing energy infrastructure, demand met by the least cost approach, AEE tuned to meet WEO	Based on existing energy infrastructure, demand met by the least-cost approach	Short-/mid-term: tuned to meet Current Policies Scenario of WEO 2010, long-term: regional trend proj. for end-use sectors
GHG emissions	Full basket of Kyoto gases	CO_2 only, can be linked to ENV-linkages for non-CO_2	Full basket of Kyoto gases
Production	Perfect markets with CRS-technology (nested CES)	Energy market equilibrium	Perfect markets with CRS-technology (nested CES)
Capital accumulation	Solow–Swan neoclassical growth model	–	Solow–Swan neoclassical growth model
Investment dynam.	Old (lower substitution between factors) and new capital vintages, implies longer adjustment of quantities to price changes, increasing weight to services	Capacity additions based on changes in peak demand to previous year, retirement, and governmental policies; increasing weight to services	Vintages for energy supply technologies, adjustment costs for acceleration of capacity expansion
Share of technologies	Determined by relative prices, depending on substitution elasticities	Determined by regional long-run marginal costs (Logit and Weibull functions)	Determined by relative prices, depending on substitution elasticities
Price development	Exogenous trends	Exogenous trends	Endogenous
International trade	Bilateral, Armington-trade	No information	To and from a global pool

2.2 Data basis for fossil fuel subsidies

Fossil fuel subsidies come in different types targeting consumers and/or producers. They occur, e.g. as direct financial transfers, tax credits or tax exemptions, trade restrictions, reduced prices for energy-related services, or as governmental interventions in the energy market. The consequence of fossil fuel subsidies is a gap between a reference price (hypothetically the price establishing in a free market) and the actual price paid by an end-user. In general, producer subsidies are more common in developed countries whereas consumer subsidies exist largely in developing countries and in countries of the Former Soviet Union (Ellis, 2010 and Koplow et al., 2010). This is also mirrored in the database on subsidies for fossil fuel consumption (International Energy Agency, 2013) and the OECD-inventory (OECD, 2012). Both estimate the amount of subsidies from the consumer-price wedge (price-gap method) basing the reference price on international prices (incl. quality adjustments, freight costs, insurance and distribution costs, as well as Value Added Taxes). The data base includes consumer subsidies for 37 countries from 2007 to 2011 for coal, oil, gas, and electricity. We used these data to derive consumer subsidy rates for each REMIND region, while producer subsidies have to be left out due to lack of data. Additionally, taxes on fossil fuels have been estimated (own estimates, other sources: EU-Council, 2003, GTZ, 2009 and FFI, 2011). Based on the calibration of final energy demand in the model base year in 2005, the total amount of subsidies is 350.2 billion USD (2005). Thereby, the region Middle East Asia (MEA) accounts for about 42% followed by Other Asia (OAS) and Latin America (LAM) with 17% and 14%, respectively. Relative to GDP (in purchasing power parity), the ranking differs: At the top is still MEA with 4.8% followed by Russia with 1.8% and OAS with 1.5% relative to their GDP. No subsidies are assumed for the European Union (EUR), Japan, and USA.[2] For further methodological details and base year numbers refer to Appendix A.1, Table A3 and Table A4.

Fossil fuel subsidies derived as described above yield values that are of comparable magnitude as used in the other two models: In 2010 global modelled subsidies amount to about 409 billion USD (World Energy Model/ENV-Linkages) and 440 billion USD (REMIND). Of this total amount 50% (World Energy Model/ENV-Linkages) and 56% (REMIND) are for oil. Note again that we only account for consumer subsidies. Therefore, the total amount of fossil subsidies is underestimated (see as well Koplow et al., 2010). It should also be pointed out that the REMIND model does not explicitly consider subsidies to encourage the deployment of renewable energies. However, some regions have targets for the share of renewables in electricity production (see also Table A6). Furthermore, the combination of an optimal growth model with perfect foresight and global learning curves for renewable technologies yields a positive externality in form of a price decrease for the future which in turn promotes their ramp-up before current market prices are competitive.

2.3 Scenario set-up

As mentioned above our scenario set-up spans two policy dimensions. Table 2 gives an overview, including also the comparable scenarios used in the studies by the other two models ENV-Linkages and the World Energy Model. In the climate policy dimension we gradually

[2] Subsidies for the consumption of fossil fuels in these countries are also not included in the IEA database. Existing subsidies in these countries mainly concern producer support.

increase the stringency in the level of climate targets from a reference scenario without climate policy (NoPol-Ref) over a moderate policy baseline (FragPol-Ref) to a 450 ppm stabilization goal (450Pol-Ref). Note that the moderate policy baseline includes current and planned regional climate policies, i.e. emission reduction targets (a moderate interpretation of Copenhagen pledges), technology targets, and carbon intensity projections beyond 2030. For an overview of the detailed targets for each region see Table A6.

Table 2: Overview of scenarios along the two dimensions of climate policy and a phase-out of fossil fuel subsidies.

Scenario	**Key assumptions in REMIND**
	Climate policy dimension
NoPol	Scenario without climate policies
FragPol	Includes current and planned climate policies (moderate interpretation). Trend continued by prescribing the development of carbon intensities after 2020
450Pol	The concentration of greenhouse gases is stabilized at 450 ppm
	Degree of phasing-out fossil fuel subsidies
Ref	Assuming the continuation of current fossil fuel subsidy levels
G20	Optimistic interpretation of G20-initiative to reduce subsidies
G20plus	Subsidies are removed for Iran, Nigeria, and members of APEC and G20
Zero2020	All fossil fuel subsidies are removed by 2020
Scenario	**Key assumptions in ENV-Linkages**
CS	Central Scenario. No emission constraints in OECD-countries. Removal of subsidies in many non-OECD countries (unilateral and multilateral).
CS-caps	Includes emission caps according to Copenhagen Declarations.
CS-caps-el	As CS-caps but electricity-subsidies are not phased-out.
Elast	Sensitivity scenarios with inelastic or higher/lower fossil fuel supply elasticities.
Scenario	**Key assumptions in the World Energy Model**
CPS	Current Policies Scenario: policies continue unchanged, includes subsidy phase-out for few net-exporters
NPS	New Policies Scenario: adds moderate climate policies. Phase-out of subsidies for net-importers by 2020
450	50% change for 2°-target. Subsidy phase-out also by net-exporting regions by 2035 except MEA

The second scenario dimension is that of the phase-out of fossil fuel subsidies. In the reference case (Ref) both taxes and subsidies are held constant at current levels. In that case, by 2020 subsidies make up 0.7% of global GDP in REMIND as well as in ENV-Linkages. This corresponds to about 730 billion USD in REMIND. There are three scenarios with increasing stringency of the phase-out of subsidies. In order to clearly isolate the effects of the subsidy phase-out fossil fuel taxes are held constant in all of those. The first two scenarios cover partial phase outs based on currently published plans. An optimistic interpretation of the G-20 initiative of reducing subsidies mentioned in the beginning is the scenario G20. We assume a gradual reduction by 2020 for China (all subsidies by 50%), India (heating oil by 100%), Latin America (subsidies for Argentina, all oil subsidies for Mexico), OAS (coal subsidies for Korea, oil and gas subsidies for

Indonesia), and Russia (all categories reduced by 100%). There are no changes in Africa (AFR), Middle East Asia (MEA), and the Rest of the World (ROW).

In the extended APEC-G20 scenario (G20plus), we assume that APEC as an important Asia–Pacific economic forum also joins the initiative and the G20 as well as the APEC countries completely phase-out their subsidies on the consumption of fossil fuels. Additionally, Iran and Nigeria are reducing their subsidies as indicated in national plans. Thus, some subsidies still remain with MEA (for oil, electricity, and gas), LAM (for oil, electricity, and gas), OAS (mainly for electricity and gas), ROW (gas), and AFR (electricity). In both of these partial phase-out scenarios the level of subsidies achieved in 2020 is held constant after that. An overview of these targets is also given in Table A5. Finally, a complete phase-out of all subsidies (all regions, all types) by 2020 is assumed in the scenario Zero2020, with zero subsidies after that.

3 Discussion of results

A phase-out of subsidies is expected to have two main effects: on domestic demand in the region undertaking the phase-out and on prices of fossil fuels in the world market due to the changes in demand. Though domestic consumers and producers will react with lower demand and adjust to lower market prices, respectively, when subsidies are being removed, a net benefit of such a removal is generated due to reduced government spending. At the global level, we illustrate total price-quantity effects of a subsidy phase-out in Fig. 1. The size of the effect depends on the volume of subsidies being reduced which is by far largest in the Zero2020 scenario and smallest in G20. In general, quantities demanded as well as world market prices are lower in phase-out scenarios compared to the reference case. In the Zero2020 scenario, global oil prices drop by about 5% and gas prices by about 10%, while in the G20 scenario, the change for oil prices is about −2% and gas prices almost do not change at all. Coal prices decline over time from 2% to 10% in the Zero2020 scenario, and are constantly lower by 2% in the G20 scenario.

Furthermore, the results are influenced by the interplay of regions with respect to their levels of subsidies, their phase-out goals and their role as an exporter or importer of fossil fuels. Some of the importers (EUR, JPN) have no subsidies at all whereas the highest fossil fuel subsidies are paid in the largest exporting regions of fossil resources (Russia, MEA). One effect of this is the short-lived rebound effect seen in Fig. 1 in the middle of the century, where quantities get slightly larger under phase-out than with subsidies. This is due to a demand increase in regions that depend on fossil imports but which do not subsidize fossil fuels themselves (e.g. EUR). These regions adjust their fossil fuel demand in response to the lower world market prices under phase-out scenarios. This rebound effect matters for emissions (carbon leakage) and the energy system (energy demand) and will be discussed below. Based on this general expectation framework we analyze our scenarios in the following sections, specifically focusing on the aspects of emissions, welfare and transitions in the energy system.

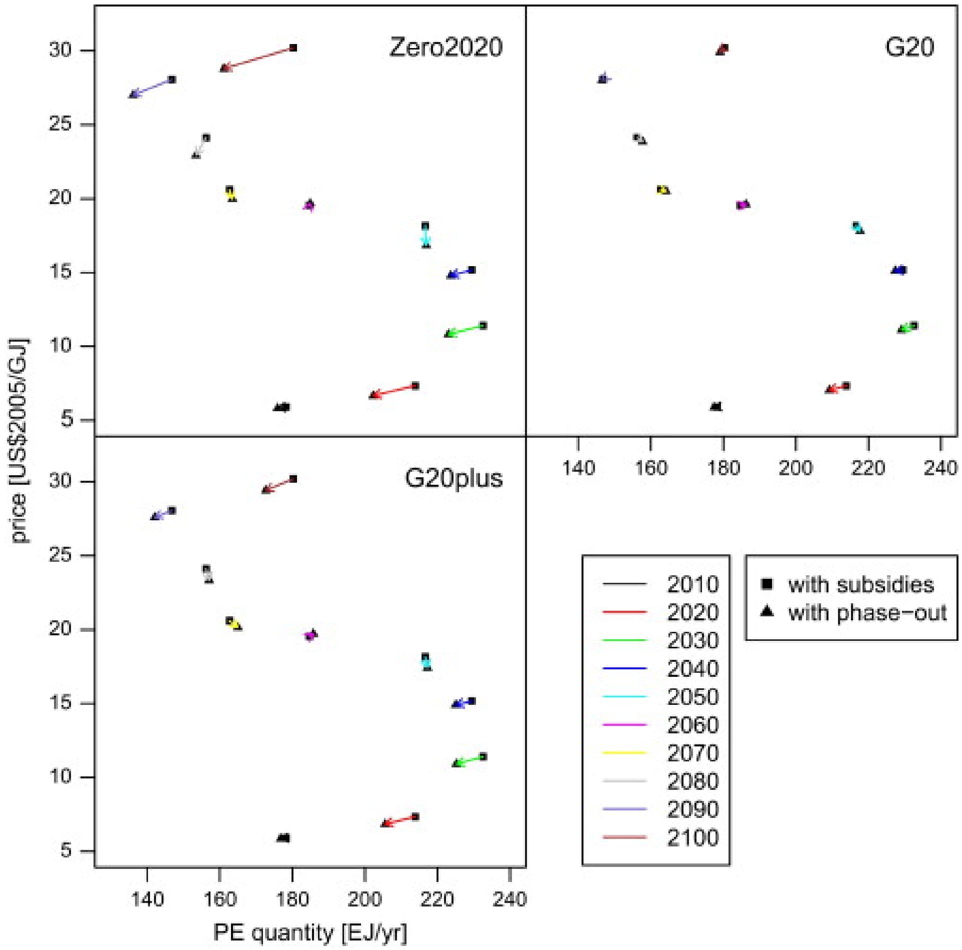

Figure 1: Global oil supply vs. demand over time (scenarios without climate policies). The black squares indicate the reference scenario (Ref), the black triangles the respective subsidy phase-out scenario. Two connected points are at the same point in time, the colour of the connecting line indicates the year. The arrow indicates the shift from a scenario with subsidies to one with a phase-out.

3.1 Impacts on the mitigation of climate change

The phase-out of subsidies on fossil fuels is often cited by NGOs as one measure to reduce greenhouse gas emissions and possibly an important step towards achieving emission targets set to curb climate change (Bast et al., 2012 and Koplow, 2012). Our results support that notion in the sense that all phase-out scenarios lead to reduced greenhouse gas emissions in comparison to the reference case. We consider here the total emissions of CO_2, CH4 and N2O. Over the whole time frame until 2100 the cumulative savings range from 50.6 Gt (0.6%) in the G20 scenario[3] to 220.8 Gt (2.7%) in scenario Zero2020. However, this is very small compared to reductions achieved in climate policy scenarios. The FragPol-Ref scenario yields cumulative savings of 1285.5 Gt (15.6%). A scenario achieving a GHG concentration of 450 ppm by 2100 (approximately reaching the 2-degree target set by the international community, refer to Meinshausen et al., 2009 and UNFCCC, 2009) essentially reduces annual emissions to zero by the end of the century.

[3] To increase readability, scenarios without climate policy are not specified with "NoPol", but only named after the subsidy phase-out scenario, i.e. G20 means NoPol-G20. Policy scenarios are named specifically if they are discussed.

Looking at global emissions over time and comparing to the reference case (Fig. 2), largest drops in emissions occur in the middle of the century in all phase-out scenarios without climate policies. The strongest and most immediate reduction is seen in the Zero2020 scenario, consistent with the quick, complete phase-out in all regions, while the G20 scenario has the smallest effect on emissions. However, it is important to note that these emission reductions are not sustainable. By the end of the century, all phase-out scenario emissions are returning to the same level as in the reference case, since the effects of the phase-out are less important than other effects that drive emissions like population, GDP growth, or resource depletion. On the other hand, the two scenarios with climate policies are quite different, reducing emissions also in the long run according to the set policy goals. The FragPol-G20 scenario stabilizes emissions around 2060, while in the 450Pol-G20 case they continue to drop to around zero. Clearly the phase-out of fossil fuel subsidies has a much weaker effect on the reduction of fossil fuel use (and therefore emissions) compared to a defined climate policy target, as also discussed in Section 3.3.

These results are supported by good agreement with the previous studies. Relative reductions seen in REMIND of 3.6% in 2020 for the Zero2020 scenario are close to the value of 4.7% found by the World Energy Model (refer to WEO, 2010 and WEO, 2011). By 2035 the relative reductions in REMIND are only slightly lower (5.3% vs. 5.8%). The ENV-Linkages model studies reductions in 2050 with a focus on regional differences (Burniaux and Chateau, 2011) instead of dedicated climate policies. We find relative reductions in 2050 which are somewhat lower in comparison, but similar in overall orders of magnitude (6.4% reduction of global emissions in the Zero2020 scenario vs. 8% in Burniaux and Chateau, 2011).

Burniaux and Chateau (2011) also discuss the carbon leakage effect connected to the increase of fossil fuel demand, imports and consequently emissions in regions without fossil subsidies due to lower world market prices (rebound effect discussed above). To investigate this, and for a direct comparison with Burniaux and Chateau (2011), we plot regional CO_2 emissions accumulated over the century in comparison to the reference case (Fig. 3). While the REMIND regional configuration is not quite the same as in ENV-Linkages, our regional distribution of emissions decreases and increases is very similar, though the relative effects are somewhat smaller. Note that Burniaux et al. only look at the year 2050, which we do not believe to be sufficient since effects can change over time as discussed above.

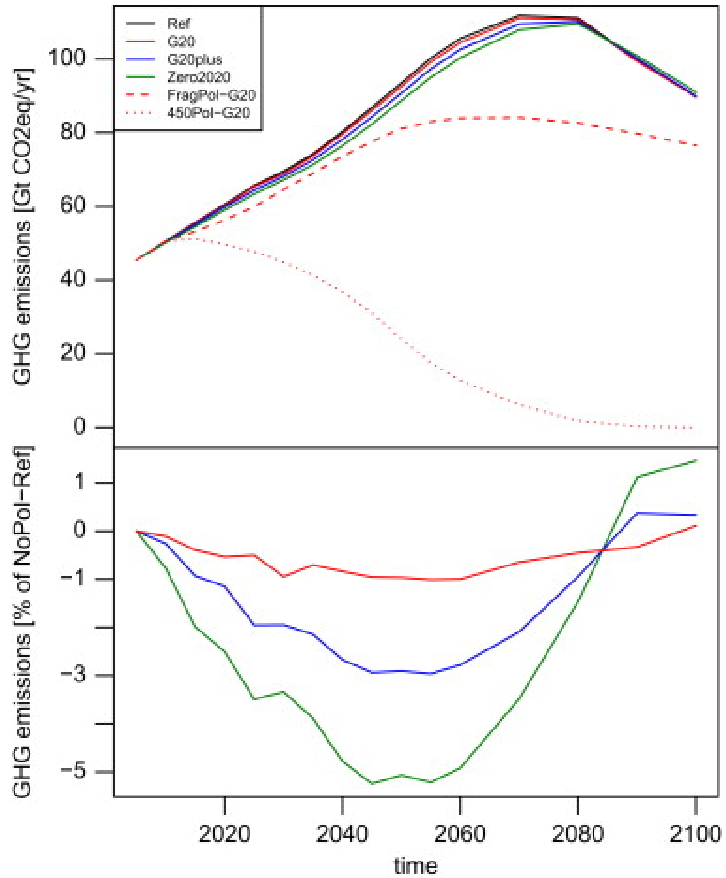

Figure 2: Greenhouse gas emission pathways for the different phase-out scenarios without climate policy as well as, for comparison, for two policy cases (upper panel). The lower panel zooms in on emission path-ways of the phase-out scenarios only, showing them relative to the reference case. GHG included are CO_2, N2O, and CH4.

Emission increases due to the carbon leakage effect are seen in the phase-out scenarios for Africa, Europe, USA, and Japan. It is strongest in the Zero2020 scenario for Europe, USA, and Japan. However, it should be emphasized that, despite the leakage effect, on the global level, net emission reductions are seen, with highest reductions in the Zero2020 scenario. Therefore leakage does not provide a convincing counter-argument to phasing-out of subsidies. The leakage effect is overcome by climate policy, though in the fragmented policy case this is only true for those regions with strong climate policies, while an even larger leakage increases emissions in Africa and Japan. The effects of fragmented climate policies are discussed in more detail in Aboumahboub et al. (accepted for publication) and Currás et al. (in press). In the 450Pol scenario, the policy goal dominates strongly and the small differences between phase-out scenarios carry no weight anymore.

The two main exporting and subsidy paying regions generally show mixed reaction to the phase-out scenarios, which can be explained with their individual phase-out goals. In the G20 scenario, MEA hardly shows changes in cumulative emissions, while it is affected strongly in the other scenarios. The reason is that MEA does not reduce subsidies in the G20 scenario and its domestic fossil fuel consumption stays at the same level. Russia on the other hand reduces all its subsidies to zero already in the G20 scenario. Moreover, fossil fuel imports are not expanding in Russia. We therefore observe similar emission reductions across all phase-out scenarios. It should be stressed that Russia is the region with the largest emission reductions (almost −15% while all other regions stay below 4%). This region's ambitious goals to remove fossil fuel subsidies (van Gelder et al., 2010) do clearly set it apart from the limited goals of the other G20 members. MEA, on the contrary, is the region with the highest level of subsidies but modest reduction plans. It only shows a large effect on emissions in the Zero2020 scenario.

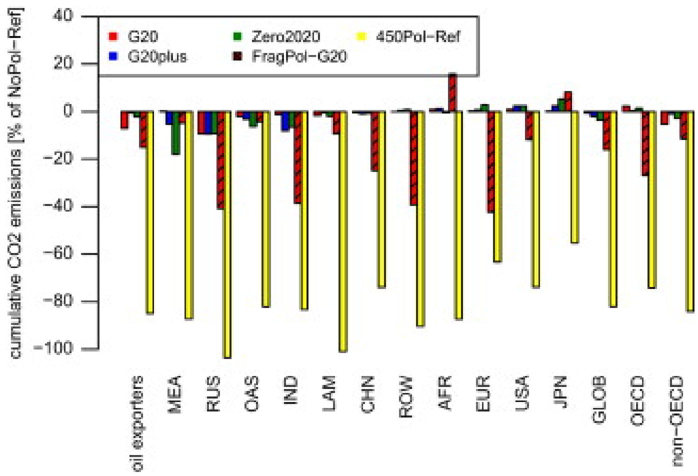

Figure 3: Changes in cumulative regional CO_2 emissions from 2005 to 2100 for different phase-out scenarios without climate policies and, for comparison two cases with climate policies, relative to the reference case. Oil exporters include ROW, Russia, MEA, and USA. OECD includes the regions ROW, Europe, Japan, and USA. Without climate policy, the carbon leakage effect is clear, though emissions are reduced on the global level.

From this discussion, taking into account the long-term perspective of REMIND, it becomes clear that, contrary to previous assumptions, e.g. in WEO (2010), long-term mitigation targets only benefit to a very limited degree from emission reductions achieved via fossil subsidies removal. In the short term (until 2020), the strongest phase-out scenario (Zero2020) achieves a reduction of greenhouse gas emissions of 1.6 Gt CO_2 or 3.6%. In comparison to the pathways in the FragPol or even 450 ppm climate policy scenarios, this amounts to about 27% and 13% of the necessary reductions, respectively. A combination with climate policies, as for example shown for the FragPol-G20 scenario, is essential, also to overcome the leakage effect.

3.2 Implications for the distribution of welfare

As subsidies for fossil fuels are market distortions, welfare gains in the phase-out scenarios are expected in comparison to the reference scenario. Note that, as the focus is on subsidies, a constant level of equally distorting taxes is used in the scenarios. This prevents welfare gains to be achieved to the largest extent theoretically possible. Being a main driver of the welfare optimization in REMIND, we use the total net present value of consumption over the whole simulation period (2005–2150) as an welfare indicator. The inclusion of current accounts is not necessary, as these are required to balance out over this time. The discount rate is 5%. Again we emphasize that, as the sign of the effect can change from year to year, the evaluation via a cumulative approach is preferred over focusing on one year alone.

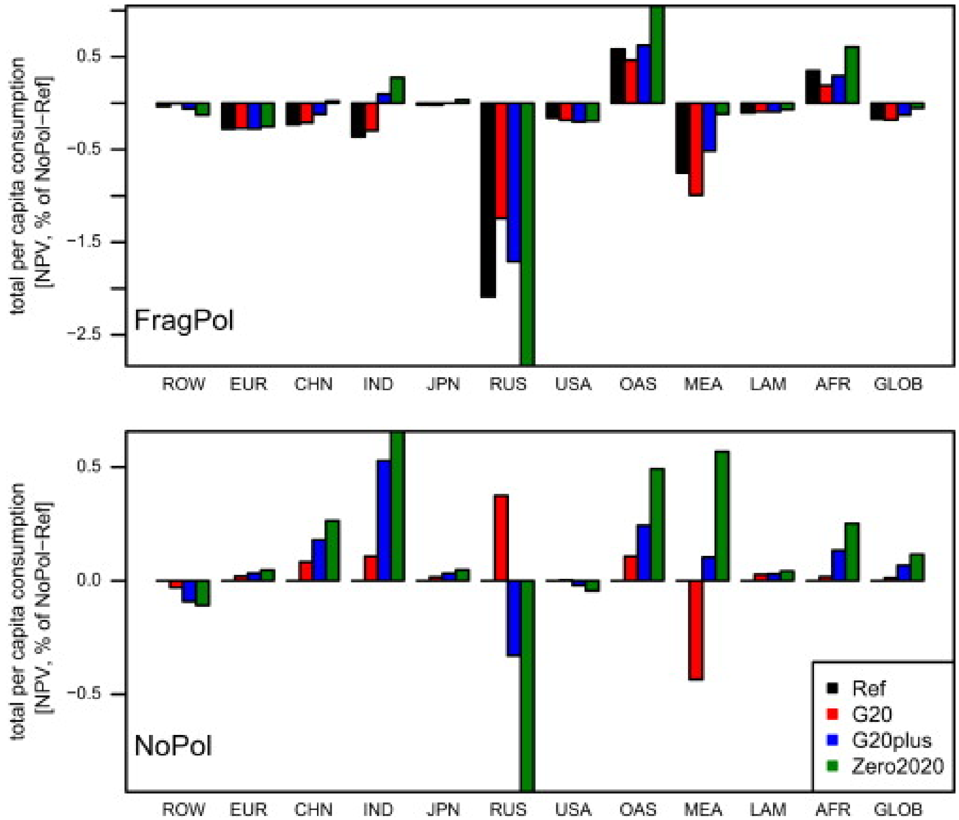

Figure 4: Net present value of consumption, summed up from 2005 to 2150 using a discount rate of 5%, across the two dimensions subsidy phase-out (different bar colours for each region) and climate policy scenario (different panels). Effects of the individual scenarios are shown relative to the NoPol-reference case. The 450Pol case is not shown, as there are no notable differences between the phase-out scenarios and there is a general turn to consumption losses.

We first discuss the case without climate policies. On the global level, total consumption increases in all phase-out scenarios, strongest in the Zero2020 scenario and only marginally in the G20 scenario (Fig. 4). Regionally, “winners” and “losers” can be identified, related to their levels of subsidies, their phase-out goals and their role as an exporter or importer of fossil fuels as discussed above. The largest gains are realized in India, OAS, Africa, and China, i.e. in developing regions with medium levels of subsidies and large dependencies on fossil imports. They profit from price drops of fossils on the world market due to the subsidy phase-out as discussed above. The winning regions found with REMIND are in agreement with the results of Burniaux and Chateau (2011), though the magnitudes cannot be compared as the measures are different.[4] The regions without subsidies (Europe, Japan, and the USA) show very little impacts, the USA together with ROW are the only regions with small consumption losses. They are both fossil exporters, though on a much smaller scale than MEA and Russia. The results for these two big exporters depend on the scenario and are exactly opposite. In the G20 scenario, Russia gains significantly, largest among all regions, while MEA loses equally strong. The contrary is true for the G20plus and in particular the Zero2020 scenario. This can be explained again by the different subsidy removal targets as well as by the different trade developments of the two regions. In the G20 scenario, MEA has no phase-out while Russia phases out all subsidies.

[4] Due to the lack of regional markets in REMIND, a calculation of the equivalent variations in income as done in Burniaux and Chateau (2011) is not possible.

Regarding the two exporters with their largest levels of subsidies this can almost be seen as a unilateral removal of subsidies by Russia. World market prices drop only a little, as the overall removal of subsidies is not too large and the global demand for fossil energy resources barely drops. Russia then benefits several-fold – domestically due to the money saved from subsidies as well as from domestic efficiency gains, and also through its income increases over time as an exporter. With the lower domestic demand more fuels are available for export at only slightly reduced world market prices. MEA on the other hand has no subsidy reductions and suffers somewhat from the lower global demand and prices.

Global demand drops more significantly in the G20plus scenario and substantially when all subsidies are phased-out in the Zero2020 case, where the prices also drop strongest. This leads to welfare losses for the large exporter Russia as the export revenues fall, thereby off-setting positive efficiency gains. MEA initially benefits through domestic effects caused by the removal of its large subsidies as well as from an increase in its gas export compared to the other scenarios. However, over the course of the century it reduces its exports of oil and gas almost completely, while Russia remains an exporter. These results of the benefit of essentially unilateral removals (in the G20 scenario for Russia) with shifts in the case of multilateral removals (G20plus, Zero2020) are consistent with Burniaux and Chateau (2011) and with theory as discussed above.

Differences between phase-out scenarios are strongly reduced in the cases with climate policy, in particular with a 450 ppm goal. This is due to the larger costs of the mitigation policies, which dominate the behaviour and lead to global consumption losses. In the FragPol scenarios, this is especially true for regions with more ambitious goals like Europe, while China, India, Russia, OAS, MEA, and Africa (having no or small emission reduction goals) still show some dependence on phase-out scenarios. Africa and OAS are the only clear winners in the FragPol case, while India gains under the more extensive phase-out scenarios, but loses in the reference and G20 cases. These regions do not have any or only weak targets in the moderate policy baseline and remain importers of fossil fuels, benefiting from the price drops due to the overall lowered demand in such a climate policy world. MEA does not have policy goals either but as a fossil exporter suffers from the price drops. However its losses are still smallest in the complete phase-out (Zero2020) scenario – the positive effect of the removal of its large subsidies still has an effect. Finally it is possible to decompose the consumption effects into various contributions as shown in detail in Lüken et al. (2011), Luderer et al. (2012b) and Aboumahboub et al. (accepted for publication). Some of these components stemming from the energy system are discussed in more detail in the following sections.

3.3 Triggering a sustainable transition of the energy system?

Phasing out subsidies for the consumption of fossil fuels can potentially support a sustainable transition of the domestic energy system via two basic causal chains. Both are connected with higher end-user prices induced by the reduction of subsidies. Firstly, this may lower total (domestic) consumption of final energy (efficiency increase). Secondly, higher end-user prices may also trigger a substitution of fossil fuels by cleaner alternatives (cleaner production). These domestic effects, however, can be offset by the rest of the world as energy markets are globally connected: price differentials between alternative fuels do not only change domestically but also at world markets (as already discussed in Section 3.1). Therefore, it is not a priori clear whether a removal of fossil fuel subsidies supports a sustainable transition. Notably, a large reduction in demand for a particular fuel can also lower international prices to an extent that the demand for energy carriers in regions abroad increases – the second manifestation of the rebound effect. It depends on a region's responsiveness to price changes. In addition, there is also a potential backlash connected with substituting fuels. The key factor for a net benefit w.r.t. a sustainable transition is to trigger a shift towards cleaner technologies and not, e.g. a substitution of oil by coal causing an expansion of carbon active pollutants (Krewitt, 2002 and GEA, 2012). In the following, we discuss the results obtained with REMIND regarding the two causal chains.

Table 3 shows net-savings in global energy demand for different fossil fuel phase-out scenarios combined with varying degrees of climate policies. A complete phase-out of fossil fuel subsidies (Zero2020) leads to a reduction by 20–26 EJ (4–6%) in the year 2020 assuming no climate policies or moderate, fragmented policies (NoPol-Zero2020, FragPol-Zero2020). In contrast, the implementation of G20-plans results only in a reduction by 5–15 EJ moving along the same policy dimensions. The amount saved in Zero2020 (20–26 EJ) is comparable to the results of the WEO model (25 EJ (4%) for a complete phase-out and 19 EJ for a modest phase-out in the New Policies Scenario, WEO, 2011). Note that global energy savings were slightly higher (by 5%) in WEO (2010) and Burniaux and Chateau (2011) as input data for fossil fuel subsidies differ. Table 3 also shows that energy savings are largest in the next decades for no or moderate climate policies. By 2100 savings amount to just 32–46 EJ in total (NoPol and FragPol combined with Zero2020). However, the largest benefit is not generated along the fossil fuel subsidies axis but along the climate policy axis: In the 450 ppm climate stabilization scenario a reduction by 241 EJ (24%) is achieved already without any removal of subsidies. A complete removal just adds 3%. As shown in Fig. A1, most important net-savings are realized in countries removing fossil fuel subsidies, i.e. in MEA, Russia, India, and LAM while USA, EUR, Japan, and ROW expand their demand due to decreasing world market prices for fossil fuels. But this rebound effect is small and it even reverses in the presence of stringent climate policy. This is consistent with the results on GHG emissions discussed earlier.

Table 3: Savings in final energy. Numbers are given as differences in EJ relative to NoPol-Ref. For NoPol-Ref absolute numbers are provided.

Subsidy & Climate Policies	Ref	G20	G20plus	Zero2020
NoPol	2020: **460**	2020: −5	2020: −11	2020: −20
	2050: **701**	2050: −2	2050: −14	2050: −28
	2100: **986**	2100: −3	2100: −18	2100: −32
FragPol	2020: −8	2020: −15	2020: −18	2020: −26
	2050: −9	2050: −12	2050: −22	2050: −35
	2100: −8	2100: −19	2100: −41	2100: −46
450Pol	2020: −48	2020: −52	2020: −56	2020: −63
	2050: −178	2050: −181	2050: −190	2050: −200
	2100: −241	2100: −245	2100: −253	2100: −267

We now turn to the discussion of substitution processes triggered in the energy system. We first analyze substitutions taking place among fossil fuel resources and second, we study how the share of low carbon technologies changes across scenarios. The first remarkable finding is that the amount of solid coal used in final energy increases substantially in mid-term when subsidies phase out, refer to Fig. 5. This is accompanied by an increase of the share of coal in primary fossil resources, e.g. from 29% in 2020 to 47% in 2100 in the no policy reference case. This renaissance of coal as a final energy carrier is not only fueled by a boost in its domestic consumption as world prices fall (in India, China, OAS, LAM, and AFR) but also by increases in the amount of coal traded. For example, almost all coal extracted in Russia and the USA is dedicated to export. It is worth mentioning that coal export becomes remunerative for the EU under fragmented climate policies towards the end of the century in G20plus and Zero2020. The revival of solid coal can only be prevented if a global, stringent climate policy regime is in place (compare with 450 ppm scenarios in Fig. 5). In a 450 ppm scenario, higher carbon prices offset the comparative price advantage for coal from phasing out fossil fuel subsidies. Note also that in the 450 ppm scenarios the shares of electricity, heat, and hydrogen in final energy are growing with time. This transition towards modern, grid-based technologies is accelerated by removing fossil-fuel subsidies, albeit the lion's share clearly originates from climate policies.

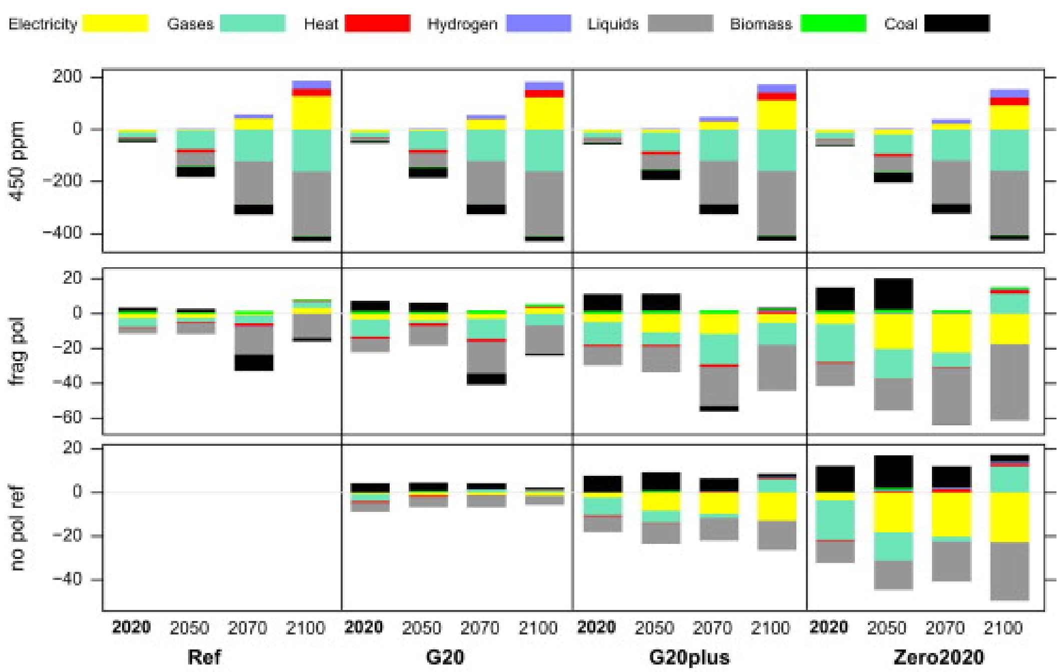

Figure 5: Differences in global final energy per types in comparison to the reference case (in EJ). Only a 450 ppm global climate policy regime can prevent a mid-term renaissance in the use of solid coal.

The renaissance of solid coal when phasing out fossil fuel subsidies in scenarios without or fragmented climate policies is striking. Is it due to a substitution within coal processing technologies? Is coal replacing oil and gas? Are low carbon technologies crowded out? We find evidence for all, however it needs to be kept in mind that overall phasing out fossil fuel subsidies still leads to net-savings in final energy. It should also be pointed out that the results are somewhat dependent on model assumptions: Assuming a high substitution elasticity between final energy types for heating, the use of solids has a comparative advantage.[5] Furthermore, if it is less favourable to use coal for other purposes than as a solid, this type of consumption will increase. This is the case in the subsidy phase-out scenarios, as subsidies for solid coal use are comparatively low. Therefore the phase-out of all subsidies increases the attractiveness of solid coal use. Note finally that in an intertemporally optimizing framework expectations about future price developments and resource availability also influence today's decisions.

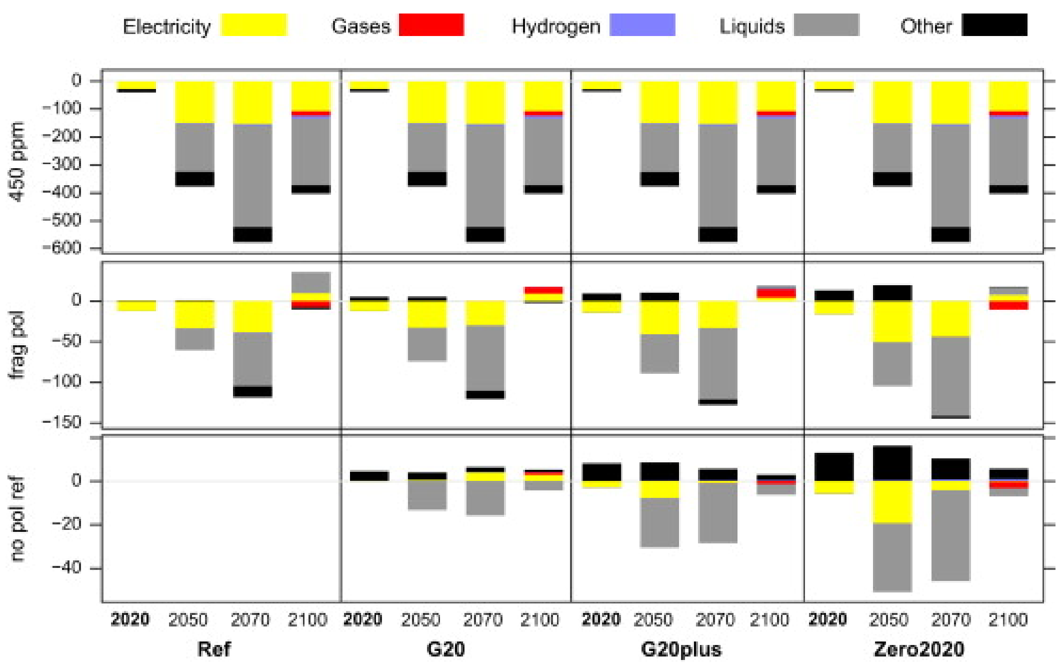

Figure 6: Differences in primary energy consumption of coal in comparison to reference scenario at the global level (in EJ). There is a net-increase in coal in short-term if climate policies are absent or fragmented. In later decades the increase in coal used as solids is compensated by using less coal in liquids and electricity.

Despite the renaissance of solid coal, in all scenarios less fossil resources are extracted over the century (Table 4). Yet again, while a phase-out of subsidies unlocks energy savings in final energy, the decisive contribution stems from climate policies which provide stronger incentives to leave fossil resources under ground. In the absence of climate policies, the extraction of fossil resources altogether is reduced by 1–4% compared to the reference scenario. In the case of fragmented climate policies, a reduction by 9–11% is possible (for FragPol-Ref: −7%). In 450 ppm scenarios subsidies have relatively little impact. Phasing out fossil fuel subsidies even causes an additional rise of resource extraction in the short-term for NoPol-Zero2020 and FragPol-Zero2020 (about 3% in 2020) and in the long-term for FragPol-G20 and FragPol-G20plus (up to 4% in 2100). Moreover, short-term expansions are connected with net-increases in the use of coal which is most pronounced in Zero2020. Only in later decades net-savings in coal are realized. As shown in Fig. 6, the increase in coal used as solids is only later compensated by decreasing amounts of coal used for electricity and liquids. This finding mirrors the set-up of

[5] Non-monetary factors like e.g. air pollution standards might limit the shift from gas to coal but are not represented in this analysis.

the subsidy scenarios (note that the end-use of solids is less subsidized compared to liquids and electricity corresponding to a comparative price-advantage).

Table 4: Changes in % for cumulative resource extraction of fossils in this century at the global level. Absolute numbers in EJ are given for the reference scenario.

Subsidy & climate policies	Ref	G20	G20plus	Zero2020
NoPol	Coal: **35 128**	Coal: −0.9	Coal: −2.4	Coal: −3.8
	Gas: **26 875**	Gas: −0.3	Gas: −1.8	Gas: −3.9
	Oil: **18 315**	Oil: −0.4	Oil: −1.4	Oil: −2.8
FragPol	Coal: −13	Coal: −14	Coal: −15	Coal: −16
	Gas: −4	Gas: −9	Gas: −11	Gas: −10
	Oil: −1	Oil: +0.1	Oil: −1	Oil: −4
450-Pol	Coal: −88	Coal: −88	Coal: −88	Coal: −88
	Gas: −60	Gas: −61	Gas: −61	Gas: −62
	Oil: −29	Oil: −30	Oil: −30	Oil: −30

However, the phase-out of fossil fuel subsidies affects the composition of primary energy carriers. Remarkably, the share of renewables in primary energy consumption is affected by a subsidy phase-out in an unfavourable way w.r.t. a low carbon transition (Table 5). While the share of renewables is growing with the stringency of climate policies, this is not always the case when subsidies are being removed. Towards the end of the century, the share of renewables can even stay 2.5% below the no-policy reference case (refer to FragPol-Zero2020). The removal of subsidies in 450 ppm scenarios also decreases the share of renewables: Instead of achieving 98% by 2100, only 89% are attained if all subsidies are reduced to zero. Again, it is the effect of relative price changes in the world markets. Removing subsidies not only affects relative prices between fossil resources but also prices of renewables. The comparative advantage of solids may then cause a decrease in the share of renewables. In consequence, the sustainable transition of the energy system is decelerated or even reversed. However, note again that we only consider subsidies on the consumption of fossil fuels. Producer subsidies are not taken into account (albeit they are smaller in sum). Domestic and world market prices would also change with the removal of this type of subsidies but in the opposite direction, leading to advantages for renewables. Also note that overall emissions do still decrease in the phase-out scenarios.

Table 5: Changes in the share of renewables in global primary energy consumption. Both the numbers in bold for NoPol-Ref as well as the differences for the other scenarios are given in %.

Subsidy & climate policies	Ref	G20	G20plus	Zero2020
NoPol	2020: **11.7**	2020: −0.1	2020: +0.3	2020: +0.6
	2050: **7.8**	2050: −0.0	2050: −0.0	2050: −0.0
	2100: **36.7**	2100: +0.4	2100: −1.6	2100: −2.6
FragPol	2020: +1.8	2020: +2.1	2020: +2.2	2020: +2.5
	2050: +2.5	2050: +2.5	2050: +2.4	2050: +2.4
	2100: −0.9	2100: +0.2	2100: −0.1	2100: −2.5
450-Pol	2020: +2.5	2020: +2.7	2020: +2.8	2020: +2.9
	2050: +36.2	2050: +36.2	2050: +35.5	2050: +35.0
	2100: +61.2	2100: +61.1	2100: +52.4	2100: +51.9

4 Conclusions and policy implications

This paper is the first to study effects of fossil fuel subsidy phase-out scenarios with an intertemporal optimization model covering the whole 21st century. This provides the opportunity to compare to results found previously with other models and to assess their robustness (WEO, 2010, WEO, 2011 and Burniaux and Chateau, 2011). In addition, it enables the exploration of different effects due to the different modelling approaches. We confirm the magnitude of greenhouse gas emission reductions and global net energy savings found in previous studies as positive global effects of phasing out fossil fuel subsidies. The carbon leakage effect plays little role, since emission increases in some regions are smaller than the reductions in others. We also find a global gain in consumption, albeit differences in the regions. Developing regions that import fossil fuels (India, China, OAS, Africa) are "winners", while results for exporting regions such as Russia and MEA are mixed. The balance of increasing exports due to falling world market prices for fossil resources, increasing domestic efficiency, and overall lower global demand matters. It plays out differently in across scenarios. For Russia, an almost unilateral phase-out (G20 scenario) seems more beneficial than multi-lateral action.

We find it to be of great importance not only to focus on the next few decades but also to take into account the long-term effects when designing policies to phase-out fossil fuels. We show that phase-out achievements (savings in net energy and the greenhouse gas emissions reductions) are short-lived and pathways shift back towards the reference case by the end of the century. Thus, the long-term gains are small. In 2100 the extraction of fossil resources is reduced by not more than 5% if subsidies are completely removed. The total amount of greenhouse gas emissions saved reaches only 15% of the reductions achieved in the current climate policy scenario (FragPol-Ref), which is still far from what would be needed to reach a 2-degree target. In fact, the greenhouse gas emissions in our phase-out scenarios in the year 2020 are around 59–60 Gt CO_2eq per year, which is above the range "preserving the option of meeting a 2 °C target", as recently found by Rogelj et al. (2013). It is therefore misleading to judge effects based on the short-term results only. Policy initiatives to phase-out fossil fuel subsidies are by far not sufficient to compensate for stringent climate policies on a global scale, or to even deliver a considerable step along the way. However, it should be noted that such initiatives can instigate political and societal dynamics leading to more stringent long-term goals, which we cannot capture in our model.

In line with that, our analysis further reveals that substitution processes resulting from a fossil fuel phase-out need to be carefully taken into account. Using an intertemporal optimization model we find that a complete phase-out of fossil fuel subsidies leads to a substitution within coal technologies towards solids. This renaissance of solid coal is caused by the comparatively low subsidies paid for it as fuel. In a subsidy phase-out scenario, this fuel therefore gains in relative competitiveness, even though oil and gas prices also drop. A competitive price advantage is also given compared to renewable and nuclear resources. Furthermore, more coal is available for direct use as a solid fuel, since the demand e.g. for coal-to-liquid conversion declines. Countries therefore increase coal extraction to realize trade benefits. As this effect is also prevailing in climate policy scenarios (i.e. a fossil fuel phase-out leads to a decrease in the price of carbon), low carbon resources face a disadvantage which would have to be compensated to make them competitive. A detailed study of ways to offset such unfavourable developments while reducing fossil fuel subsidies is left to future work.

To some degree these results are influenced by the consideration of consumer subsidies only. This is dictated by a lack of data on producer subsidies as mentioned in Section 2.3. On one hand producer subsidies are estimated to amount to about 100 billion USD (one-fifth of consumer subsidies in 2011). Yet, a recent report on progress with the implementation of G20 initiatives states that in particular producer subsidies for coal in Australia, USA, and Canada are on the rise (G20-Report, 2012). Taking them into account explicitly and modelling their phase-out would influence our result on the coal renaissance. However, the direction of this influence could be a decrease or an increase depending on whether subsidies are used to directly support the extraction of resources or not.

Like any model, certain characteristics of REMIND also lead to limitations of this study. In particular we should note again the limited regional resolution (REMIND is limited to 11 world regions) and the limited, i.e. only stylized, representation of end-use sectors. Furthermore, REMIND only implicitly accounts for energy infrastructure (e.g. power grid, transportation, pipelines). Also, REMIND does not distinguish between rural/urban population and there is no sub-regional differentiation of access to energy services (e.g. electricity). Hence, we can say little about the implications for households with low income. Furthermore, the assumed high substitution elasticity between final energy types for heating benefits the use of solids and the coal renaissance. Finally, strategic behaviour of resource exporters is not considered.

Politically, a complete phase-out of fossil fuel subsidies currently does not seem realistic. According to the recent G20-Report (2012) “G20 failed to advance the progress in this regard”. On the other hand, the G20 also has goals to improve energy efficiency and to increase the share of clean technologies. These goals seem to find a higher level of agreement among the G20 members. As our results show, these goals are complementary to a removal of fossil fuel subsidies, which by itself does not lead to high emission savings and a transformation towards a low-carbon energy system. Nevertheless, ultimately the achievement of ambitious climate targets requires some form of a global carbon price regime, for which the prospect is currently unclear.

Acknowledgements

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Appendix A. Model assumptions

A.1. Comparison of regional and macro-economic assumptions

Native model regions are defined as follows (note that countries are abbreviated using 3-digit country codes):

REMIND resolves 5 countries (CHN, IND, JPN, RUS, USA) and 6 macro-regions (AFR – Subsaharan Africa without ZAF, EUR – European Union, LAM – Latin America, MEA – Middle East Asian countries incl. North Africa and stan-countries of FSU, OAS – Other Asia, ROW – Rest of World). Refer to Luderer et al. (2013) for a detailed documentation of the model.

The World Energy Model resolves 12 countries (BRA, CAN, CHE, CHN, IND, IDN, JPN, KOR, MEX, RUS, ZAF, USA) and 13 macro-regions (OECD Europe with 3 regional models, OECD Asia Oceania with 2 country models and the region AUS–NZL, Easter Europe/Eurasia with 1 country and 3 regions, Non-OECD Asia with 3 country models and 2 regions, LAM with BRA and the rest of the region, Middle East as 1 region, Africa with 1 country and 2 regional models comprising the whole continent). Refer to International Energy Agency (2012) for further details.

ENV-Linkages resolves 7 countries (BRA, CAN, CHN, IND, JPN, RUS, USA) and 5 macro-regions (AUS–NZL; European Union and EFTA; Oil producing countries with IDN, VEN, Rest of Middle East, IRN, Rest of North Africa and NIG; Rest of Annex 1 countries with CRV and Rest of FSU; Rest of World). Refer to Burniaux and Chateau (2010) for further details.

Assumptions on economic growth are compared in Tables A1 and A2.

Table A 1: Comparison of annual compound GDP growth rates for selected regions. Sources: WEO (2012) and baseline of REMIND.

Model region	Historic	World Energy Model			REMIND			
	1990–2000 (%)	2010–2020 (%)	2020–2035 (%)	2010–2035 (%)	2010–2020 (%)	2020–2035 (%)	2010–2035 (%)	2035–2100 (%)
AFR*	2.5	4.6	3.4	3.8	3.9	3.3	3.6	5.5
CHN	9.9	7.9	4.3	5.3	8.7	5.2	6.6	0.8
EUR	2.1	1.7	1.8	1.8	1.5	1.3	1.4	1
IND	5.6	7.1	5.8	6.3	7.8	6.4	6.9	2.7
JPN	1.1	1.2	1.1	1.2	1.4	1.3	1.3	0.2
LAM	2.9	4.1	3	3.4	3.9	3.3	3.6	2.3
MEA**	3.8	3.9	3.7	3.8	4.2	3.7	3.9	2.4
RUS	–3.9	3.9	3.2	3.5	3.9	3.1	3.4	0.9
USA	3.4	2.6	2.2	2.4	2.5	1.7	2.1	1
World	2.9	4	3.2	3.5	4.3	3.6	3.9	2.2

Asterisks indicate that native model regions do not exactly match among the models.

Table A 2: Comparison of annual compound growth rates for selected model regions. Sources: Duval and de la Maisonneuve (2010) and baseline of REMIND.

Model region	OECD				REMIND			
	2005–2015 (%)	2015–2025 (%)	2025–2050 (%)	2005–2050 (%)	2005–2015 (%)	2015–2025 (%)	2025–2050 (%)	2005–2050 (%)
CHN	8.3	5	3.2	4.7	10	7.4	3.3	5.7
EU**	1.6	2.1	1.7	1.8	1.3	1.4	1.2	1.3
IND	7.4	6.7	5.5	6.2	8.2	7.3	5.3	6.4
JPN	0.5	1.5	1	1	0.7	1.5	0.7	0.9
MEA**	4.6	4.7	5.3	5	4.6	4	3.5	3.8
RUS	3.1	2.6	2.1	2.5	3.8	3.5	2.1	2.8
USA	1.9	2.4	2.2	2.2	1.6	2.3	1.3	1.6
World	3.4	3.6	3.4	3.5	3.8	4.1	3.1	3.5

Asterisks indicate that native model regions do not exactly match among the models.

A.2. Base year calibration of fossil fuel subsidies

We used the IEA database on subsidies for fossil fuel consumption (International Energy Agency, 2013) which contains data for 37 countries (2007–2011). Data are broken down to 4 categories: coal (incl. hard coal, lignite, peat), oil (incl. LPG, gasoline, diesel, kerosene), gas (natural gas), and electricity (excluding subsidies for nuclear and renewable energy). Recently, 2011 data became available. Oil subsidies increased strongly in India, China, Algeria, Venezuela, and countries in Asian Oceania. Other categories' changes are small.

To calibrate subsidies for the base year 2005, we took the average of 2008–2010. Using energy demand data for 2008–2010 (Source: ENERDATA), base year subsidies for coal, oil, gas, and electricity have been allocated to final energy types as represented in REMIND. These are solids, heating oil, gas, and electricity used in the stationary sector as well as petrol and diesel needed in the transport sector. Additionally, taxes on fossil fuels have been estimated (own estimates, other sources: EU-Council, 2003, GTZ, 2009 and FFI, 2011). How subsidies are allocated to REMIND regions is shown in Table A3. Table A4 shows absolute as well as relative amounts of subsidies as percentage of GDP in purchasing power parity (total and categories).

Table A 3: Allocation of subsidies for fossil fuel consumption to REMIND regions (37 countries) and G20 members in REMIND regions (boldface), APEC members. Subsidy information based on International Energy Agency (2013).

Region	**Data coverage and member economies of G20 and APEC**
AFR	Data: AGO, NGA
CHN	Data available, member of G20 and APEC
EUR	No data, G20 members: **DEU**, **FRA**, **ITA**, **ESP**, **GBR**
IND	Data available, member of G20
JPN	no data, member of G20 and APEC
LAM	Data: **ARG**, COL, SLV, ECU, **MEX**, PER, VEN
	Other G20 members: **BRA**, APEC members: MEX, CHL, PER
MEA	Data: ALG, AZE, EGY, IRN, IRQ, KAZ, KWT, LBY, QTR, **SAU**, TKM, ARE, UZB
OAS	Data: BGD, **IDN**, MYS, PAK, PHL,**KOR**, LKA, TWN, THA, VNM
	APEC: BRN, IDN, KOR, MYS, PHL, PNG, SGP, THA, TWN, VNM
ROW	Data: **ZAF**, UKR;
	Other G20 members: **AUS**, **CAN**, **TUR**; APEC: AUS, CAN, NZL
RUS	Data available, member of G20 and APEC
USA	No data available, member of G20 and APEC

Table A 4: Subsidies for fossil fuel consumptions per category in REMIND regional aggregation in absolute terms [billion USD2005] and relative as % of GDP (purchasing power parity) in the base year 2005. Data are based on International Energy Agency (2013).

	Absolute subsidies					As percentage of GDP				
Region	Total	Coal	Oil	Gas	Electr.	Total	Coal	Oil	Gas	Electr.
AFR	5.7	–	4.7	–	1	0.6	–	0.5	–	0.1
CHN	24.2	3.3	14.2	1.3	5.4	0.4	0.1	0.3	≈0	0.1
EUR	–	–	–	–	–	–	–	–	–	–
IND	25.4	–	18.9	2.2	4.2	1	–	0.7	0.1	0.2
JPN	–	–	–	–	–	–	–	–	–	–
LAM	48.3	–	35.8	5.9	6.6	1	–	0.7	0.1	0.1
MEA	147	0.5	97	19.8	29.7	4.8	≈0	3.2	0.7	1
OAS	58.1	2.8	31.8	8	15.5	1.5	0.1	0.8	0.2	0.4
ROW	11.6	–	0.1	6.5	4.9	0.3	–	≈0	0.2	0.1
RUS	29.8	–	–	13.6	16.2	1.8	–	–	0.8	1
USA	–	–	–	–	–	–	–	–	–	–
World	350.2	6.6	202.6	57.7	83.5					

Table A 5: Subsidy reduction targets for fossil fuel consumption per category in REMIND regional aggregation in USD2005/GJ for the year 2020. Targets are given for the three scenarios Ref→G20→G20plus, a change is indicated in bold. Only one value is given if it does not change in any of the scenarios. All subsidies are removed by 2020 in the Zero2020 scenario. For India there is a reduction of subsidies for heating oil to zero in the G20 scenario, the other oil subsidies remain constant. In all scenarios, the subsidies decrease linearly over time to the target levels in 2020.

	Coal	**Oil**	**Gas**	**Electricity**
Region	**Ref→G20→G20plus**	**Ref→G20→G20plus**	**Ref→G20→G20plus**	**Ref→G20→G20plus**
AFR	–	3.01→3.01→**0**	–	2.95→2.95 →**0.67**
CHN	0.11→**0.06**→**0**	1.36→**0.68**→**0**	1.14→**0.57**→**0**	0.75→**0.37**→**0**
EUR	–	–	–	–
IND	–	5.52→5.52→**0**	3.81→3.81→**0**	2.51→2.51→**0**
JPN	–	–	–	–
LAM	–	3.55→**2.29**→**1.99**	1.99→**0.71**→**0.7**	2.02
MEA	0.62	12.36→12.36→**4.51**	6.89→6.89→**3.5**	13.16→13.16→**9.4**
OAS	0.27→**0.2**→**0**	2.62→**1.15**→**0.27**	3.46→3.46→**2.57**	3.91→**2.86**→**2.01**
ROW	–	0.01→0.01→**0**	1.29	0.96→0.96→**0.31**
RUS	–	–	4.93→**0**→0	8.02→**0**→0
USA	–	–	–	–

A.3. Targets for the moderate policy baseline (FragPol)

See Table A6.

Table A 6: Emissions and technology targets for the individual regions in the moderate policy baseline. The target year is 2020 unless noted otherwise, the base year is 2005. The renewable energy share includes wind and solar targets. For RUS the increase in emissions compared to 2005 still means a 15% reduction compared to 1990. For the composite regions ROW, LAM and OAS, where some countries have emission targets and others do not, the target for 2020 is calculated with respect to the emission increase between 2005 and 2020 in the respective BAU run, i.e. it is slightly different for each subsidy removal scenario, hence we give here the range. Compared to the BAU emission increase, the increases in the moderate policy baseline are reduced by 7.7% for OAS and 16.6% for LAM.

Target	Across-the-board GHG emission reduction target incl. LULUCF	Modern renewable energy share in electricity production	GHG intensity target	Nuclear energy target
AFR	–	–	–	–
CHN	–	25%	−40%	41 GW
EUR	−15%	20%	–	–
IND	–	–	−20%	20 GW
JPN	−1%	–	–	–
LAM	+23.8 to +24.9%	–	–	–
MEA	–	–	–	–
OAS	+27.1 to +32.1%	–	–	–
ROW	−7.3%	13%	–	–
RUS	27%	4.50%	–	34 GW by 2030
USA	−5%	13%	–	–

A.4. Regional results for final energy

See Fig A1.

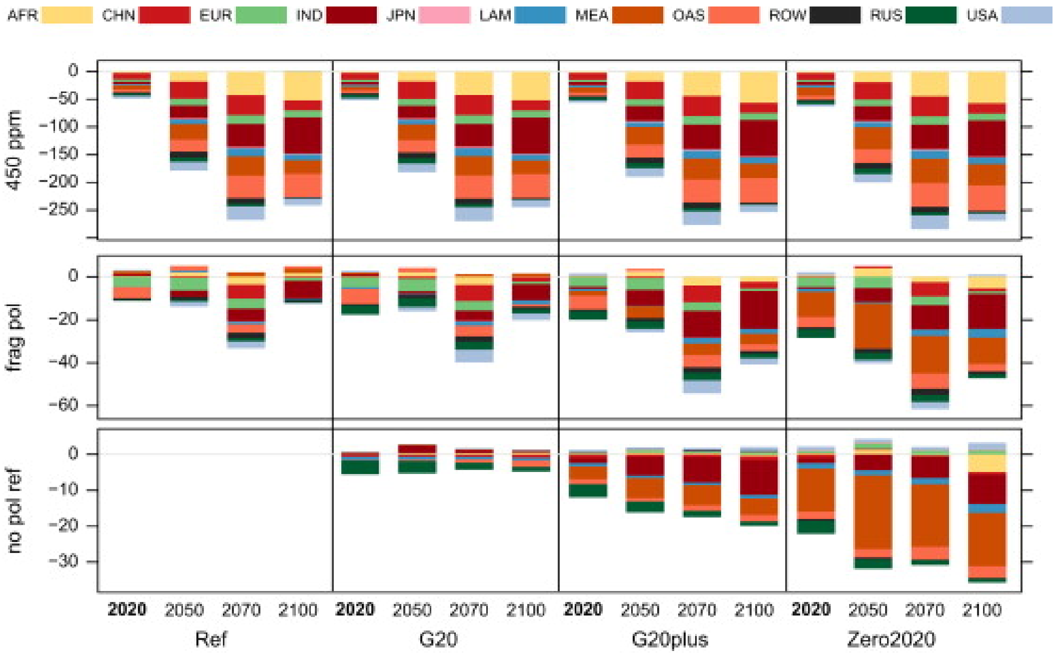

Figure A 1: Regional differences in final energy in comparison to the reference case (in EJ). Subsidies are increasingly removed from left to right. From bottom to top the stringency of climate policies increases. At the global level net-savings in final energy demand are realized along both dimensions. Regions removing fossil fuel subsidies and/or implementing climate policies reduce their demand strongest. Note the different scales.

Appendix B. Supplementary materials

A spreadsheet containing the detailed calculations of the subsidy levels, as well as the tax levels is stored as supplementary material to this article under:

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