Supplementary Information for *Limited emission reductions from fuel subsidy removal except in energy exporting regions*

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Methods

Defining fossil fuel subsidies

There are two main ways to define and calculate fossil fuel subsidies. The most widely-used approach is to define subsidies as all government interventions which make the cost of fossil fuels and electricity generated from fossil fuels lower than under normal market conditions. This is the definition we use in this manuscript and reflects the IEA and OECD approach to measuring fossil fuel subsidies either using a price-gap method[1-3] or through an inventory of budgetary expenditures[4]. The budget inventory approach is also used by two independent non-profit organizations Overseas Development Institute (ODI) and International Institute for Sustainable Development (IISD) for estimating fossil fuel production subsidies[5,6]. A less-common approach to measuring fossil fuel subsidies considers not only support mechanisms which decrease the price of a fuel below its competitive price but also include un-priced social, fiscal, and environmental externalities as subsidies, or all cases where a fuel is not taxed at the "Pigouvian" tax rate[7-9]. This approach, followed by the IMF and what they call the "post-tax subsidies", increases the fossil fuel subsidy estimate by up to 10 times[8].

We opted to use the narrower definition for four reasons. First, the goal of our study is to tease out the effect of subsidy removal as a policy measure distinct from climate, environmental, health and other policies. This goal cannot be achieved if we mix subsidy removal with imposing a carbon tax or pricing other externalities such as air pollution. Second, it is in-line with global fossil fuel subsidy inventories which were set up following the G20 commitment to phase-out subsidies[10,11]. In order to understand the implications of such a phase-out, it is important to use a definition of subsidies which is as close to the political meaning of this pledge as possible. The third reason is that we believe the political dynamics of fossil fuel subsidy phase-out are distinct from the political dynamics of pricing environmental externalities. A number of recent scholarly contributions have explored the political economy of fossil fuel subsidies[12] as a case of rent-seeking behavior[13] or crude poverty alleviation and development policy[14]. Neither of these explanations applies to the political dynamics of pricing energy externalities which likely follow different logics[15-17]. Finally, this is closest to the definition used in most previous assessments of the energy and emissions impact of removing fossil fuel subsidies[1,18,19] which makes it possible to relate our results to this previous work.

Energy price and subsidy data

We compiled historic price data for primary energy prices, end-use energy prices, and fossil fuel and electricity subsidies (see also ref. 20). The primary energy price data was from the British Petroleum[21]. For both the end-use prices and fossil fuel subsidy data, we aimed for as globally-comprehensive a dataset as possible. The end-use energy price data was compiled from three globally-comparative sources (Enerdata[22], IEA[23], GIZ's inventory of gasoline and diesel prices[24]) and a handful of national or regionally-focused sources[25-28]. Where multiple data sources were available, the most comprehensive data source was used (generally Enerdata); any gaps were filled in by other data sources (e.g. IEA price data for IEA Member countries[23], sector-specific reports[25,26] and national data sources[27-29]). Wherever possible, price data was calculated as the average from 2006 to 2010. In instances where multiple fuels are used in a given sector (such as gasoline and diesel in transport), the different product prices were aggregated to the sectoral level using energy data from the IEA[30]. In all cases, the prices were converted to USD_{2005}/GJ using the World Bank Inflation index[31] and the energy conversion factors listed in Supplementary Table 20. Regional price levels were aggregated from country-level data based on a weighted average.

For fossil fuel subsidies, we compiled a comprehensive data set of consumption and production subsidies based on the IEA's dataset on consumer subsidies[2,3,32], the OECD's inventory of fossil fuel support in OECD countries as well as six large countries (Brazil, Russia, India, Indonesia, China, and South Africa – Supplementary Text 5)[4] and GIZ's inventory of gasoline and diesel prices[24]. We constructed one dataset for 2013 (which represents subsidies under high oil prices) and one dataset for 2015 (which represents subsidies low oil prices). The IEA datasets were available for both 2013[2] and 2015[3,32]. Since the other two datasets[4,24] did not cover the period of recently low oil prices we used the fact that subsidies have historically tracked the oil price (Supplementary Figure 1) to extrapolate subsidy rates under low oil prices by scaling them down (Supplementary Figures 2 and 3, Supplementary Text 4).

For compiling the subsidy dataset, when multiple values were available for a given fuel/sector combination we prioritized the IEA[2,3,32] and OECD[4] over the GIZ dataset[24] since these two datasets focus on subsidies. When both the IEA and OECD provided an estimate for the same fuel-sector-country, we generally used the larger of the two values since we wanted to err on the side of over-estimating subsidies. We also performed a sensitivity analysis of our results with a higher estimate of production subsidies published by the ODI and IISD[5,6] (Supplementary Table 18). (The ODI and IISD estimates of production subsidies are several times bigger than the OECD estimates since they include several measures which OECD member and partner countries do not consider subsidies.)

Getting the prices right and modeling fossil fuel subsidies

There were two main model developments which were required to effectively model fossil fuel subsidy removal: (1) calibrating final (end-use) and primary (resources) energy prices and (2) incorporating a specific representation of energy subsidy and tax rates. In the first step, we needed to make sure that the energy prices in each model are consistent with those that have been observed in reality. Historically, integrated assessment models have had trouble reproducing observed prices. Instead, modelling teams have typically focused on calibrating the *relative* price differences between fuels and technologies. In this exercise, that approach would not work because if the prices in the model are lower than what has been observed in reality, the change in energy and emissions from removing an energy subsidy in the model would be inaccurate. In addition, global integrated assessment models usually calculate energy prices endogenously. In the present study we slightly deviate from this practice by requiring the models to target two distinct oil price paths after the year 2020, while retaining the endogenous price formation features of the models to the greatest extent possible. Each modelling team calibrated their model based on the model structure and features. This leads to two oil price paths: one in which oil stays below 60 USD_{2005} per barrel (the low oil scenario) and another in which it stays above 100 USD_{2005} per barrel (the high oil scenario). In calibrating different fuel prices to the two oil price levels, we assumed that crude oil and natural gas prices follow each other. (We also did a sensitivity and ran a case where we de-coupled the oil and gas prices – Supplementary Text 8 and Supplementary Figures 18-22).

In the second step in modeling subsidies, we added fossil fuel subsidies based on empirical subsidy data to the prices of energy carriers (oil, natural gas, coal and electricity). For the high oil price scenario, we ensured that all models in the base year show bulk level subsidies which are within 10% of those empirically observed under the high oil price (see Energy price and subsidy data). For this scenario, the subsidy rate remained the same in 2020 and throughout the rest of the modelling period. For the low oil price scenario, the subsidy rate starts at the same level and reaches the empirically observed (see Energy price and subsidy data) in 2020, the same year the oil price reaches below 60 USD_{2005} per barrel (Figure 1). For the phase-out scenarios, subsidy phase-out, starts in 2020 and is completed by 2030.

In GEM-E3 taxes and subsidies on products (incl. energy products) are part of the Input-Output table transactions and are included in the base year calibration of the model. The projection of energy prices to 2050 for the different scenarios was made by setting an exogenous crude oil and natural gas base price. The end-use prices are then endogenously calculated. In the current study the subsidy rates were imposed in the base year so as to calibrate end user prices to the prices derived from the historical price data. Different subsidy rates were used to differentiate between industry, transport and the residential sector.

In IMAGE, the sectoral energy price of each energy carrier at the end-use level (coal, oil, gas, bio-energy, electricity, hydrogen) is calculated endogenously based on the primary energy price, energy taxes, the costs of energy conversion throughout the energy supply chain and a price adjustment factor that calibrates the endogenously calculated prices to historical fuel prices. Primary energy prices are calculated endogenously, based on resource depletion, technology learning and a second price adjustment factor to correct for price influences other than production costs, such as periods of geopolitical instability. These primary energy prices are calibrated to historically observed primary energy prices. To model the high and low oil prices cases, we changed the price adjustment factors to reach the target settings of >100 USD_{2005} per barrel and <60 USD_{2005} per barrel. For natural gas, the relative price difference in the oil market was used to shift the regional gas prices accordingly. The subsidies were added explicitly at both the primary and end-use level.

In MESSAGE, 2020 prices are calculated endogenously and represent the technical cost of bringing a product to market: the extraction, refining, transport and distribution costs. In order to calibrate these endogenous prices to historical price data (and represent non-technical costs such as fossil fuel subsidies, taxes and profits to firms), we use price adjustment factors. The price adjustment factor builds in these previously unrepresented components so that the endogenous prices which the model produces matches real-world prices. At the primary level, crude oil and coal were calibrated to a single global price since they are both globally-traded commodities. For natural gas, three different regional market prices were used representing the regionally-fragmented natural gas markets though they were all scaled along with the high and low oil price cases since natural gas and crude oil typically follow each other. Then, to depict the high and low oil price cases, we shifted the crude oil and natural gas supply curves to reach the target price levels in 2020: 110 USD_{2005} per barrel for high-oil prices and to 45 USD_{2005} per barrel for a low-oil prices. At the end-use level, we added price adjustment factors at the regional level for individual fuels and sectors. For this calibration, we also applied price adjustment factors (but not subsidy rates) to "new fuels" which are still niche fuels and thus which we do not have historical data for (e.g. biofuels or compressed natural gas in transport) to avoid distortions. Electricity subsidies in $Russia^+$ and MENA as well as Brazil's oil-power production subsidies were allocated to electricity production based on the power generation of those regions. Where the subsidy rate for an oil product was higher under the low oil price scenario in MESSAGE, the subsidy rates for the high oil price was adjusted to the empirically observed value from 2020.

In REMIND, prices for fossil fuels are endongeously calculated based on the interaction of the long-term depletion of resources represented by different bins with increasing extraction costs and short-term constraints on increases and declines of extraction from these different regional quality bins. The latter constraints lead to higher prices in the short- to mid-term and thus ensure that price developments in the model broadly follow historic trends[33]. In the high and low oil price cases, adjusted versions of the "Low fossils" and "High fossils" specifications for gas and oil resources of the cited study[33] were used, so that the emerging prices comply with the target price levels in the present study. All taxes and subsidies are recycled through the overall representative household budget constraint in each region.

In WITCH, 2005 prices were calibrated to historical price data. At the final energy level, we used 'price adjustment factors' to match endogenous price data from the model to historical values. Through this calibration, and similar to MESSAGE, the endogenous prices from WITCH are brought to the real-world prices. At the primary level, crude oil and coal were calibrated to a single global price since they are both globally-traded commodities. To depict the high and low oil price cases, we shifted the crude oil and natural gas supply curves to reach the target price levels in 2020: 110 USD_{2005} per barrel for high-oil prices and to 40 USD_{2005} per barrel for low-oil prices. For natural gas, regional price mark-ups reflect the different prices across the three main regional gas markets. At the end-use level, we added price adjustment factors at the regional level for individual fuels and sectors. All price adjustment factors were kept constant under the subsidized scenarios. All taxes and subsidies are recycled through the overall representative household budget constraints in each region.

Modeling nationally determined contribution range

One of the key features of the recent Paris climate Agreement is that every country submits a national climate plan, or "nationally determined contribution" (NDC). These plans lay out what the country plans to do to stabilize or decrease GHG emissions[34]. Unlike earlier climate efforts, which took a top-down approach to determining how much countries need to decrease GHG emissions, in the Paris Agreement countries themselves determined their plans and national goals. Since these plans were formulated by national governments, with little to no coordination between countries, they vary in their scope and exactly how they define planned emission reductions. As a result, there is uncertainty into how much the NDCs add up to[34,35].

In this paper, we draw on a comprehensive set of scenarios which systematically evaluates NDC emission reductions on a comparable bases including defining uncertainties due to the ambiguity about how NDCs are formulated[36]. As explained in the Methods of that paper (p. 10), the NDCs are aggregated from the national level to the respective model region. The actual NDCs are formulated in terms of: emission targets (which that paper calls 'constraints'), energy mix (share) targets (e.g. 20% from renewable energy by 2030), or generation targets (e.g. 20 GW of nuclear by 2030). The targets are defined with respect to a historic levels (e.g. 2000) or a future year (e.g. 2030). The emission targets are expressed in terms of an absolute amount of emissions, a percentage of reduction against the base year, or a reduction in the emission intensity of GDP. The paper recalculated all these types of targets into modelling constraints as follows:

- National **emission targets** were translated into 2030 emission constraints depending on how these targets were formulated. For historically-defined targets, the model used historical emission inventories. For targets defined in terms of reductions against the Baseline, constraints were calculated using either national baseline emission projections or down-scaled projections from the regional no-policy reference scenario. The intensity targets were recalculated to absolute targets using GDP projections from shared socio-economic pathways (Supplementary Text 7) with various levels of GDP growth, hence defining uncertainty ranges. The national emission constraints were then up-scaled to regional emission constraints in 2030 used in the modelling.
- National **energy/electricity mix (share) targets** were aggregated from the national level to regional energy mix constraints using the current shares of national energy supply in the respective region as explained in detail in ref. 36 (page 10).
- National **generation targets** were recalculated to regional energy constraints using current capacity factors for the specific type of generation.

- Where no national target was defined, baseline emissions were used as a constraint.

For the main results in the paper, we use a set of scenarios with a middle of the road baseline (SSP2)[37] similar to our fossil fuel subsidy case and explore a range of scenarios which address five main types of uncertainties: historical emission variation, alternative energy accounting methods, attribution of non-commercial biomass, ranges within the NDCs themselves, and conditionality (see also Supplementary Table 15). For the Baseline sensitivity, we use the NDCs under SSP1 and SSP3 assumptions as well (Supplementary Text 7, Supplementary Figures 14-17). The modeled NDCs represent national plans as of September 3, 2016 and do not account for political uncertainty related to national plans changing such as the US' plan to pull out of the Paris climate agreement all together (the US NDC remains unchanged as of July 2017).

In order to make the effects of subsidy removal comparable to the effects of NDCs, we only included CO_2 emission reductions from fossil fuel and industry modeled in NDC scenarios. In regions which do not have binding emissions constraints (but rather technology and emission intensity targets), NDCs can actually lead to slightly higher regional emissions due to carbon leakage. This carbon leakage is triggered by lower global fossil fuel prices from constrained demand in regions with more conditional climate plans. Note that there is very little overlap between fossil fuel subsidy removal efforts and NDCs; only about a dozen countries include subsidy reform as part of their NDCs[38] and those that do are not the biggest subsidizers nor the biggest emitters.

Code availability

All models included in this study either have or are in the process of making all or part of their code publicly available. This section details the current state of code availability of each model and documents contact details to where any queries should be addressed for each model. Additionally, Model documentation is included in Supplementary Text 1 and also available on the ADVANCE wiki: http://themasites.pbl.nl/models/advance/index.php/ADVANCE_wiki.

The current code base of GEM-E3, developed at the Energy-Economy-Environment Modelling Laboratory (E3MLab), is not currently available in a publicly shareable version, however future model developments will be shareable in the form of both code and documentation, but not the datasets. The code will continue to be developed and hosted by E3MLab (http://www.e3mlab.ntua.gr/e3mlab/). Requests for code should be addressed to the E3MLab team (central@e3mlab.eu).

The current code of IMAGE is not available in a publicly shareable version, although efforts are being made to have the most important parts of future model versions shareable under an open source license. The code will continue to be developed and hosted by PBL. In addition to the documentation in this paper, a detailed documentation of IMAGE is available at: http://themasites.pbl.nl/models/image/index.php/Welcome_to_IMAGE_3.0_Documentation. Requests for code should be addressed to the IMAGE team (IMAGE-info@pbl.nl).

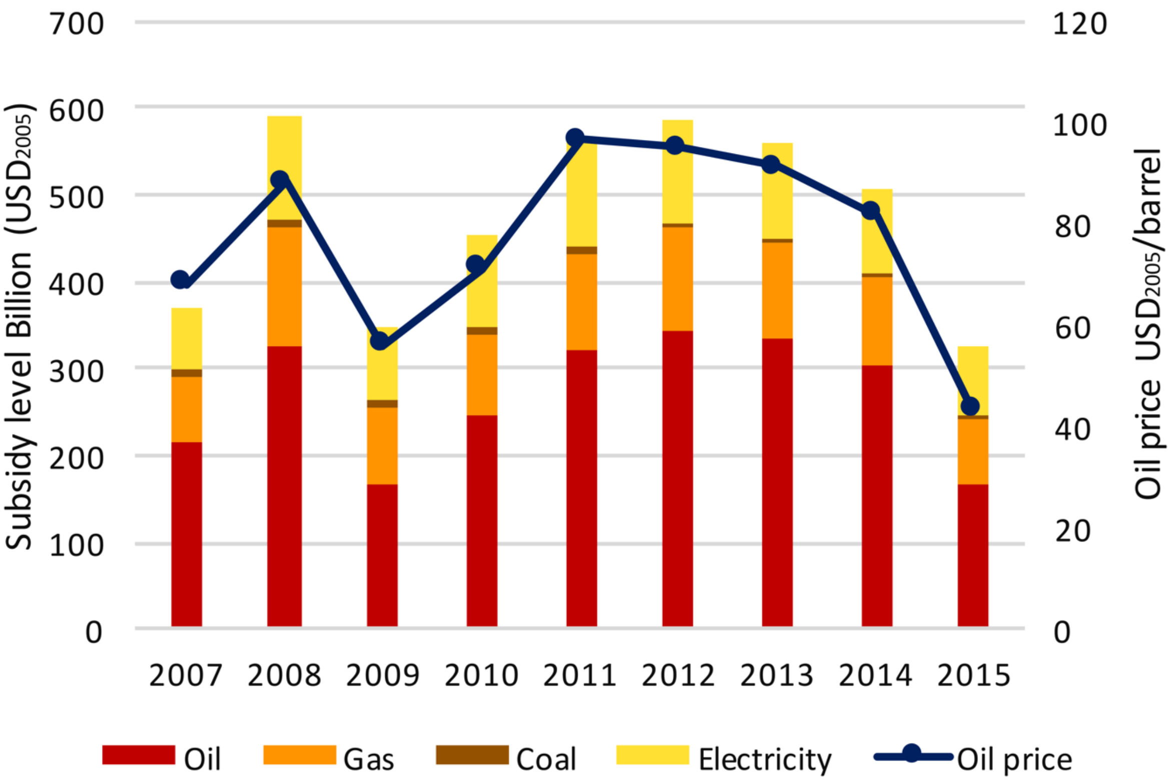
The current code base of MESSAGE is not available in a publicly shareable version. Future model versions which are currently under development will be shareable and under an open source license. The code will continue to be developed and hosted by IIASA's Energy Program: http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE.en.html). Requests for code should be addressed to the MESSAGE team (webapps.ene.admin@iiasa.ac.at).

The source code of REMIND can be downloaded from the institute's webpage (https://www.pik-potsdam.de/research/sustainable-solutions/models/remind) for the purpose of reading, thus enabling transparency and review. A license that would allow further uses is currently under discussion.

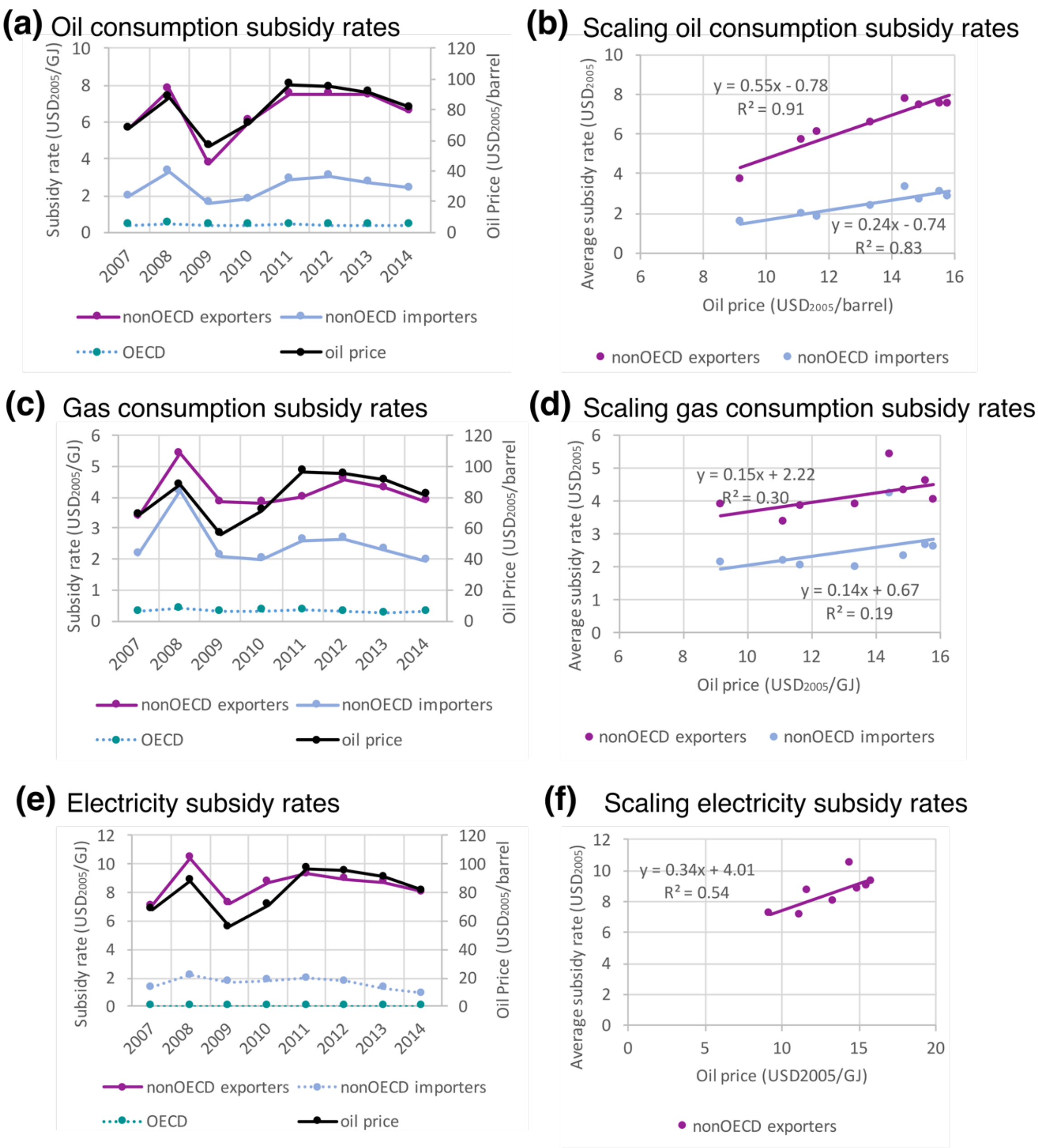
The current code base of WITCH, is currently not available in a publicly shareable version. A version of the WITCH source code is however available upon request. The public release of a future version of the model under an open source license is planned at: https://github.com/witch-team. Requests for code should be addressed to the WITCH team (witch@feem.it).

Supplementary Figures

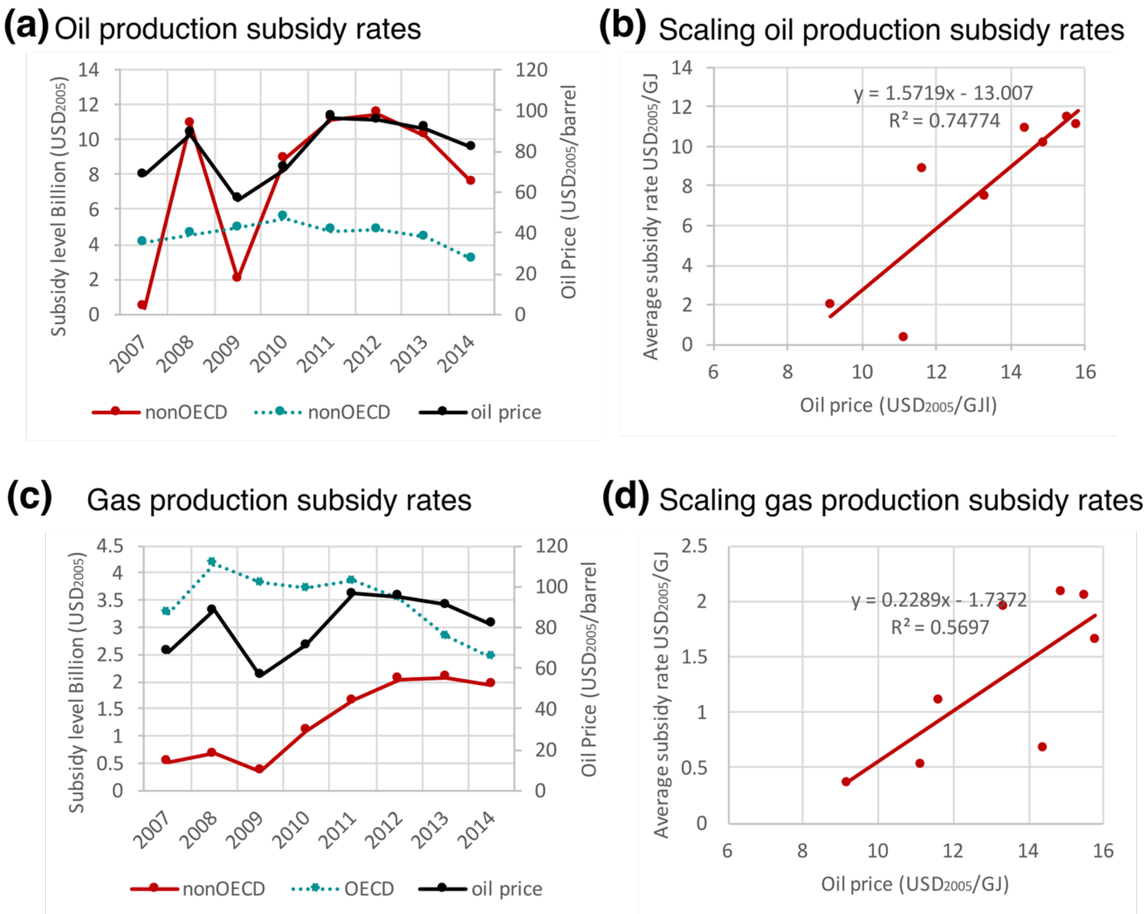
Supplementary Figure 1. Historic energy subsidies and the oil price. Historical subsidy data are compiled from refs. 2-4,39,40.



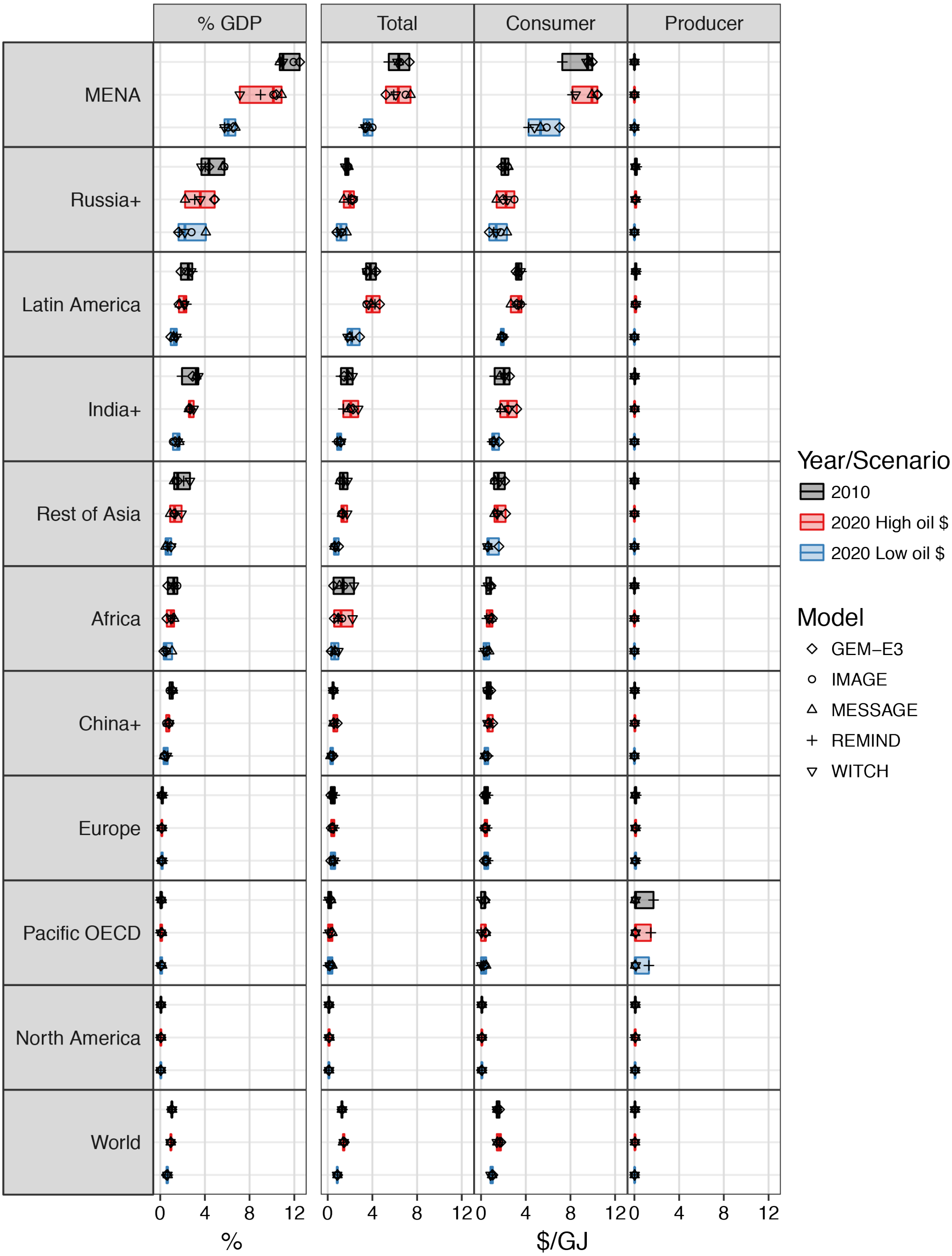
Supplementary Figure 2. Scaling fossil fuel subsidies for OECD[4] and GIZ[24]. Panels (a), (c) and (e) show the weighted average of oil, gas, and electricity consumption subsidies for different groups of countries and how they change with the oil price. Panels (b), (d) and (f) show how we regress these data against the oil price in order to scale them down for the low oil price scenario (see Supplementary Text 4 for explanation.) Subsidies with a solid line are scaled down in the low oil price scenario whereas those depicted with the dashed line are not. Data are compiled from refs. 2,3,24,39,40.



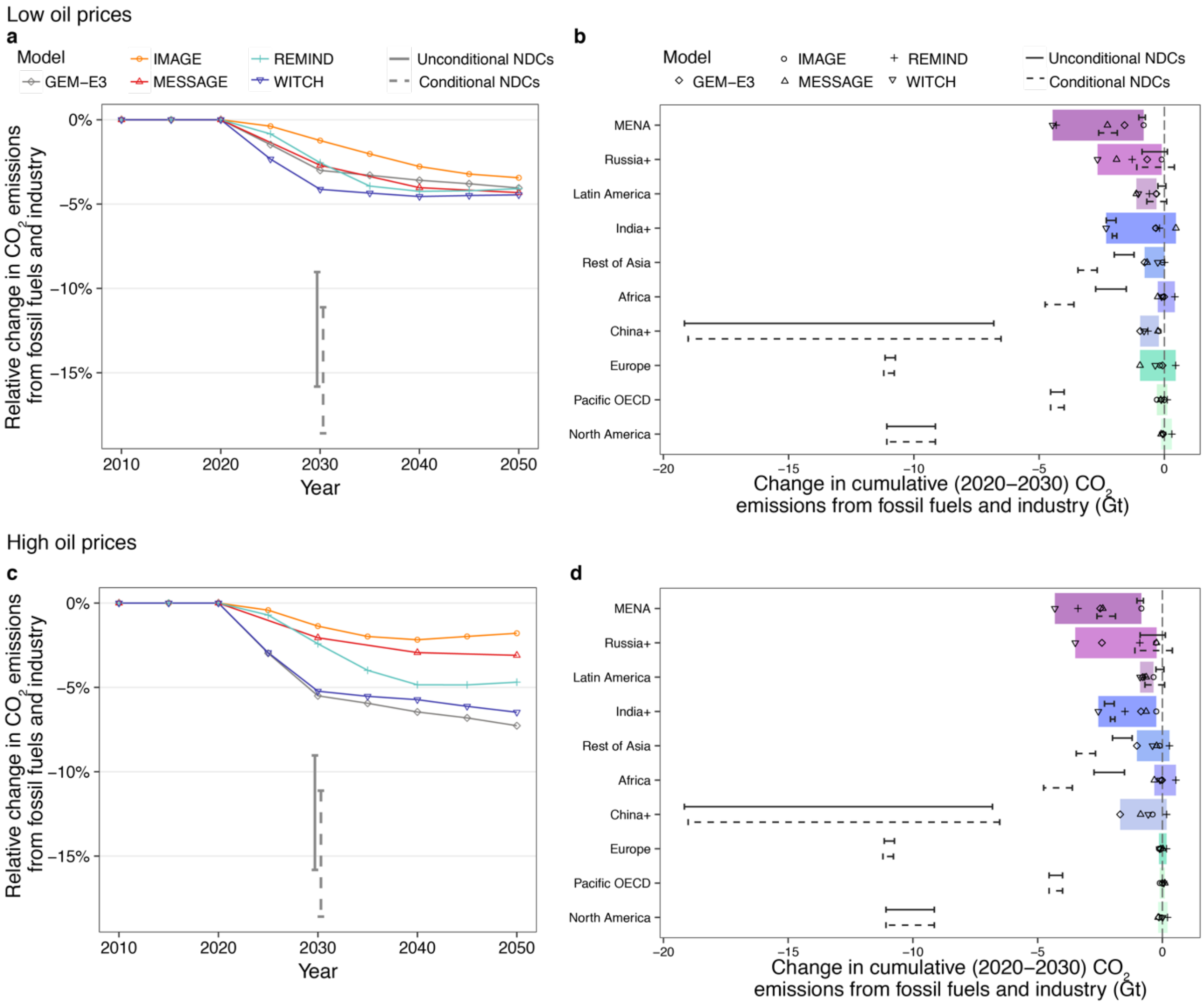
Supplementary Figure 3. Scaling oil and gas production subsidies for OECD[4]. Panels (a) and (c) show the weighted average of oil and gas production subsidies for different groups of countries and how they change with the oil price. Panels (b) and (d) how we regress these data against the oil price in order to scale them down for the low oil price scenario (see Supplementary Text 4 for explanation. Subsidies with a solid line are scaled down in the low oil price scenario whereas those depicted with the dashed line are not. Data are from ref. 4.



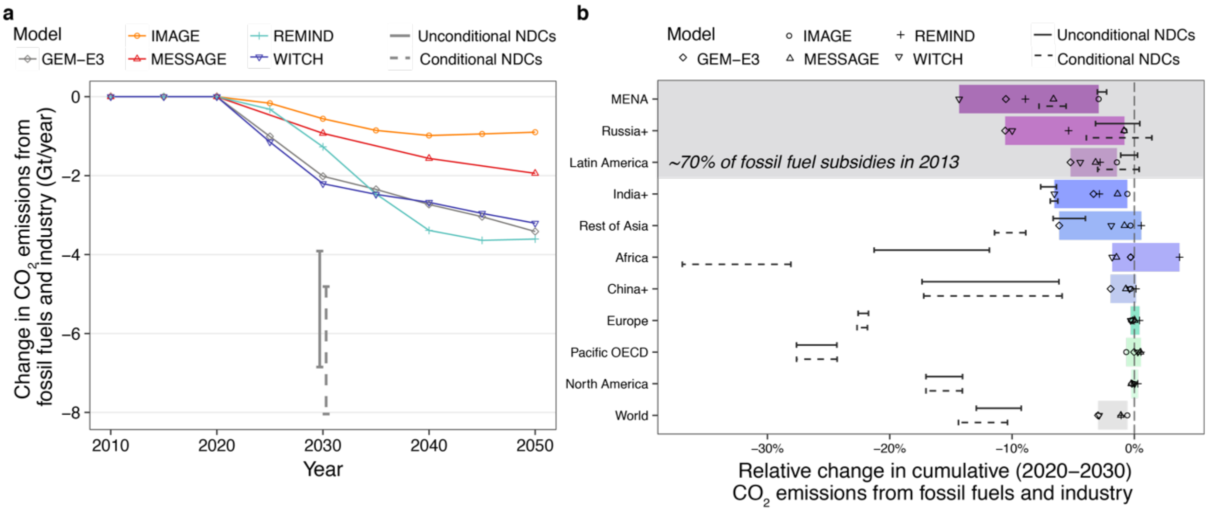
Supplementary Figure 4. Regional subsidy rates. The first column represents subsidies as a proportion of regional GDP. The second column represents the total subsidies divided by total primary energy supply of fossil fuels. The third column is the total consumer subsidies divided by total final energy supply. The fourth column is total producer subsidies divided by total fossil fuel extraction.



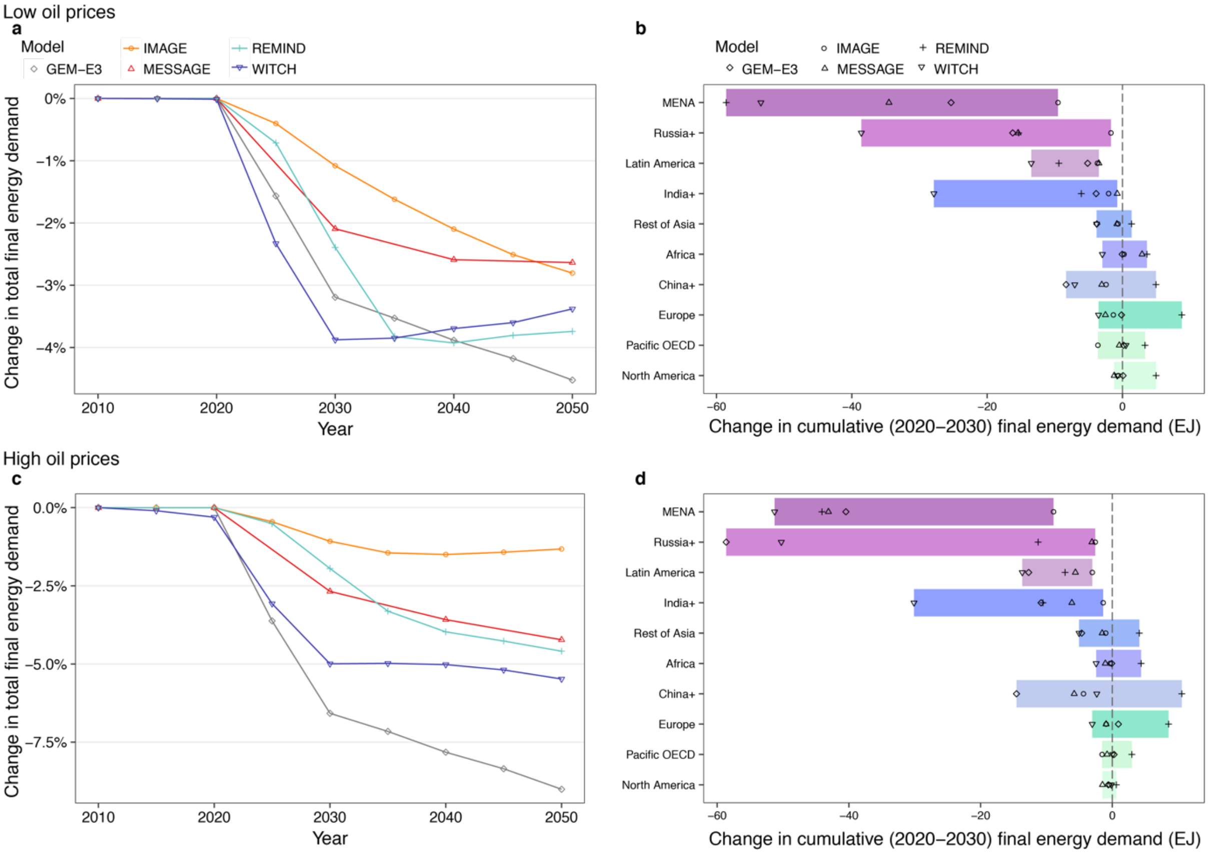
Supplementary Figure 5. Global and regional impact of subsidy removal and NDCs on CO_2 emissions. Panels (a) and (c) show the impact of subsidy removal on global annual CO_2 emissions from fossil fuels and industry compared to each model's Baseline in %. Panels (b) and (d) show the cumulative change in CO_2 emissions from fossil fuels and industry from 2020 to 2030 at the regional level from subsidy removal (colored bars – in Gt). In the top two panels, (a) and (b), the changes are shown under low oil prices; the bottom two panels, (c) and (d), show the changes under high oil prices. In all panels, we compare the emissions impact of fossil fuel subsidy removal to the emissions impact from the NDCs under the Paris climate agreement. Unconditional NDCs are represented with solid lines and conditional NDCs with dashed lines. The NDC results are modeled using MESSAGE[36]. The uncertainty range for the NDCs represents variations in their effect arising from different historical emissions inventories, alternative accounting methods, attribution of non-commercial biomass and ranges within the NDCs themselves (see Methods, Supplementary Table 15 and ref. 36). Note the regional definition (Supplementary Table 10 – Supplementary Table 14) can influence the absolute size of emission changes in panels (b) and (d).



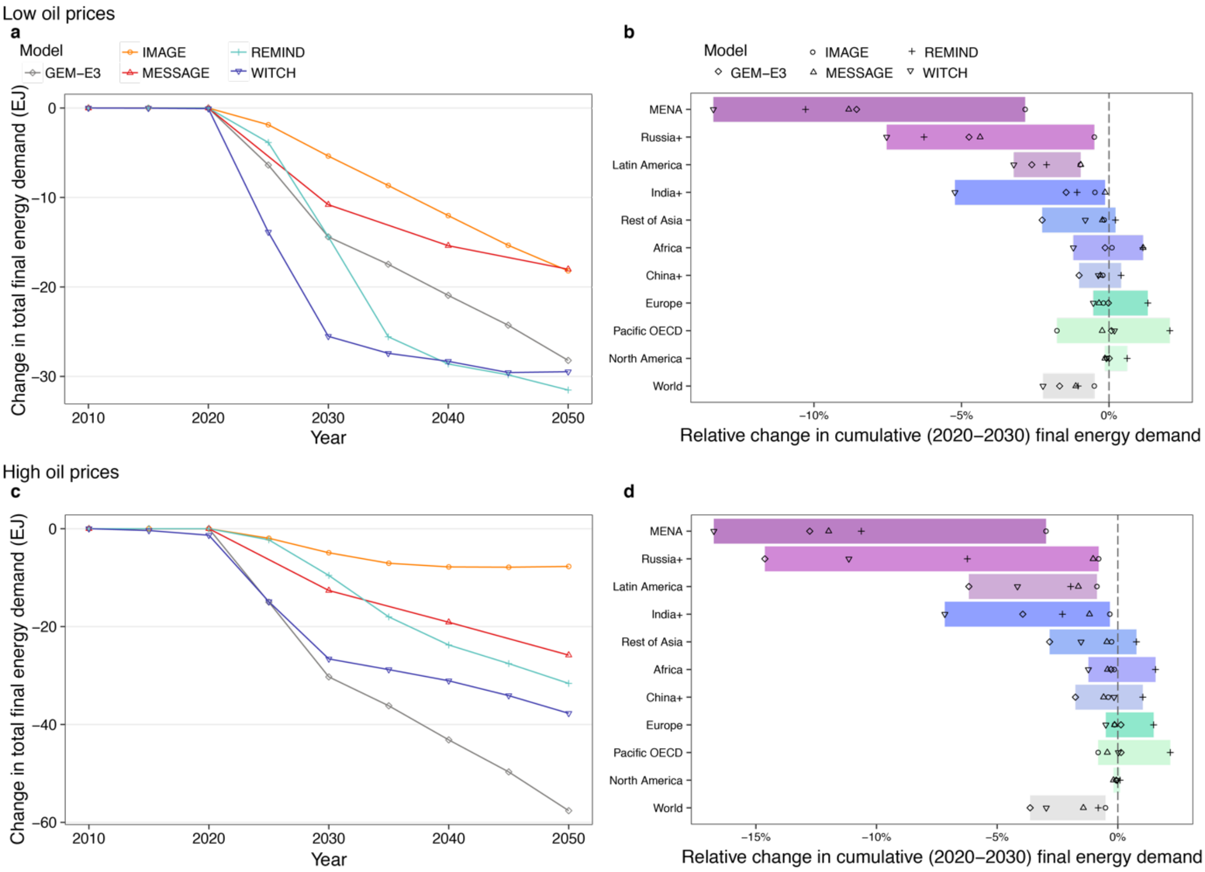
Supplementary Figure 6. Global and regional impact of subsidy removal and NDCs on CO_2 emissions under high oil prices. (a) The impact of subsidy removal on global annual CO_2 emissions from fossil fuels and industry compared to each model's Baseline in Gt/year. (b) Cumulative change in CO_2 emissions from fossil fuels and industry from 2020 to 2030 at the regional level from subsidy removal (colored bars – in %). In both panels, we compare the emissions impact of fossil fuel subsidy removal to the emissions impact from the NDCs under the Paris climate agreement. Unconditional NDCs are represented with solid lines and conditional NDCs with dashed lines. The NDC results are modeled using MESSAGE[36]. The uncertainty range for the NDCs represents variations in their effect arising from different historical emissions inventories, alternative accounting methods, attribution of non-commercial biomass and ranges within the NDCs themselves (see Methods, Supplementary Table 15 and ref. 36).



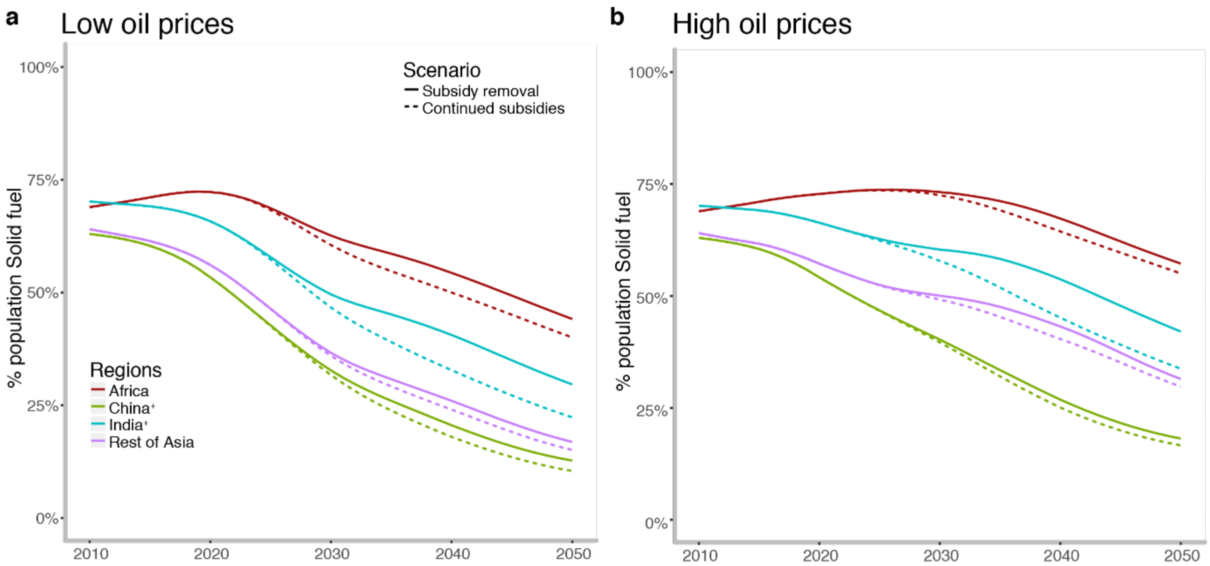
Supplementary Figure 7. Global and regional impact of subsidy removal on final energy demand. Panels (a) and (c) show the impact of subsidy removal final energy demand compared to each model's Baseline in %. Panels (b) and (d) show the cumulative change in final energy demand from 2020 to 2030 at the regional level from subsidy removal (colored bars – in EJ). In the top two panels, (a) and (b), the changes are shown under low oil prices; in the bottom two panels, (c) and (d), shows the changes under high oil prices. Note the regional definition (Supplementary Table 10 – Supplementary Table 14) can influence the size of energy demand changes.



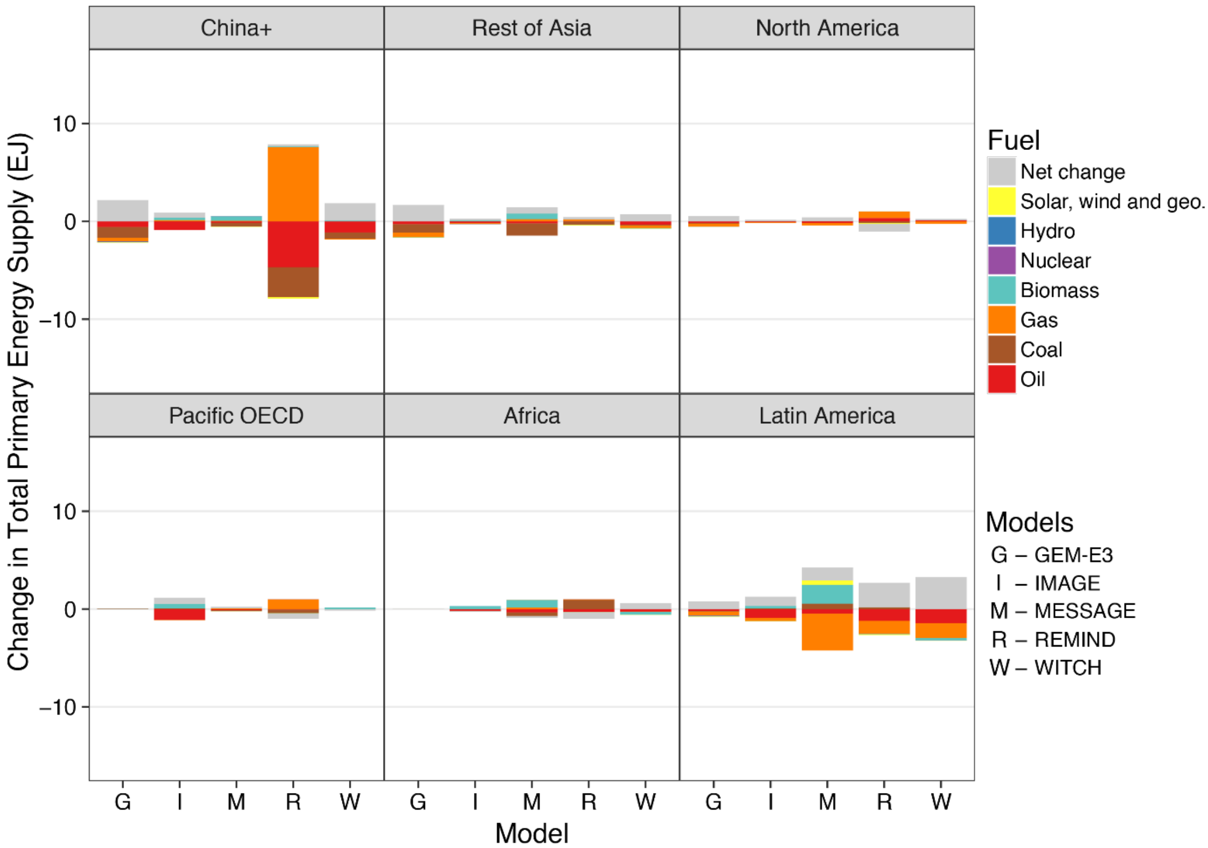
Supplementary Figure 8. Energy demand impacts of subsidy removal. Panels (a) and (c) show the impact of subsidy removal on global energy demand compared to each model's Baseline energy demand. Panels (b) and (d) Cumulative change in energy demand from 2020 to 2030 at the regional level. In the top two panels, (a) and (b), the changes are shown under low oil prices; in the bottom two panels, (c) and (d), the changes are shown under high oil prices.



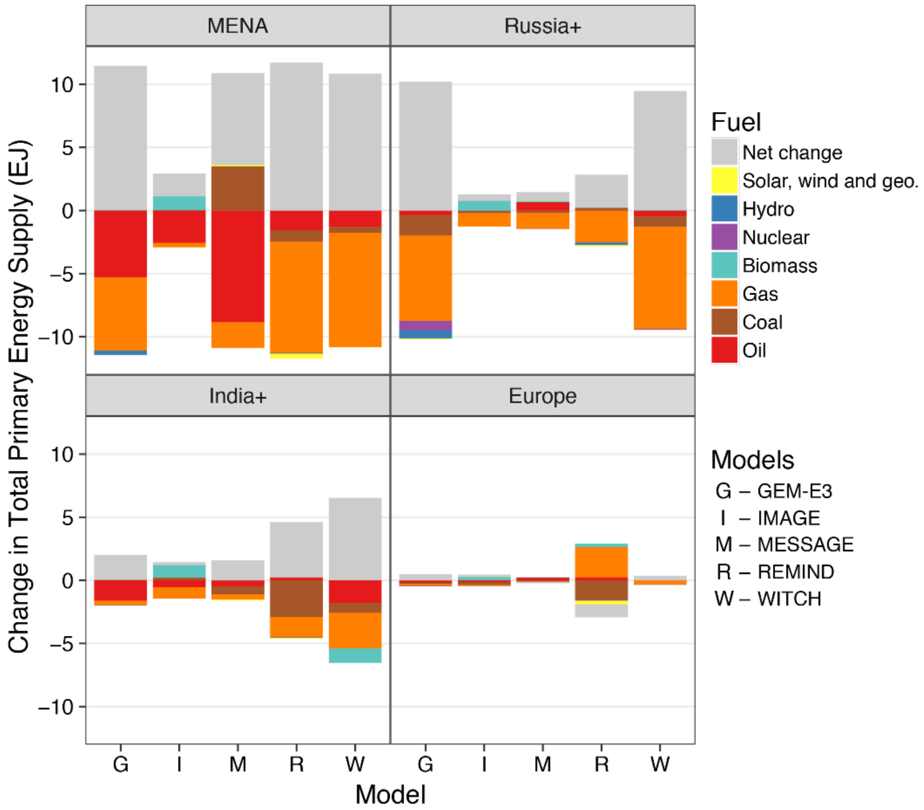
Supplementary Figure 9. The impact of fossil fuel subsidy removal on the use of solid fuels (coal and traditional biofuels) in developing regions. Under subsidy removal, a higher percentage of the population depends on solid fuels. Panel (a) shows the development under low oil prices while panel (b) shows the development under high oil prices. Analysis with IMAGE.



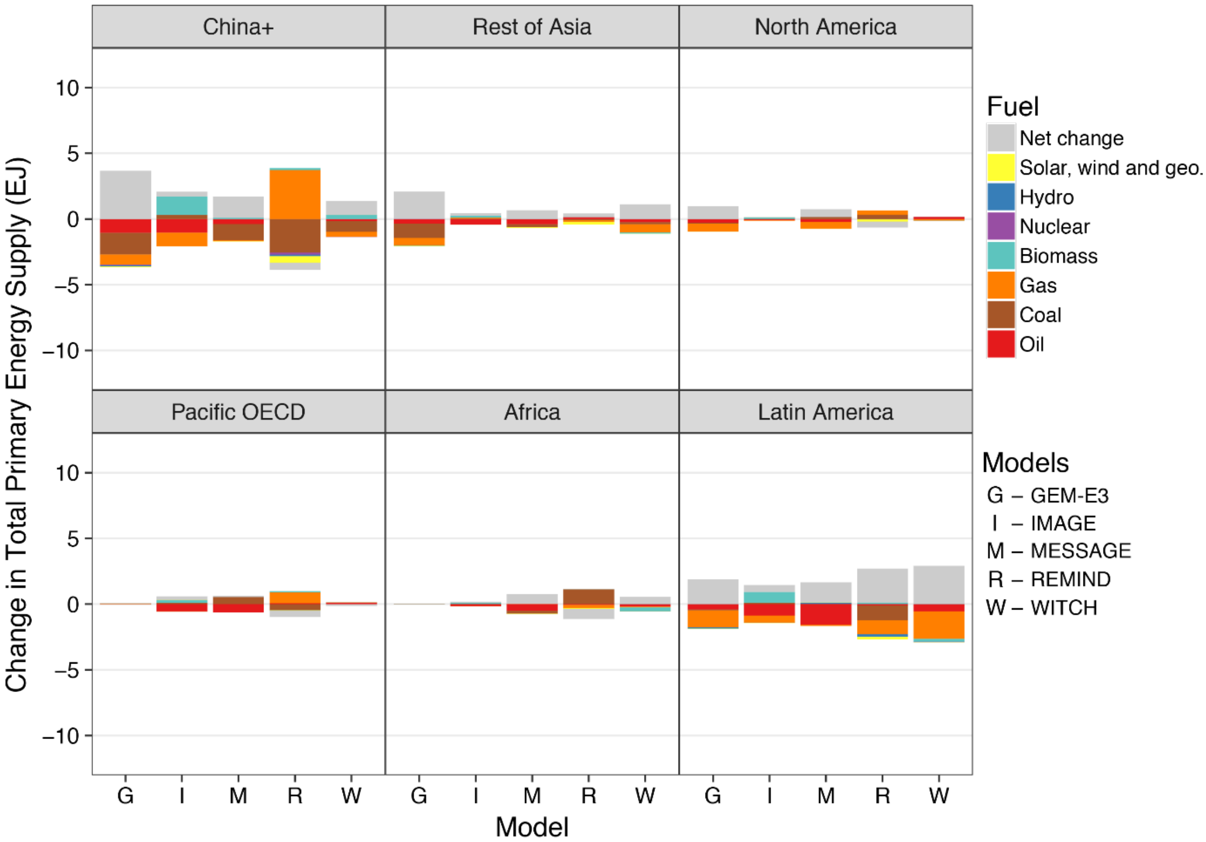
Supplementary Figure 10. Change in supply of different fuels from subsidy removal in 2030 under low oil prices. "Solar, wind and geo." indicates the aggregate change in solar, wind and geothermal power. Positive values of "Net change" indicate a decrease in the total primary energy supply, negative values an increase. Note that the region definition (Supplementary Table 10 – Supplementary Table 14) can influence the size of energy system changes.



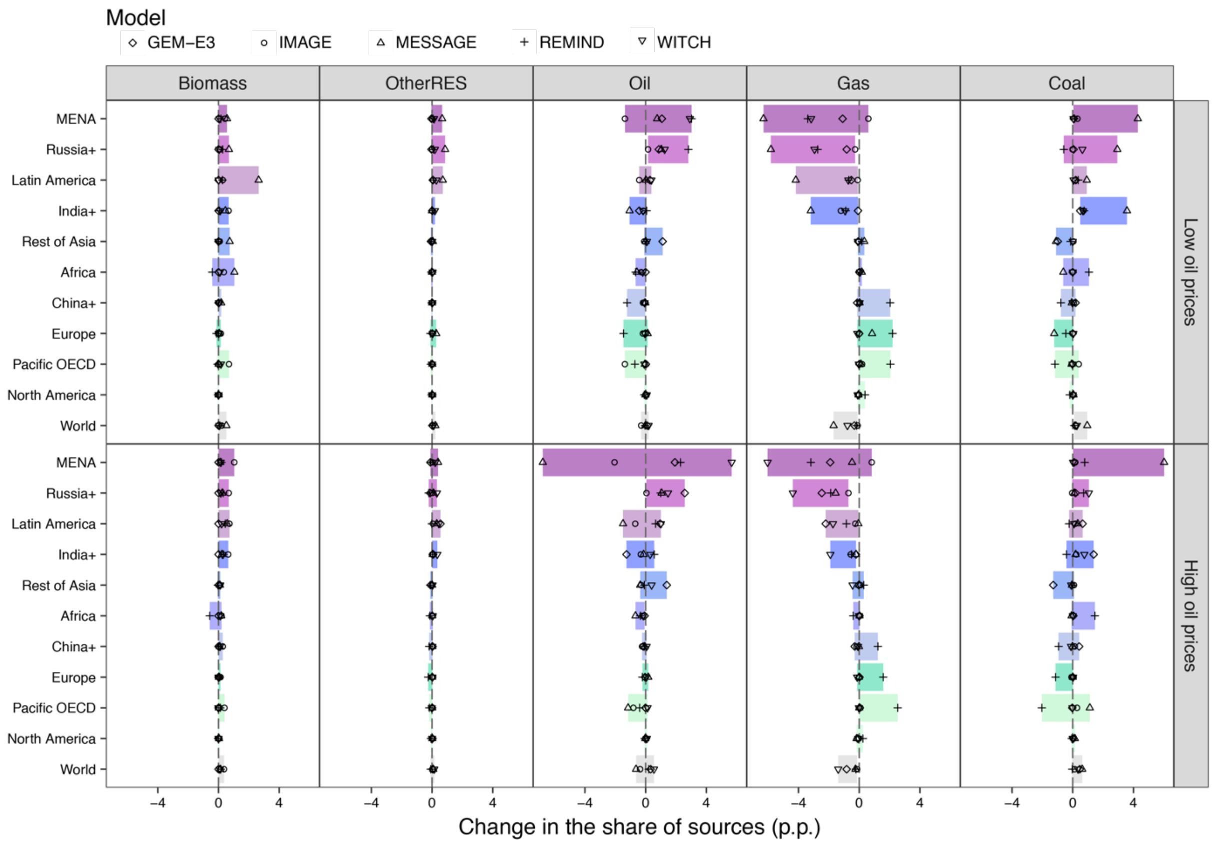
Supplementary Figure 11. Change in supply of different fuels from subsidy removal in 2030 under high oil prices. "Solar, wind and geo." indicates the aggregate change in solar, wind and geothermal power. Positive values of "Net change" indicate a decrease in the total primary energy supply, negative values an increase. Note that the region definition (Supplementary Table 10 – Supplementary Table 14) can influence the size of energy system changes.



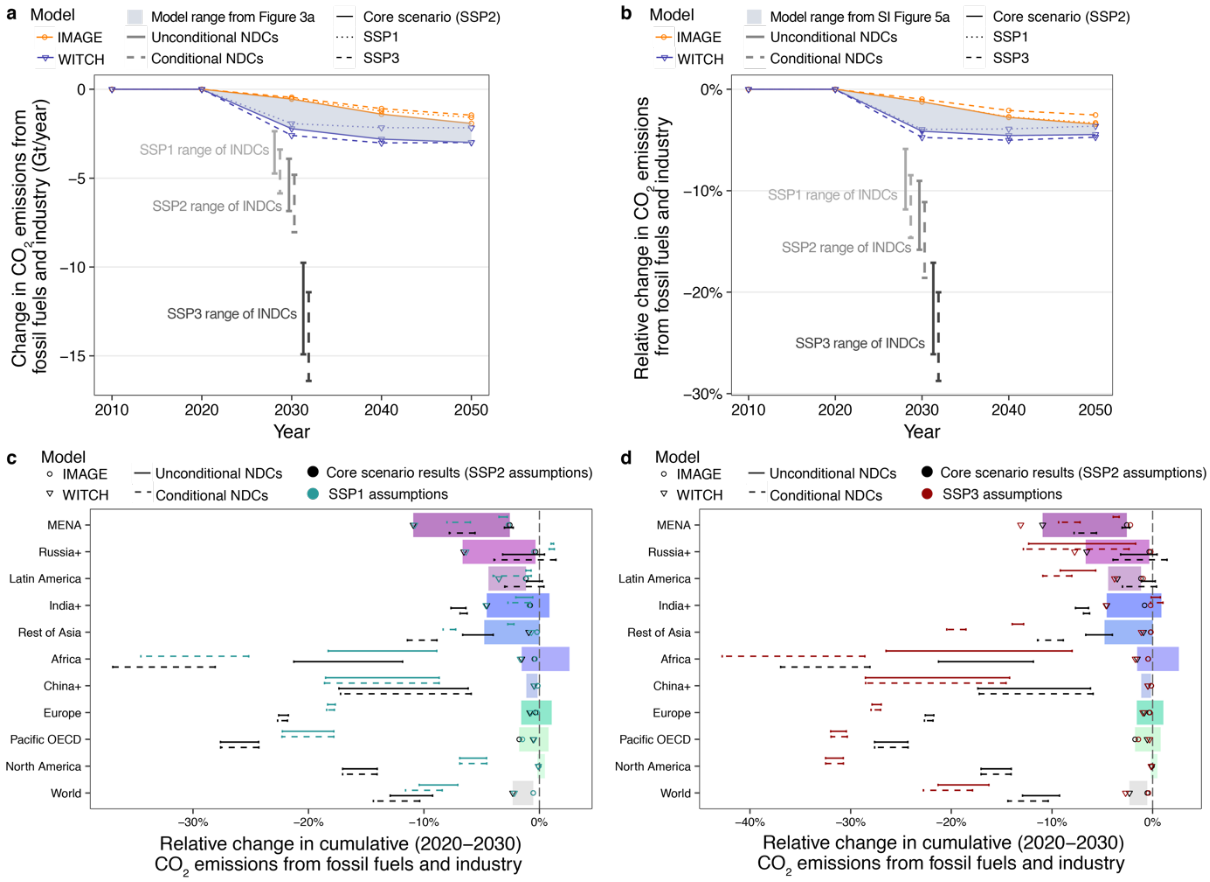
Supplementary Figure 12. Change in supply of different fuels from subsidy removal in 2030 under high oil prices. "Solar, wind and geo." indicates the aggregate change in solar, wind and geothermal power. Positive values of "Net change" indicate a decrease in the total primary energy supply, negative values an increase. Note that the region definition (Supplementary Table 10 – Supplementary Table 14) can influence the size of energy system changes.



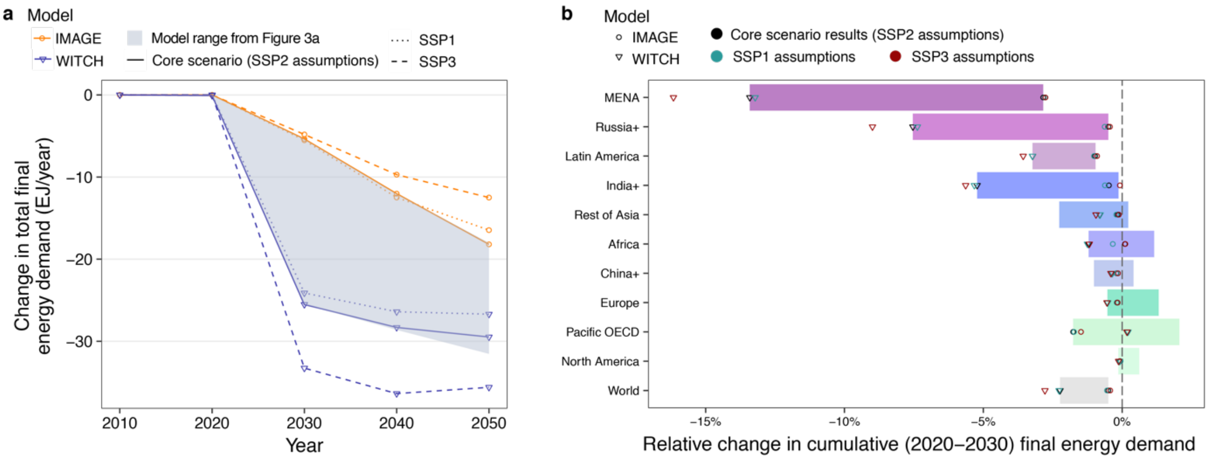
Supplementary Figure 13. Change in shares in cumulative Primary Energy Supply of different fuels from subsidy removal from 2020-2030. The effect of subsidy remove on shares of different energy sources in cumulative Primary Energy Supply (PES) in 2020-2030 by region under low and high oil prices. The columns correspond to different energy sources, where "OtherRES" includes hydro, wind, solar, and geothermal energy. The rows correspond to the 11 global regions and the world as a whole. The top pane shows the low oil price case and the bottom pane – the high oil price case. The dots in the figure represent how much a share of a given energy source in a given region will change as a result of subsidy removal (in percentage points (p.p.) of PES aggregated over 2020-2030) according to a specific model. The bars encompass the range of modelling results. The Figure demonstrates that the shares of renewable energy are not notably affected by subsidies removal (OtherRES column) globally or in any of the regions. Another notable effect are increases in the share of oil and coal in several models in MENA and Russia+. Finally, the Figure shows a largely similar effect of subsidy removal under low and high oil price cases.



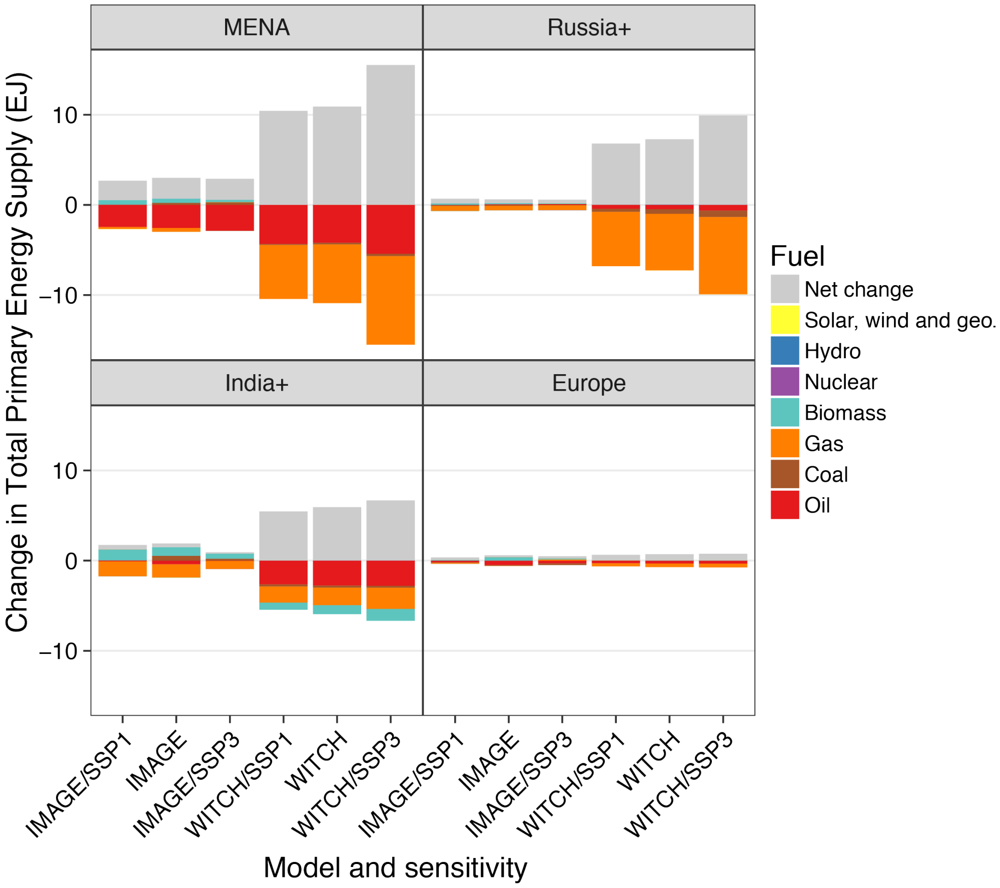
Supplementary Figure 14. Sensitivity of emissions results to different SSP assumptions. All changes are shown relative to the relevant SSP Baseline and under low oil prices. Panels (a) and (b) show sensitivity of the impact of subsidy removal on global annual CO_2 emissions from fossil fuels and industry to varying the baseline assumptions. (See discussion in the main text and Supplementary Text 7). In both panels, the grey range shows the model range from Figure 3a and Supplementary Figure 6a respectively and the difference is compared to each model's Baseline in absolute terms in panel (a) and relative terms in panel (b). In panels (a) and (b), SSP1 is represented with a dotted line and SSP2 is represented with a dashed line. Panels (c) and (d) show the sensitivity of the impact of subsidy removal on regional cumulative CO_2 emissions from fossil fuels and industry to varying baseline assumptions. In both panels, the change represents the cumulative change in CO_2 emissions from fossil fuels and industry from 2020 to 2030 at the regional level from subsidy removal (Gt). The range from all the models is represented by the colored bars and the core scenario result from the paper is represented with black. The SSP1 sensitivity is represented with green in panel (c) and the SSP3 sensitivity is represented with red in panel (d). In all panels, emission reductions from unconditional NDCs are represented with solid bar ranges and emission reductions from conditional NDCs are represented with dashed bar ranges. The NDC results are modeled using MESSAGE[36]. The uncertainty range for the NDCs represents variations in their effect arising from different historical emissions inventories, alternative accounting methods, attribution of non-commercial biomass and ranges within the NDCs themselves (see Methods, Supplementary Table 15 and ref. 36).



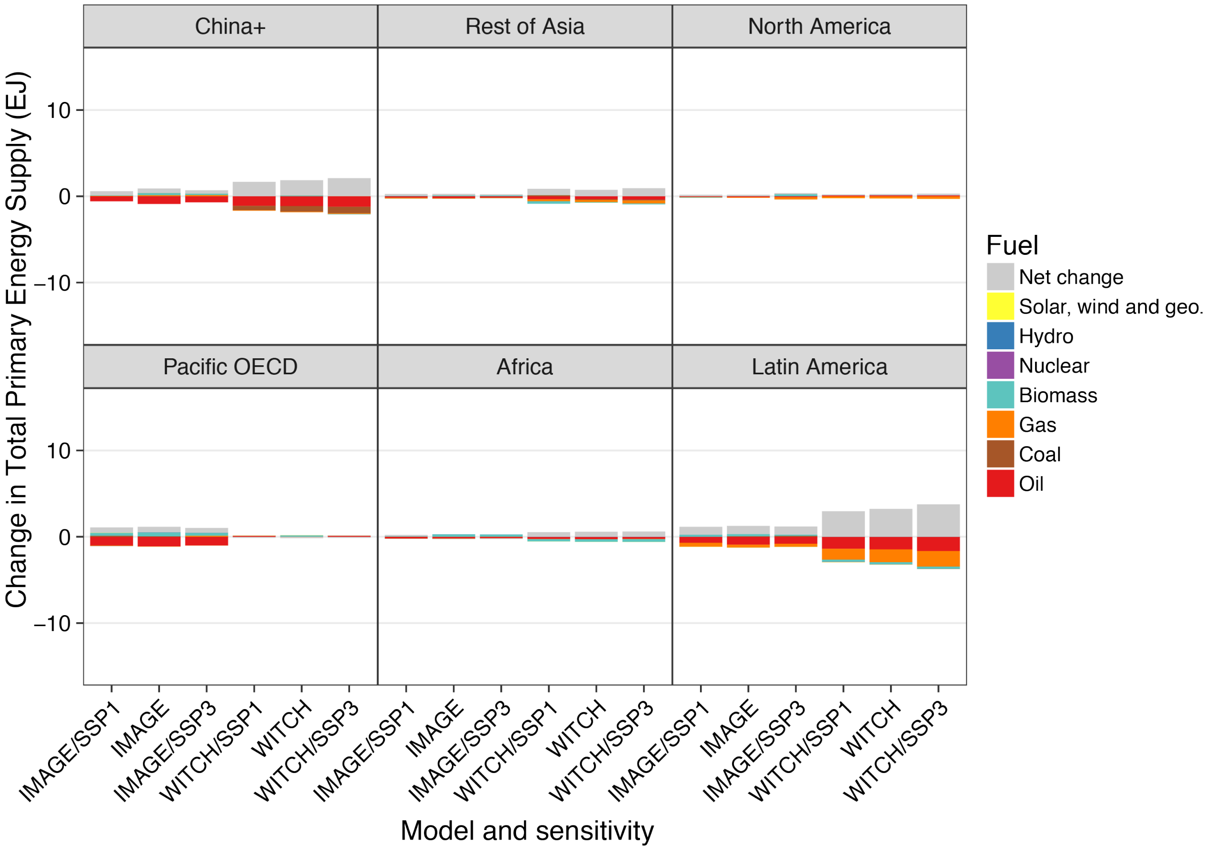
Supplementary Figure 15. Sensitivity of energy demand results to different SSP assumptions. All changes are shown relative to the relevant SSP Baseline. Panel (a) shows the sensitivity of the impact of subsidy removal on global final energy demand to varying the baseline assumptions. (See discussion in the main text and Supplementary Text 7). The grey range shows the model range from Figure 3a and the difference is compared to each model's Baseline in absolute terms. Panel (b) shows the sensitivity of the cumulative final energy demand to varying baseline assumptions: SSP1 is represented with a dotted line and SSP2 is represented with a dashed line. The change in panel (b) represents the cumulative change in final energy demand from 2020 to 2030 at the regional level from subsidy removal. The range from all the models is represented by the colored bars and the core scenario result from the paper is represented with black. In panel (b), the SSP1 sensitivity is represented with green dots and the SSP3 sensitivity is represented with red ones. All results are under low oil prices.



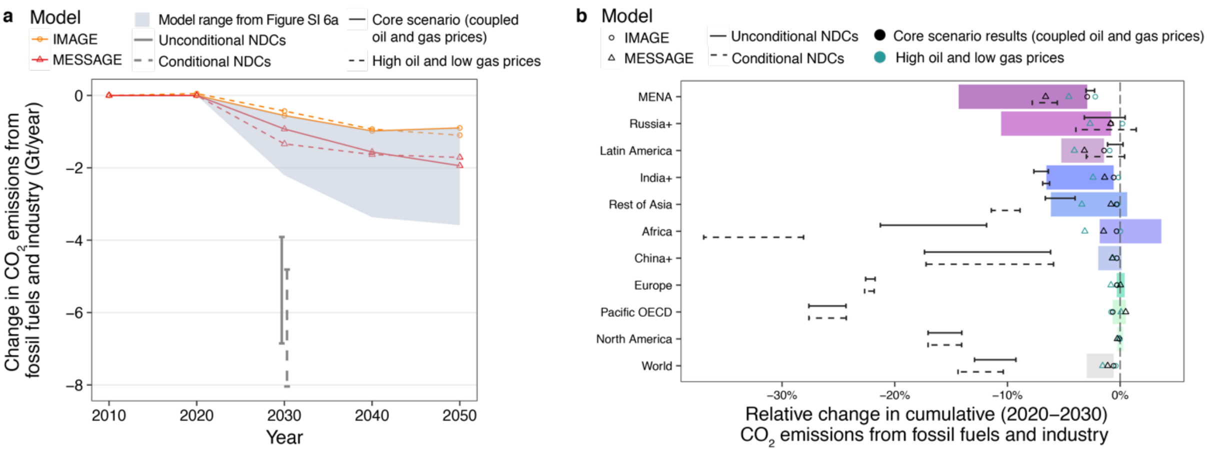
Supplementary Figure 16. Sensitivity of changes in change of supply of different fuels to different SSP assumptions for four representative regions. All changes are shown relative to the relevant SSP Baseline under low oil prices. "Solar, wind and geo." indicates the aggregate change in solar, wind and geothermal power. Positive values of "Net change" indicate a decrease in the total primary energy supply, negative values an increase. Central scenario is the main scenario from the paper and consistent with SSP2 assumptions (see Supplementary Text 7).



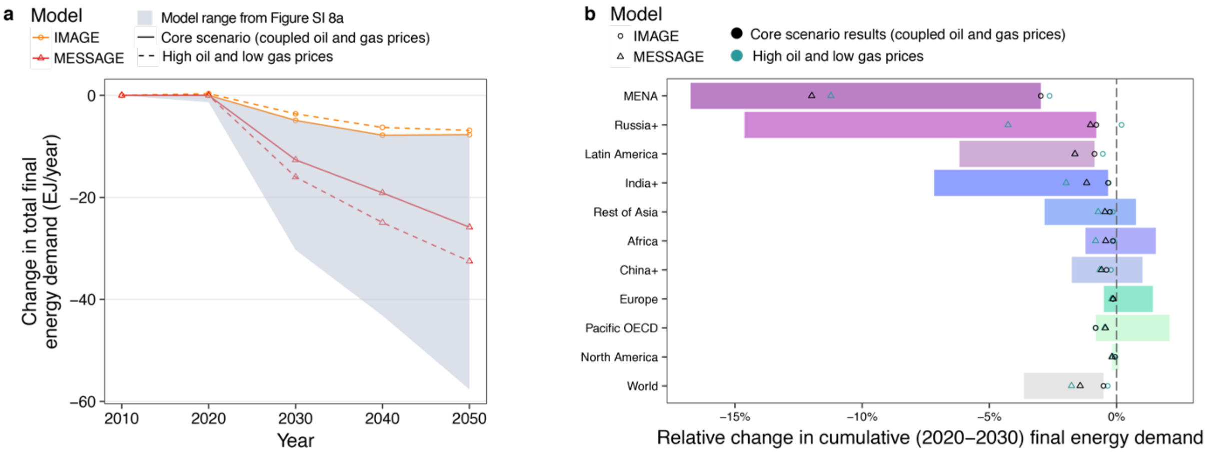
Supplementary Figure 17. Sensitivity of changes in supply of different fuels to different SSP assumptions for six remaining regions. All changes are shown relative to the relevant SSP Baseline under low oil prices. “Solar, wind and geo.” indicates the aggregate change in solar, wind and geothermal power. Positive values of “Net change” indicate a decrease in the total primary energy supply, negative values an increase. Central scenario is the core scenario from the paper and consistent with SSP2 assumptions (see Supplementary Text 7).



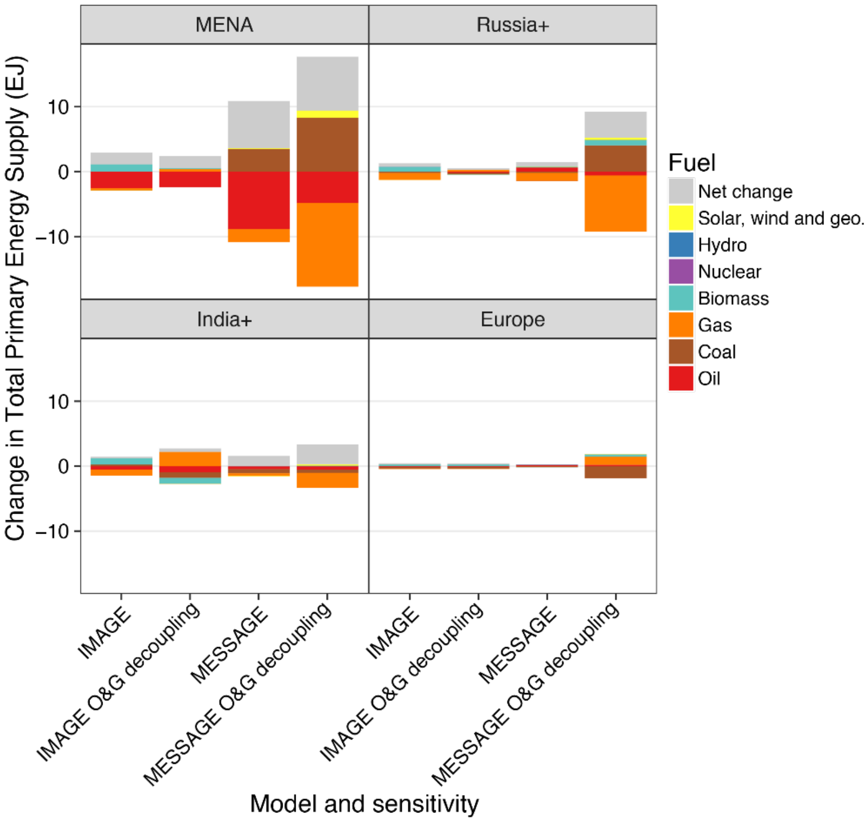
Supplementary Figure 18. Sensitivity of emissions results to decoupling oil and gas prices under high oil prices. Panel (a) shows sensitivity of the impact of subsidy removal on global annual CO_2 emissions from fossil fuels and industry to low gas prices in the high oil price case. (See Methods). In panel (a), the grey band shows the model range from Supplementary Figure 6a and the difference is compared to each model's Baseline. The high oil scenario is represented by a solid line, the sensitivity where gas prices stay low and oil prices rise is represented with a dashed line. Panel (c) shows the sensitivity of the impact of subsidy removal on regional cumulative CO_2 emissions from fossil fuels and industry to decoupling oil and gas prices at the regional level. The change represents the cumulative change in CO_2 emissions from fossil fuels and industry from 2020 to 2030 at the regional level from subsidy removal (Gt). The range from all the models for the high oil price case (in Supplementary Figure 6b) is represented by the colored bars and the scenario result from the high oil scenario where oil and gas prices are coupled is shown with black. The sensitivity under which gas prices are decoupled from oil prices is represented with green in panel (b). (For more details see also Supplementary Text 8). In both panels, we compare the emissions impact of fossil fuel subsidy removal to the emissions impact from the NDCs under the Paris climate agreement. Unconditional NDCs are represented with solid lines and conditional NDCs with dashed lines. The NDC results are modeled using MESSAGE[36]. The uncertainty range for the NDCs represents variations in their effect arising from different historical emissions inventories, alternative accounting methods, attribution of non-commercial biomass and ranges within the NDCs themselves (see Methods, Supplementary Table 15 and ref. 36).



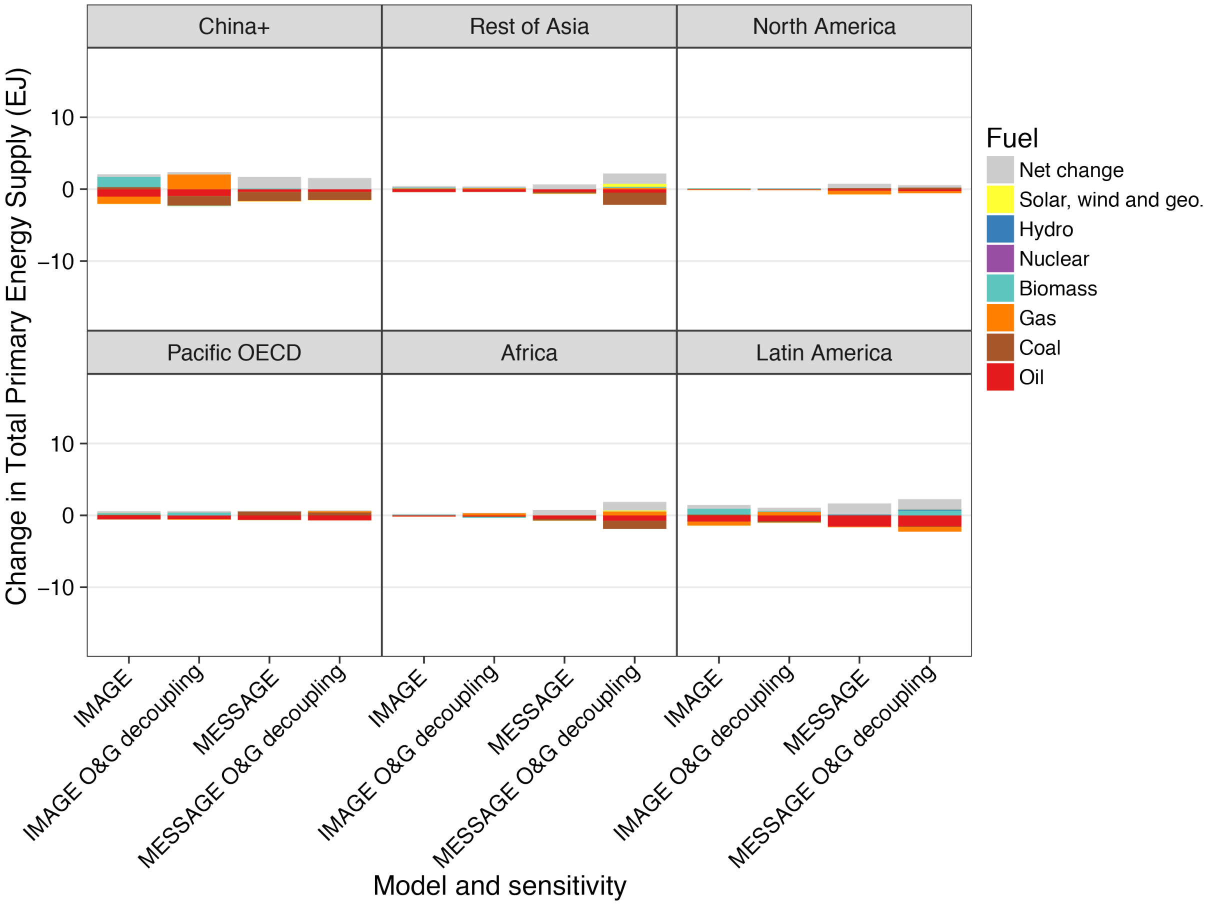
Supplementary Figure 19. Sensitivity of final energy demand results to decoupling oil and gas prices under high oil prices. Panel (a) shows the sensitivity of global final energy demand reductions from subsidy removal under high oil prices with low gas prices. (See also Supplementary Text 8). Panel (b) shows the sensitivity of regional final energy demand reductions from subsidy removal under high oil prices with low gas prices. In both panels, the changes are shown under high oil prices. In panel (a), the grey range shows the model range from subsidy removal under high oil prices (Supplementary Figure 8a). In panels (a), the core scenario is represented with a solid line and the sensitivity under high oil prices and low gas prices is represented with a dashed line. In panel (c) the range from all the models for the regional impact on final energy demand is represented by the colored bars and the scenario result from the high oil scenarios from the main paper is represented in black whereas the sensitivity with under de-coupled oil and gas prices in green.



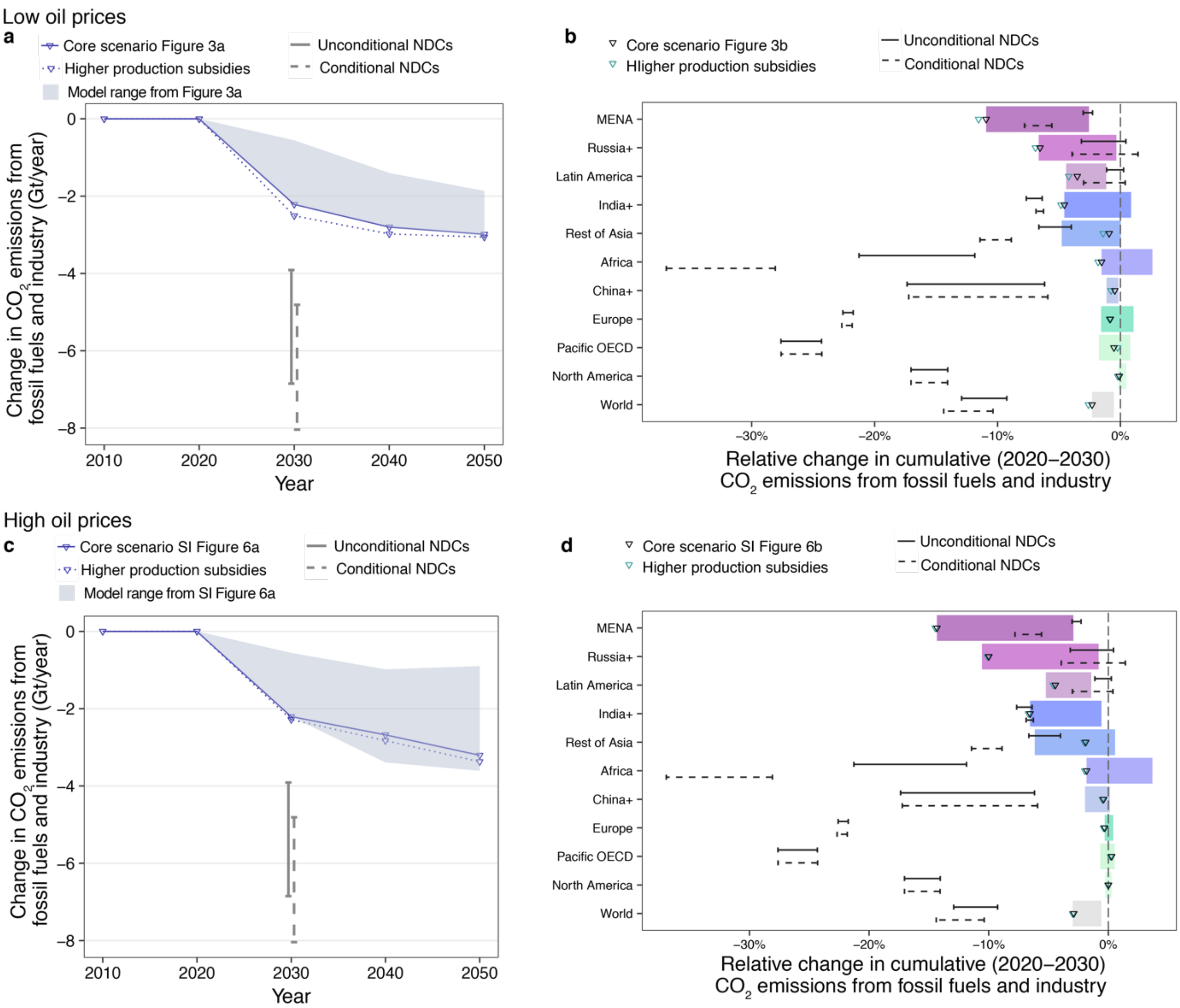
Supplementary Figure 20. Sensitivity of changes in different fuel supply to de-coupled oil and gas prices in four representative regions. “Solar, wind and geo.” indicates the aggregate change in solar, wind and geothermal power. Positive values of “Net change” indicate a decrease in the total primary energy supply, negative values an increase. Scenarios labeled “IMAGE” and “MESSAGE” are changes from subsidy removal under high oil prices also depicted in Supplementary Figure 11.



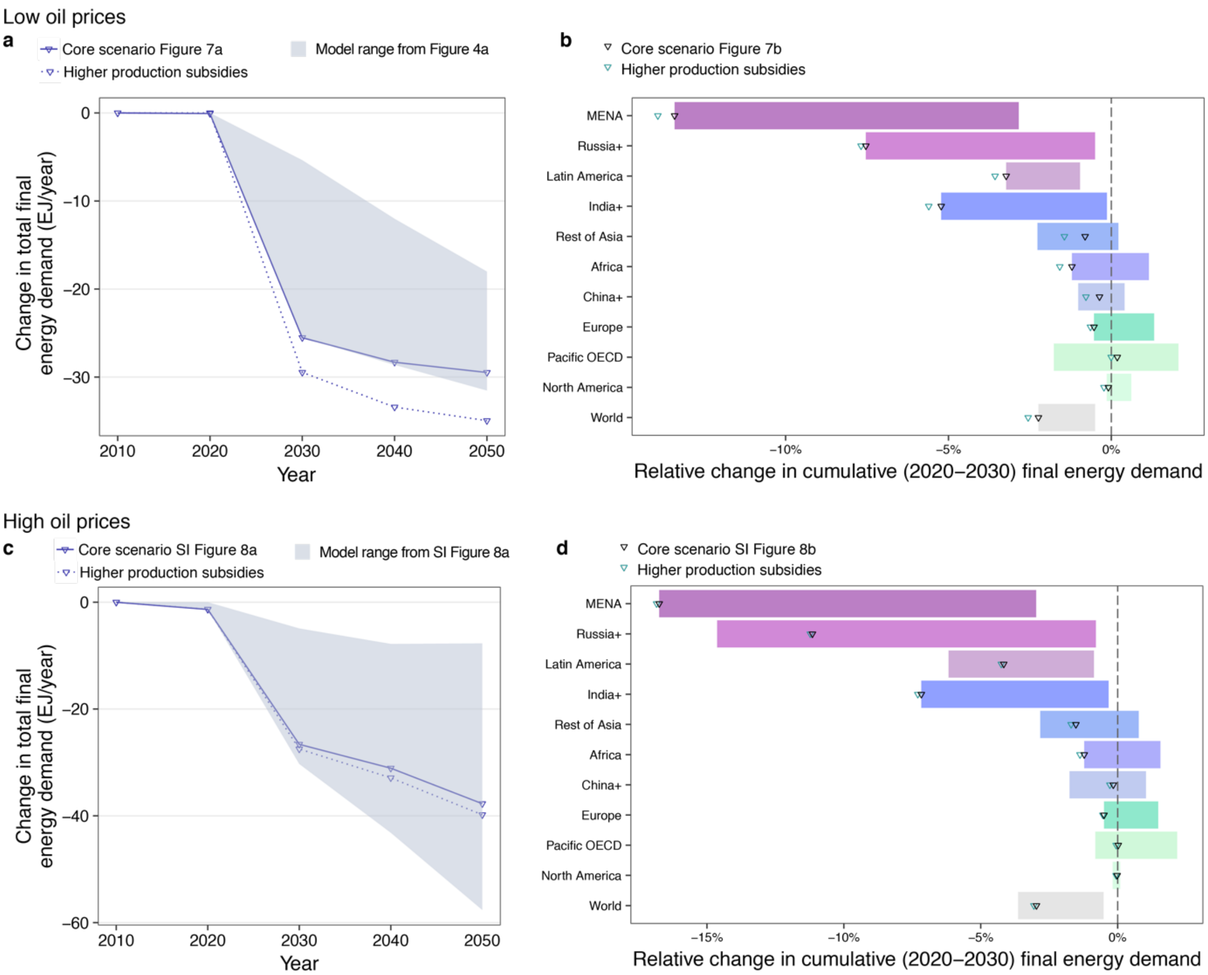
Supplementary Figure 21. Sensitivity of changes in different fuel supply to de-coupled oil and gas prices in six remaining regions. "Solar, wind and geo." indicates the aggregate change in solar, wind and geothermal power. Positive values of "Net change" indicate a decrease in the total primary energy supply, negative values an increase. Scenarios labeled "IMAGE" and "MESSAGE" are changes from subsidy removal under high oil prices also depicted in Supplementary Figure 11.



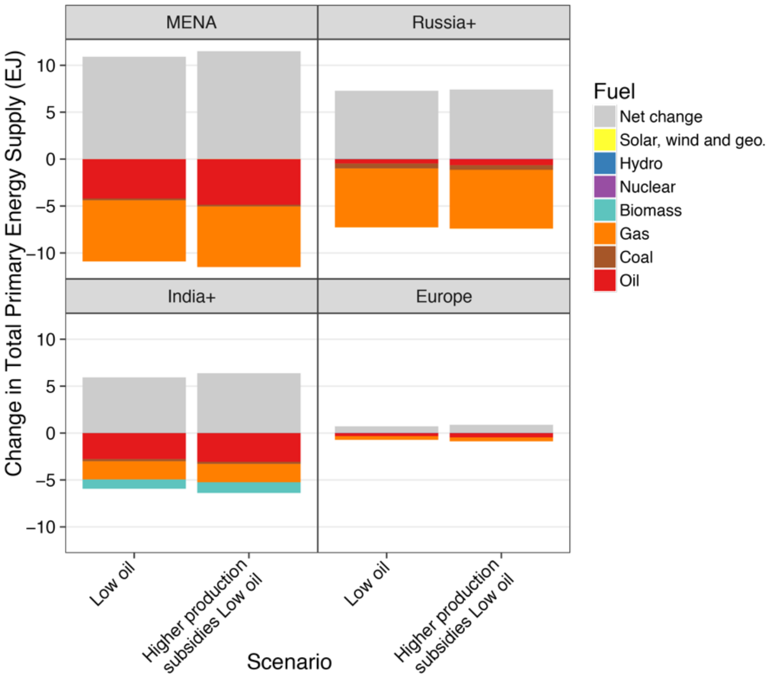
Supplementary Figure 22. Sensitivity of emissions results to higher production subsidies. Sensitivity analysis with the WITCH model. Panels (a) and (c) show the sensitivity of global emission reductions from subsidy removal to higher production subsides. (See also Supplementary Text 9). Panels (b) and (d) show the sensitivity of regional emission reductions from subsidy removal to higher production subsidies. In panels (a) and (b), the changes are shown under low oil prices; in panels (c) and (d), the changes are shown under high oil prices. In panels (a) and (b), the grey range shows the model range from subsidy removal under low and high oil prices (Figure 3a and Supplementary Figure 6a respectively). In panels (a) and (c), the core scenario is represented with a solid line and sensitivity with higher production subsidies is represented with a dotted line. In panels (c) and (d), the range from all the models for the regional impact on CO_2 emissions is represented by the colored bars and the scenario result from the low and high oil scenarios from the main paper is represented in black whereas the sensitivity with higher production subsidy values is represented in green. In all panels, emission reductions from unconditional NDCs are represented with solid bar ranges and emission reductions from conditional NDCs are represented with dashed bar ranges. Unconditional NDCs are represented with solid lines and conditional NDCs with dashed lines. The NDC results are modeled using MESSAGE[36]. The uncertainty range for the NDCs represents variations in their effect arising from different historical emissions inventories, alternative accounting methods, attribution of non-commercial biomass and ranges within the NDCs themselves (see Methods, Supplementary Table 15 and ref. 36).



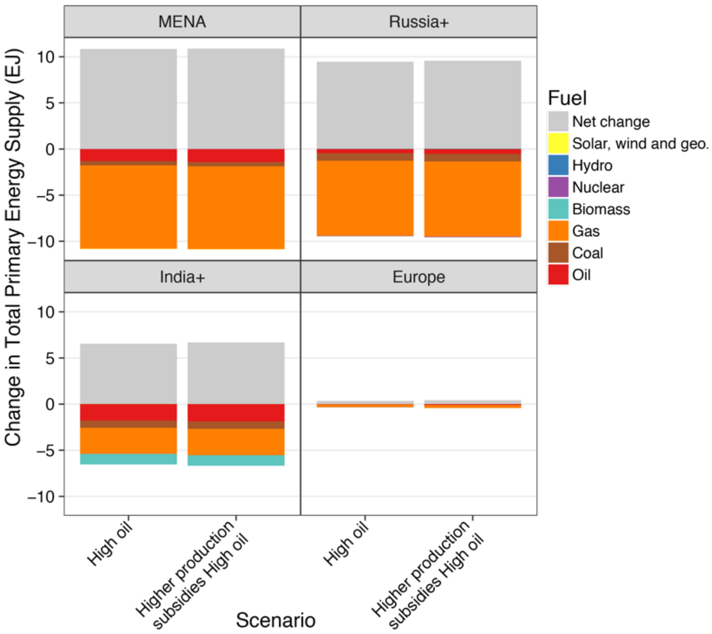
Supplementary Figure 23. Sensitivity of energy demand to higher production subsidies. Sensitivity analysis with the WITCH model. Panels (a) and (c) show the sensitivity of global final energy demand reductions from subsidy removal to higher production subsides. (See also Supplementary Text 9). Panels (b) and (d) show the sensitivity of regional final energy demand reductions from subsidy removal to higher production subsidies. In panels (a) and (b), the changes are shown under low oil prices; in panels (c) and (d), the changes are shown under high oil prices. In panels (a) and (b), the grey range shows the model range from subsidy removal under low and high oil prices (Figure 4a and Supplementary Figure 8a respectively). In panels (a) and (c), the core scenario is represented with a solid line and sensitivity with higher production subsidies is represented with a dotted line. In panels (c) and (d), the range from all the models for the regional impact on final energy demand is represented by the colored bars and the scenario result from the low and high oil scenarios from the main paper is represented in black whereas the sensitivity with higher production subsidy values is represented in green.



Supplementary Figure 24. Sensitivity of changes in fuel supply to higher production subsidies under low oil prices. Sensitivity analysis with the WITCH model. Higher production subsidies from refs. 16, 17 and described in Supplementary Text 9. Changes under low oil prices are changes from Figure 5 in the paper. "Solar, wind and geo." indicates the aggregate change in solar, wind and geothermal power. Positive values of "Net change" indicate a decrease in the total primary energy supply, negative values an increase.



Supplementary Figure 25. Sensitivity of changes in fuel supply to higher production subsidies under high oil prices. Sensitivity analysis with the WITCH model. Higher production subsidies described in Supplementary Text 9. Changes under high oil prices are changes from Supplementary Figure 11. "Solar, wind and geo." indicates the aggregate change in solar, wind and geothermal power. Positive values of "Net change" indicate a decrease in the total primary energy supply, negative values an increase.



Supplementary Tables

Supplementary Table 1. Summary of key model characteristics

Model	No. of regions	Equilibrium type	Modeling approach	***Flexibility of Supply* TI-p[(1)]**	***Flexibility of Demand* CoEI[(2)]**
GEM-E3	18	Computable general equilibrium	Recursive dynamic	Low[(3)]	High
IMAGE	26	Partial equilibrium	Recursive dynamic	Mixed	Low
MESSAGE	11	General equilibrium	Intertemporal optimization	High	Low
REMIND	11	General equilibrium	Intertemporal optimization	High	Low
WITCH	13	General equilibrium	Intertemporal optimization	Low	High

[(1)] The TI-p or the Transformation Index (primary energy) classification of model behavior under carbon taxes from Kriegler et al.[41] "Low" indicates a relatively smaller transformation of primary energy supply compared to other models whereas "High" indicates a relatively larger transformation of the primary energy system compared to other models. Models which are "low" are general said to be "stiff" in terms of supply changes whereas those that are "high" are "flexible" in terms of supply changes.
[(2)] CoEI or the carbon intensity over energy intensity indicator characterizes model behavior under carbon taxes from Kriegler et al.[41] "Low" indicates models which have a stronger reduction in carbon intensity relative to energy intensity compared to other models whereas "High" indicates models which have a stronger demand response compared to growth in low carbon energy sources. Models which are "low" are general said to be "stiff" in terms of energy demand changes whereas those that are "high" are "flexible" in terms of energy demand changes.
[(3)] From GEM-E3 modeling team.

Supplementary Table 2. Oil price elasticity, energy demand price elasticity and income elasticity in the transport sector in 2030. Price elasticity in column two is calculated from the difference in oil price and oil demand between the scenarios with and without subsidies under both low and high oil prices in the transport sector in 2030 for regions which show at least a 5% price difference between the two scenarios. The range reflects the relative flexibility of oil demand in different regions. Implicit price elasticities for IMAGE, MESSAGE, REMIND, and WITCH in column three represent the mean from the price shock scenarios as reported in ref. 42 (price elasticity for WITCH is reported to an additional significant digit to that reported in the paper). Income elasticities are the mean of the values reported in ref. 42. See Supplementary Text 3 for more discussion.

	Oil price elasticity	**Energy demand price elasticity**	**Income elasticity[42]**
	Regional range for scenarios in this study	From price shocks analysis[42]	
GEM-E3	-0.33 – -0.08	-0.01[a]	0.8[a]
IMAGE	-0.71 – -0.20	-0.4	0.6
MESSAGE	-1.29 – -0.11	-0.4	*Not available*
REMIND	-0.35 – 0.01	-0.3	0.4
WITCH	-0.51 – -0.07	-0.01	1.0

[a] For GEM-E3, the shock price and income elasticity is calculated by the GEM-E3 modeling team for this study.

Supplementary Table 3. Subsidy levels under high oil prices (2013) by the MESSAGE regions. All subsidy values are in Billion USD_{2005}. Regional estimates in other models may vary slightly depending on regional definitions (See Supplementary Table 10 –Supplementary Table 14). Totals sometimes do not equal to the sum of the underlying components due to rounding. The last column shows the share of government revenues spent on subsidies. Government revenues are calculated based on data from IMF ref. 43.

	Production				**Consumption**					***Total***	
billion USD_{2005}	Oil	Gas	Coal	*Total prod.*	Oil	Gas	Coal	Elect.	*Total cons.*		% Govt Revenues
World	**15**	**5**	**2**	***22***	**324**	**107**	**4**	**110**	***545***	***567***	***3%***
MENA	0	0.02	0	*0*	134	40	0	44	*218*	***218***	*22%*
Russia[+]	5	0.2	0.3	*6*	6	37	2	26	*71*	***77***	*10%*
Latin America	4	0.4	0	*4*	54	11	0	17	*82*	***86***	*6%*
India[+]	0.6	0	0.01	*0.6*	30	10	0	9	*49*	***50***	*15%*
Rest of Asia	0	0	0.1	*0.1*	25	0.5	0.3	7	*33*	***33***	*6%*
Africa	0	0	0	*0*	9	0.4	0	0.7	*10*	***10***	*4%*
China[+]	0.5	1	0	*2*	38	2	0	7	*46*	***48***	*2%*
Europe	0.5	0.3	1	*2*	18	6	1	0	*25*	***27***	*0.4%*
North America	4	2	0.3	*6*	2	2	0.1	0.4	*5*	***11***	*0.2%*
Pacific OECD	0.2	0.5	0.2	*0.9*	6	0.008	0	0.4	*6*	***7***	*0.4%*

Supplementary Table 4. Bulk subsidy levels under low oil prices (2015) by the MESSAGE regions All subsidy values are in Billion USD_{2005}. Regional estimates in other models may vary slightly depending on regional definitions. (See Supplementary Table 10 –Supplementary Table 14). Totals sometimes do not equal to the sum of the underlying components due to rounding. The last column shows the share of government revenues spent on subsidies. Government revenues are calculated based on data from IMF ref. 43.

	Production				**Consumption**					***Total***	
billion USD_{2005}	Oil	Gas	Coal	*Total prod.*	Oil	Gas	Coal	Elect.	*Total cons.*		% Govt. Revenues
World	**3**	**3**	**2**	***7***	**166**	**70**	**2**	**82**	***320***	***327***	***2%***
MENA	0	0.02	0	*0.02*	65	29	0	35	*129*	***129***	*19%*
Russia[+]	0	0	0.1	*0.1*	3	21	0.8	17	*41*	***41***	*9%*
Latin America	0	0	0	*0*	26	6	0	13	*45*	***45***	*4%*
India[+]	0	0	0.01	*0.01*	12	5	0	3	*20*	***20***	*5%*
Rest of Asia	0	0	0.1	*0.1*	9	0.1	0.1	5	*14*	***14***	*2%*
Africa	0	0	0	*0*	3	0.03	0	2	*5*	***5***	*2%*
China[+]	0	0	0	*0*	22	0.1	0.002	6	*28*	***28***	*1%*
Europe	0.4	0.3	1	*2*	18	6	1	0	*25*	***28***	*0.4%*
North America	2	2	0.3	*4*	3	3	0.07	0.5	*6*	***15***	*0.2%*
Pacific OECD	0.2	0.4	0.01	*0.7*	6	0.008	0	0.4	*6*	***7***	*0.4%*

Supplementary Table 5. Historical and future subsidy levels under different oil prices. Dollar units are in USD_{2005}. The subsidy rate represents the total subsidies divided by total primary energy supply of fossil fuels. 2030 values reflect the full model range. At the regional level, where models differ on their exact regional definitions, 2013 and 2015 values are reported for the MESSAGE regions and are calibrated to a dataset which we compiled from different sources[2-4,24,32] (see also Methods). For 2013 and 2015 calculations, energy data are from the IEA[44] and GDP data from the IMF[43]. Base year ranges for all models as well as for 2020 are reported in Supplementary Table 7. For regional definitions see Supplementary Tables 9 – 14.

	2013			**2015**			**2030**					
	High oil prices			**Low oil prices**			**High oil prices**			**Low oil prices**		
	bln. $	% GDP	$/ GJ	bln. $	% GDP	$/ GJ	bln. $	% GDP	$/GJ	bln. $	% GDP	$/GJ
World	**567**	**1%**	**1.2**	**327**	**0.6%**	**0.7**	**755-963**	**0.8-1.0%**	**1.4-1.9**	**556-687**	**0.6-0.7%**	**0.9-1.1**
MENA	218	11%	5.3	129	6%	3.0	268-364	6.3-10.4%	5.8-7.4	193-267	5.0-6.5%	3.3-4.5
Russia+	77	6%	1.7	41	3%	0.9	40-114	1.4-4.9%	1.3-2.6	28-78	1.6-2.8%	0.9-1.7
Latin America	86	2%	3.5	45	1%	1.8	69-140	1.3-2.1%	3.4-4.9	39-96	0.9-1.4%	1.7-3.0
India+	50	3%	1.7	20	1%	0.7	94-122	1.6-3.0%	1.6-3.0	50-71	1.0-1.6%	0.9-1.4
Rest of Asia	33	1%	1.2	14	0.5%	0.5	41-88	0.7-1.6%	1.3-1.7	24-45	0.4-0.9%	0.6-1.2
Africa	10	1%	1.5	5	0.4%	0.7	3-22	0.5-1.2%	0.6-2.0	2-19	0.3-0.8%	0.3-0.9
China+	48	0.8%	0.4	28	0.4%	0.2	67-103	0.3-0.7%	0.5-1.1	36-88	0.2-0.6%	0.3-0.6
Europe	27	0.2%	0.5	26	0.2%	0.5	21-28	0.09-0.1%	0.3-0.5	21-42	0.1-0.2%	0.3-0.6
North America	11	0.1%	0.1	11	0.07%	0.1	5-15	0.02-0.08%	0.06-0.2	7-12	0.03-0.06%	0.07-0.1
Pacific OECD	7	0.3%	0.1	7	0.1%	0.3	0.6-9	0.01-0.1%	0.04-0.4	0.5-12	0.008-0.2%	0.02-0.5

Supplementary Table 6. Fossil fuel subsidies as share of energy-related market transactions. Calculation based on the GEM-E3 model. The numerator includes all subsidies and the denominator is the value of all energy transactions at the end-use level including taxes.

	2015	**2020**	**2030**	**2040**	**2050**
High oil prices	10%	10%	13%	15%	17%
Low oil prices	10%	6%	8%	9%	10%

Supplementary Table 7. Base year range and 2020 subsidy levels under different oil prices. Subsidy ranges are reported to the nearest billion and percent of GDP to the nearest tenth of one percent. The subsidy rate represents the total subsidies divided by total primary energy supply of fossil fuels. The range in the base year value reflects the range between models due to base year calibration (see Methods) and regional definitions (Supplementary Table 10 – Supplementary Table 14). Dollar units are in USD_{2005}.

	Base year (2010)			**2020**					
				High oil prices			**Low oil prices**		
	billion $	% GDP	$/GJ	billion $	% GDP	$/GJ	billion $	% GDP	$/GJ
World	**530-555**	**1.0-1.1%**	**1.2-1.3**	**640-696**	**0.9-1.0%**	**1.4-1.5**	**393-490**	**0.6-0.7%**	**0.8-0.9**
MENA	205-218	10.7-12.5%	5.4-7.3	208-279	7.1-10.9%	5.2-7.4	152-183	5.8-6.7%	3.2-4.0
Russia$^+$	36-69	3.7-5.7%	1.6-1.9	42-94	2.2-4.9%	1.4-2.3	22-71	1.6-4.1%	0.8-1.7
Latin America	45-95	1.8-2.9%	3.4-4.3	56-113	1.7-2.3%	3.5-4.6	32-73	0.9-1.5%	1.7-2.9
India$^+$	25-52	1.8-3.4%	1.2-2.2	60-80	2.6-3.0%	1.4-2.7	32-50	1.1-1.7%	0.8-1.2
Rest of Asia	24-53	1.2-2.7%	1.1-1.8	29-65	0.9-1.9%	1.2-1.7	20-33	0.5-1.0%	0.6-1.0
Africa	2-13	0.7-1.5%	0.6-2.2	3-16	0.6-1.2%	0.6-2.2	1-13	0.3-1.1%	0.3-1.0
China$^+$	40-48	0.8-1.1%	0.4-0.5	56-70	0.5-0.8%	0.5-0.9	28-62	0.3-0.7%	0.2-0.5
Europe	21-36	0.1-0.2%	0.3-0.6	22-30	0.1-0.2%	0.3-0.6	20-38	0.1-0.2%	0.3-0.7
North America	7-10	0.05-0.07%	0.09-0.1	5-14	0.03-0.08%	0.07-0.2	6-11	0.03-0.07%	0.07-0.1
Pacific OECD	0.8-7	0.02-0.1%	0.04-0.3	0.6-9	0.01-0.2%	0.03-0.4	0.3-10	0.006-0.2%	0.02-0.4

Supplementary Table 8. 2050 subsidy levels under different oil prices. Subsidy ranges are reported to the nearest billion and percent of GDP to the nearest tenth of one percent. The subsidy rate represents the total subsidies divided by total primary energy supply of fossil fuels. Dollar units are in USD_{2005}.

	High oil prices			**Low oil prices**		
	billion $	% GDP	$/GJ	billion $	% GDP	$/GJ
World	**1,090-1,643**	**0.7-1.1%**	**1.6-2.4**	**799-1123**	**0.5-0.8%**	**1.0-1.5**
MENA	377-703	4.9-10.6%	6.6-7.2	275-444	3.6-6.3%	3.6-5.0
Russia$^+$	44-142	0.7-4.7%	1.3-2.7	38-86	1.2-1.9%	0.9-1.6
Latin America	95-227	0.9-2.1%	3.0-5.3	53-152	0.7-1.3%	1.6-3.3
India$^+$	159-257	1.0-2.7%	1.6-3.7	86-146	0.4-1.5%	0.6-1.5
Rest of Asia	45-151	0.4-1.4%	1.1-2.3	34-81	0.3-1.0%	0.6-1.7
Africa	5-64	0.09-1.2%	0.5-1.4	3-51	0.3-0.5%	0.4-0.8
China$^+$	83-144	0.2-0.7%	0.5-1.3	54-118	0.2-0.5%	0.3-0.8
Europe	16-32	0.05-0.1%	0.2-0.5	25-33	0.08-0.2%	0.3-0.6
North America	7-14	0.02-0.5%	0.06-0.1	8-16	0.03-0.06%	0.08-0.2
Pacific OECD	0.3-13	0.005%-0.1%	0.2-0.5	1-12	0.02-0.2%	0.07-0.5

Supplementary Table 9. General regional descriptions. Note that all modeling is carried out in models' native regions and results are mapped onto the 10-region set. The exact countries contained in the regional mapping vary slightly and are reported in Supplementary Table 10 – Supplementary Table 14. Some models also have a "Rest of the World" region.

Region	Description
Africa	Includes countries in Sub-Saharan Africa. Some models also include North African countries but others do not. For REMIND and WITCH, South Africa is included in the Rest of the World region.
China$^+$	Primarily composed of China but in some models includes additional Asian countries such as Cambodia, Vietnam, North Korea, and Mongolia.
Europe	Eastern and Western European countries (i.e. EU27) but REMIND and WITCH also include Turkey.
India$^+$	Primarily India but in some models also includes other South Asian countries such as Nepal, Pakistan, Bangladesh, and Afghanistan.
Latin America	Latin American and Caribbean countries.
Middle East & North Africa (MENA)	Middle Eastern countries such as Iran, Iraq, Israel, Saudi Arabia and Qatar. This also includes North African countries such as Algeria, Egypt, Morocco, Tunisia and for REMIND it also includes the Central Asian former Soviet states. In GEM-E3, this region also includes other major energy producing countries such as Venezuela and Azerbaijan.
North America	For most models this includes the United States of America and Canada but in REMIND, Canada is included in the Rest of the World region and for WITCH, Canada is included in the Pacific OECD region.
Pacific OECD	OECD (Organization for Economic Co-operation and Development) countries which are in the Eastern Hemisphere and abut the Pacific Ocean. For most models this region is dominated by Japan, Australia and New Zealand. For REMIND, only Japan is included, Australia and New Zealand are included in the Rest of the World region. WITCH also does not include Australia, which is instead part of the Rest of the World region. WITCH also includes Canada in the Pacific OECD.
Russia$^+$	This region is dominated by Russia. For all models except REMIND, it also includes Reforming Economies which were part of the Soviet Union such as Ukraine, Kazakhstan and Azerbaijan. WITCH also includes Turkey in this region.
Rest of Asia	Includes other Asian countries which are not in the India or China regions such as South Korea, Malaysia, Philippines, Singapore, Thailand and Indonesia. For WITCH, South Korea is included in the Rest of the World region.

This table includes a full list of the super regions along with a non-exhaustive sample of countries included in each.

Supplementary Table 10. GEM-E3 regional definitions

Region	Native model region	Countries
Africa	South Africa	South Africa
China+	China	China
Europe	EU-28, Turkey, Rest of Annex I	Andorra, Austria, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Hungary, Iceland, Ireland, Italy, Kosovo, Latvia, Lithuania, Luxembourg, Macedonia, Malta, Montenegro, Netherlands, Norway, Serbia, Switzerland, Ukraine, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Turkey, United Kingdom
India+	India	India
Latin America	Argentina, Brazil, Mexico	Argentina, Brazil, Mexico
MENA	Saudi Arabia, Rest of energy producing countries	Algeria, Azerbaijan, Iran, Iraq, Kuwait, Lebanon, Libya, Nigeria, Qatar, Saudi Arabia, Syria, United Arab Emirates, Venezuela, Yemen
North America	Canada, USA	Canada, United States of America
Pacific OECD	Oceania, Japan	American Samoa, Australia, Christmas Island, Cocos (Keeling) Islands, Cook Islands, Fiji, French Polynesia, Japan, New Zealand, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu
Russia+	Russia	Russia
Rest of Asia	Indonesia, S. Korea	Republic of Korea, Indonesia
Rest of the World	Rest of the world	Afghanistan, Albania, Angola, Antarctica, Armenia, Aruba, Bahamas, Bahrain, Bangladesh, Barbados, Belize, Benin, Bermuda, Bhutan, Bolivia, Botswana, Bouvet Island, British Indian Ocean Territory, Brunei Darussalam, Burkina Faso, Burundi, Cambodia, Cameroon, Cape Verde, Cayman Islands, Central African Republic, Chad, Chile, Colombia, Comoros, Congo, The Democratic Republic Of Congo, Costa Rica, Côte D'Ivoire, Cuba, Djibouti, Dominica, Dominican Republic, Ecuador, Egypt, El Salvador, Equatorial Guinea, Eritrea, Ethiopia, Falklands Islands (Malvinas), French Guiana, French Southern Territories, Gabon, Gambia, Georgia, Ghana, Greenland, Grenada, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, Hong Kong, Israel, Jamaica, Jordan, Kazakhstan, Kenya, Kyrgyzstan, Democratic Republic of Lao, Lesotho, Liberia, Macau, Madagascar, Malawi, Malaysia, Maldives, Mali, Mauritania, Mauritius, Moldova, Mongolia, Montenegro, Morocco, Mozambique, Myanmar, Namibia, Nepal, New Caledonia, Nicaragua, Niger, Oman, Pakistan, Panama, Paraguay, Peru, Philippines, Puerto Rico, Rwanda, Saint Lucia, Saint Vincent And The Grenadines, Sao Tome And Principe, Senegal, Sierra Leone, Singapore, Somalia, Sri Lanka, Sudan, Suriname, Swaziland, Tajikistan, Tanzania, Thailand, Togo, Trinidad And Tobago, Tunisia, Turkmenistan, Uganda, Uruguay, Uzbekistan, Vietnam, Zambia, Zimbabwe

Supplementary Table 11. IMAGE regional definitions

Region	Native model regions	Countries
Africa	East Africa, Western Africa, Rest South Africa, South Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, the Democratic Republic of the Congo, , Côte D'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Greenland, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Réunion, Rwanda, Saint Helena, Sao Tome And Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
China$^+$	China	China, Hong Kong, Macau, Mongolia, Taiwan
Europe	Western Europe, Turkey, Central Europe	Albania, Andorra, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Macedonia, Malta, Monaco, Netherlands, Norway, Poland, Portugal, Romania, San Marino, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom
India$^+$	India, Rest South Asia	Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Sri Lanka, India
Latin America	Brazil, Mexico, Rest Central America, Rest South America	Anguilla, Argentina, Aruba, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Falklands Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Kitts And Nevis, Saint Lucia, Saint Vincent And The Grenadines, Suriname, Trinidad And Tobago, Turks And Caicos Islands, Uruguay, Venezuela, Virgin Islands (British), Virgin Islands (US)
MENA	Middle East, North Africa	Algeria, Bahrain, Egypt, Iran, Islamic Republic Of, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen Western Sahara
North America	Canada, USA	Canada, Saint Pierre And Miquelon, United States of America
Pacific OECD	Japan, Oceania	American Samoa, Australia, Cook Islands, Fiji, French Polynesia, Japan, Kiribati, Marshall Islands, Micronesia, Nauru, New Caledonia, New Zealand, Niue, Norfolk Island, Palau, Pitcairn, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Wallis And Futuna
Russia$^+$	Russia, Kazakhstan region, Ukraine region	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
Rest of Asia	Indonesia, Korea, Southeast Asia	Brunei Darussalam, Cambodia, East Timor, Indonesia, Democratic Republic of Korea, Republic Of Korea, Democratic Republic of Lao, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Thailand, Vietnam

Supplementary Table 12. MESSAGE regional definitions

Region	Native model regions	Countries
Africa	Sub-saharan Africa	Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, The Democratic Republic Of Congo, Côte D'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea, Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Réunion, Rwanda, Saint Helena, Sao Tome And Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
China^{+}	Centrally planned Asia and China	Cambodia, China, Hong Kong, Democratic Republic Of Korea, Democratic Republic Of Lao, Mongolia, Vietnam
Europe	Western Europe, Eastern Europe	Albania, Andorra, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Macedonia, Malta, Monaco, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom
India^{+}	South Asia	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
Latin America	Latin America	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts And Nevis, Saint Lucia, Saint Vincent And The Grenadines, Suriname, Trinidad And Tobago, Uruguay, Venezuela
MENA	Middle East	Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria, Tunisia, United Arab Emirates, Western Sahara, Yemen
North America	North America	Canada, Guam, Puerto Rico, United States, Virgin Islands (British), Virgin Islands (US), United States of America
Pacific OECD	Pacific OECD	Australia, Japan, New Zealand
Russia^{+}	Former Soviet Union	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
Rest of Asia	Other Pacific Asia	American Samoa, Brunei Darussalam, East Timor, Fiji, French Polynesia, Indonesia, Kiribati, Republic Of Korea, Malaysia, Myanmar, New Caledonia, Papua New Guinea, Philippines, Samoa, Singapore, Solomon Islands, Taiwan, Thailand, Tonga, Vanuatu

Supplementary Table 13. REMIND regional definitions

Region	Native model regions	Countries
Africa	Sub-saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Congo, The Democratic Republic Of The, Côte D'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Réunion, Rwanda, Sao Tome And Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, United Republic Of, Togo, Uganda, Zambia, Zimbabwe
China+	China	China, Hong Kong, Macau
Europe	EU 27	Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom
India+	India	India
Latin America	Latin America and the Caribbean	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad And Tobago, Uruguay, Venezuela, Palau, Saint Kitts And Nevis, Saint Lucia, Saint Vincent And The Grenadines
MENA	Middle East and North Africa	Algeria, Armenia, Azerbaijan, Bahrain, Egypt, Georgia, Iran, Iraq, Israel, Jordan, Kazakhstan, Kuwait, Kyrgyzstan, Lebanon, Libya, Martinique, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tajikistan, Tunisia, Turkmenistan, United Arab Emirates, Uzbekistan, Western Sahara, Yemen
North America	United States of America	Puerto Rico, United States
Pacific OECD	Japan	Japan
Russia+	Russia	Russia
Rest of Asia	Other Asia	Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, East Timor, Fiji, Indonesia, Kiribati, Democratic Republic Of Korea, Republic Of Korea, Democratic Republic Of Lao, Malaysia, Maldives, Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, Philippines, Singapore, Solomon Islands, Sri Lanka, Taiwan, Thailand, Vietnam, Vanuatu
Rest of the World	Rest of the World	Albania, Australia, Belarus, Bosnia and Herzegovina, Canada, Croatia, Iceland, Macedonia, Moldova, Montenegro, New Zealand, Norway, Serbia, South Africa, Switzerland, Turkey, Ukraine

Supplementary Table 14. WITCH regional definitions

Region	Native model region	Countries
Africa	Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, the Democratic Republic of Congo, Côte d'Ivoire, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Mozambique, Namibia, Niger, Nigeria, Réunion, Rwanda, Saint Helena, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
China	China and Taiwan	China, Hong Kong, Macau, Taiwan
Europe	Western Europe, Eastern Europe	Andorra, Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Vatican, Hungary, Iceland, Ireland, Italy, Latvia, Lichtenstein, Lithuania, Luxembourg, Monaco, Netherlands, Norway, Poland, Portugal, Romania, San Marino, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom
India	India, South Asia	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
Latin America	Latin America, Mexico and Caribbean	Anguilla, Antigua and Barbuda, Argentina, Aruba, Bahamas, Barbados, Belize, Bolivia, Brazil, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Falkland Islands, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Nauru, Netherlands Antilles, Nicaragua, Niue, Panama, Paraguay, Peru, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, Venezuela, Virgin Islands (British), US Virgin Islands
MENA	Middle East and North Africa	Algeria, Bahrain, Djibouti, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Malta, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, United Arab Emirates, Western Sahara, Yemen
North America	United States	Bermuda, United States, United States Minor Outlying Islands
Pacific OECD	Canada, Japan, New Zealand	Canada, Christmas Island, Japan, New Zealand, Saint Pierre & Miquelon
Russia	Transition Economies	Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Croatia, Georgia, Kazakhstan, Kyrgyzstan, Macedonia, Moldova, Montenegro, Russia, Serbia, Tajikistan, Turkey, Turkmenistan, Ukraine, Uzbekistan
Rest of Asia	Southeast Asia	American Samoa, Brunei Darussalam, Cambodia, Cocos (Keeling) Islands, Cook Islands, East Timor, Fiji, French Polynesia, Guam, Indonesia, Kiribati, Democratic Republic of Korea, Democratic Republic of Lao, Malaysia, Marshall Islands, Federated States of Micronesia, Mongolia, Myanmar, New Caledonia, North Mariana Islands, Palau, Papua New Guinea, Philippines, Pitcairn, Samoa, Singapore, Solomon Islands, Thailand, Tokelau, Tonga, Tuvalu, Vanuatu, Vietnam, Wallis and Futuna
Rest of World	Korea, South Africa, Australia	Australia, Republic of Korea, South Africa

Supplementary Table 15. Key uncertainties included in the NDC scenarios from ref. 36.

NDC uncertainty	Description	Implementation
historical emission inventory variation	There are different emission inventories which vary in their estimates of historical emissions. When NDCs are specified as a percentage change from a historical value, this leads to uncertainty.	NDCs are assessed with respect to three different historical emission datasets[45-47].
alternative energy accounting methods	There are different methods for calculating the percentage of non-combustible energy sources at the primary energy level. The method used influences the emission reduction estimates which contain a target to achieve a specific share of renewable or nuclear energy in the energy mix.	NDCs are assessed using two primary energy accounting methods: the direct equivalence and the partial substitution method[48].
attribution of non-commercial biomass	In many regions, a significant portion of energy demand is met by non-commercial biomass such as firewood[49]. Whether or not this source is counted as contributing to renewable energy sources can influence the emission impacts of achieving certain renewable energy targets.	Two cases: one in which non-commercial biomass is counted as contributing to renewable energy and one under which it is not.
ranges within the NDCs	Some countries do not provide a single emission reduction level but provide a range.	Two cases: one with the minimum level from each range and one with the maximum reduction level from each range.
conditionality	Some actions within NDCs are dependent upon certain conditions such as the availability of financing.	Two cases: one which includes all conditional actions and one which excludes them.

Supplementary Table 16. Change in the average carbon price from subsidy removal required to achieve 550 ppm CO_2eq under low oil prices.

	Relative	Absolute ($/t CO_2)
GEM-E3	-12%	-2.1 $/t
IMAGE	-7%	-1.2 $/t
MESSAGE	-4%	-0.7 $/t
REMIND	-4%	-0.7 $/t
WITCH	-4%	-1.3 $/t

Supplementary Table 17. Change in the average carbon price from subsidy removal needed to reach climate stabilization targets under sensitivity runs. (See Supplementary Text 6).

	550 - High oil prices		450 - Low oil prices		450 - High oil prices	
	Relative	**Absolute ($/t CO_2)**	**Relative**	**Absolute ($/t CO_2)**	**Relative**	**Absolute ($/t CO_2)**
MESSAGE	-5%	-0.7 $/t	-2%	-1.8 $/t	-4%	-2.7 $/t
REMIND	-7%	-0.7 $/t				

Supplementary Table 18. Bulk production subsidy levels under low and high oil prices and in the high production subsidies sensitivity in WITCH in 2020. (See Supplementary Text 9). The table shows the bulk subsidy values of production subsidies for the base year under high oil prices and in the higher production subsidies scenarios. The production values for the High and low oil prices scenarios from the paper are based on data from ref. 4 whereas the production values for the higher production subsidies are based on data from refs. 5,6. Totals sometimes do not equal to the sum of the underlying components due to rounding.

[billion USD_{2005}]	Core scenarios from paper								Higher production subsidies scenario							
	High oil prices				Low oil prices				High oil prices				Low oil prices			
	Oil	Gas	Coal	**Total**	Oil	Gas	Coal	**Total**	Oil	Gas	Coal	**Total**	Oil	Gas	Coal	**Total**
World	14	6	2	**22**	6	3	2	**11**	64	30	8	**94**	93	31	6	131
MENA	0	0.02	0	**0.02**	0	0.02	0	**0.02**	22	6	0	**24**	29	6	0	22
Russia+	5	0.2	0.3	**5**	0.02	0.006	0.2	**0.2**	18	5	0.5	**25**	25	6	0.3	32
Latin America	4	0.4	0	**4**	0	0	0	**0**	10	6	0.1	**16**	16	6	0.04	22
India+	0.3	0	0.01	**0.3**	0	0	0.01	**0.01**	0	0	0.1	**0.1**	0	0	0.1	0.1
Rest of Asia	0	0	0	**0**	0	0	0	**0**	0.2	0.1	0.4	**1**	0.5	0.1	0.1	0.7
Africa	0	0	0	**0**	0	0	0	**0**	0.8	0.1	0	**1**	2	0.1	0	2
China+	0.2	2	0	**3**	0	0	0	**0**	0.2	0.1	2	**3**	0.4	0.2	2	2
Europe	1	0.2	1	**2**	2	0.2	1	**3**	5	1	2	**5**	8	2	2	11
N. America	2	2	0.1	**4**	2	2	0.2	**4**	5	7	2	**14**	7	8	1	16
Pacific OECD	1	1	0.2	**2**	3	1	0.2	**4**	2	0.8	0.1	**3**	3	1	0.2	4
Rest of World	0.02	0.02	0.2	**0.3**	0.05	0.005	0.1	**0.2**	1	2	1	**3**	3	2	1	6

Supplementary Table 19. Number of people living under $3.10 per day in each region. Data are based on data from the World Bank[50]. Percentage of population living under $3.10 per day (PPP) was aggregated for countries from 2005-2015 with the most recent year available. Only those countries which have fossil fuel subsidies in our dataset were included. Aggregation is based on the MESSAGE regions. See Supplementary Text 10 for discussion.

	Millions of people	**% of population**
World	1356	28%
MENA	1.4	2%
Russia[+]	1.0	0.5%
Latin America	45	9%
India[+]	880	52%
Rest of Asia	94	26%
Africa	172	52%
China[+]	161	11%
Europe	2	2%
North America	0	0%
Pacific OECD	0	0%

Supplementary Table 20. Conversion factors from volume to energy content, with reference

Energy conversion	**Value**	**Reference**
LPG GJ/l	0.02	MIT Energy club units conversion[51]
Crude oil GJ/bl	6.1	MIT Energy club units conversion[51]
Fuel oil GJ/kg	39.3	From IEA B2020 used light fuel oil for “all other countries”[23]
Heating oil GJ/kl	39.2	From IEA B2020 used heavy fuel oil average[23]
95 gasoline GJ/l	0.03	MIT Energy club units conversion[51]
diesel GJ/l	0.04	MIT Energy club units conversion[51]
coal GJ/t	30	MIT Energy club units conversion[51]
natural gas MJ/SCM	0.038	MIT Energy club units conversion[51]

Supplementary Text 1 *Model descriptions*

In addition to the modeling descriptions below, all models are documented on the following website: http://themasites.pbl.nl/models/advance/index.php/ADVANCE_wiki.

GEM-E3: The GEM-E3 model is a multi-regional, multi-sectoral, recursive dynamic computable general equilibrium (CGE) model which provides details on the macro-economy and its interaction with the environment and the energy system[52,53]. It is an empirical, large scale model, written entirely in structural form which runs to 2050. GEM-E3 allows for a consistent comparative analysis of policy scenarios since it ensures that in all scenarios, the economic system remains in general equilibrium. In addition, it incorporates micro-economic mechanisms and institutional features within a consistent macro-economic framework and avoids the representation of behavior in reduced form[54]. The model is dynamic, recursive over time, driven by accumulation of capital and equipment. Technology progress is explicitly represented in the production function, either exogenous or endogenous, depending on R&D expenditure by private and public sector and taking into account spillovers effects. R&D is explicitly introduced in the model as a separate economic activity. R&D is a substitute for energy, capital and labor and firms decide to purchase R&D services based on relative prices (increase in prices for energy will increase energy efficiency through R&D). Knowledge is a function of R&D expenditures, learning by doing and a phasing-out effect. Knowledge is cumulative and builds up a stock that is linked to productivity. Firms optimize their optimal use of production factors including R&D. Technology diffusion is represented in two ways: i) bilateral trade and the exchange of innovative goods and their use as intermediate inputs through lower production costs, and ii) explicit technology diffusion through knowledge diffusion based on patent-citation data. Endogenous learning by doing rates are included (reduction in capital cost for each doubling of capacity). The model is modularly built allowing the user to select among a number of alternative closure options and market institutional regimes depending on the issue under study. The GEM-E3 model includes projections of: full Input-Output tables by country/region, national accounts, employment by economic activity, unemployment rate, balance of payments, public finance and revenues, household consumption, energy use and supply, GHG emissions and atmospheric pollutants. The model features discrete representation of power producing technologies, semi-endogenous learning by doing effects, equilibrium unemployment, option to introduce energy efficiency standards, formulates emission permits for GHG and atmospheric pollutants.

IMAGE: The IMAGE modeling framework focuses on the chain of global environmental change for both climate and land use. Important inputs into the system are assumptions on population and economic development. Next, two models describe the trends in the demand for key environmental services: energy and food demand. The global energy system model TIMER[55] has been developed to simulate long-term energy baseline and climate change mitigation scenarios (which run to 2100). The model describes the investments in and use of different types of energy options influenced by technology development (learning-by-doing) and resource depletion. IMAGE includes technological development in the form of learning curves for most fuels and renewable options. Costs decrease endogenously as a function of the cumulative energy capacity. It is assumed that the supply of energy always meets the demand and the decision to invest in additional capacity is based the price of energy produced per technology, using a multinominal logit equation that assigns larger market shares to the lower cost options. Inputs to the model are macro-economic scenarios and assumptions on technology development, preference levels and restrictions to fuel trade. For food and agriculture, the IMAGE system uses projections made by the computable-general-equilibrium MAGNET model. This model describes, in interaction with the main IMAGE framework, changes in food production and trade for a broad set of crops and animal products. The Terrestrial Environment System (TES) of IMAGE[56] computes land-use changes based on regional production of food, animal feed, fodder, grass, bio-energy and timber, with consideration of local climatic and terrain properties. Emissions from land-use changes, natural ecosystems and agricultural production systems, and the exchange of carbon dioxide between terrestrial ecosystems and the atmosphere are also simulated. Through the linkage to IMAGE, internally consistent projections of GDP and energy demand are calculated in an iterative fashion that takes price-induced changes of demand and GDP into account. The Atmospheric Ocean System (AOS) part of IMAGE calculates changes in atmospheric composition using the emissions from the TIMER model and TES, and by taking oceanic carbon dioxide uptake and atmospheric chemistry into consideration. Subsequently, AOS computes changes in climatic parameters by resolving the changes in radiative forcing caused by greenhouse gases, aerosols and oceanic heat transport.

MESSAGE: The MESSAGE model (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) is an energy-economic model based on a linear programming (LP) optimization approach which is used for medium- to long-term energy system planning and policy analysis and which runs to 2110[57-59]. (Version 'V.5a' of MESSAGE was used for this paper)[60]. The model minimizes total discounted energy system costs, and provides information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, and inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy. Technology diffusion in MESSAGE is determined by (soft) dynamic constraints that relate the construction of a technology added or the activity (level of production) of a technology in a period to construction or the activity in the previous period. By soft constraints we refer to the fact that technological diffusion can be accelerated at additional cost[61]. The technology diffusion patterns produced by the model have been compared to similar patterns from long-term observational data and generally been found to be consistent with these[62]. To estimate regionally-aggregated, sector-based air pollutant emissions and related pollution control costs, MESSAGE has been linked to the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model[63,64]. or the estimation of price-induced changes of energy demand, iterations between the MESSAGE model and the macro-economic model MACRO[65] are relied upon. In MACRO, capital stock, available labor, and energy inputs determine the total output of the economy according to a nested constant elasticity of substitution (CES) production function. Through the linkage to MESSAGE, internally consistent projections of GDP and energy demand are calculated in an iterative fashion that takes price-induced changes of demand and GDP into account. MESSAGE is used in conjunction with MAGICC (Model for Greenhouse gas Induced Climate Change) version 6[66] for calculating internally consistent scenarios for climatic indicators such as atmospheric concentrations, radiative forcing, annual-mean global surface air temperature and global-mean sea level implications.

REMIND: The REMIND model is a multi-regional, inter-temporal energy-economy-environment model which runs through 2100. The model is composed of two main components: (i) the macro-economic growth module that describes socio-economic developments and determines the economy's demand for final energy, (ii) a detailed energy system module describing conversion pathways from various types of primary energy via secondary energy to final[67]. A key feature of the model is that these two components are solved in an integrated, intertemporal optimization framework, thus fully accounting for all feedbacks in the system and assuming perfect foresight by economic actors. The macro-economic core of REMIND is a Ramsey-type intertemporal general equilibrium model in which global welfare is maximized. The model computes a Pareto-optimal solution, which corresponds to the market equilibrium in the absence of non-internalized externalities. The energy system module accounts for regional endowments of exhaustible primary energy resources (coal, oil, gas and uranium) and renewable energy potentials (biomass, hydro power, wind power, solar energy, geothermal energy). REMIND represents the build-up and vintaging of capacity stocks of more than 70 technologies that convert primary into secondary energy carriers or distribute these secondary energy carriers to end use sectors. The inertia of technological up-scaling and diffusion are captured by a mark-up factor on investment costs that scales with the square of the change in newly installed capacity from one time-step to the next. For renewable power generation technologies and alternative vehicle technologies, reduction of investment costs are implemented via learning rates and a conservative estimate on floor costs. Learning-by-doing effects are explicitly represented via global learning curves for wind and solar technologies as well as electric vehicles. There is no further direct representation of R&D in the model, as the autonomous energy efficiency improvement is implemented through the calibration.

WITCH: The WITCH (World Induced Technical Change Hybrid) model is a global integrated assessment model with two main distinguishing features: a regional game-theoretic setup, and an endogenous treatment of technological innovation for energy conservation and decarbonization[68,69]. A top-down inter-temporal Ramsey-type optimal growth model is hard linked with a representation of the energy sector described in a bottom-up fashion, hence the hybrid denomination. The time horizon is 2150. The regional and intertemporal dimensions of the model make it possible to differentiate and assess the optimal response to several climate and energy policies across regions and over time. The non-cooperative nature of international relationships is explicitly accounted for via an iterative algorithm which yields the open-loop Nash equilibrium between the simultaneous activity of a set of representative regions. Regional strategic actions interrelate through GHG emissions, dependence on exhaustible natural resources, trade of fossil fuels and carbon permits, and technological R&D spillovers. R&D investments are directed towards either energy efficiency improvements or development of carbon-free breakthrough technologies. Such innovation cumulates over time and spills across countries in the form of knowledge stocks and flows. R&D investments along with investments in energy technologies and the final goods sector are endogenously determined in the intertemporal optimization. Within the energy sector, for new renewable energy sources (wind and solar), battery development, and advanced biofuels, learning is also taken into account through one or two factor learning curves, which determine future capital costs. The competition for land use between agriculture, forestry, and bioenergy, which are the main land-based production sectors, is described through a soft link with a land use and forestry model (GLOBIOM, Global Biosphere Management Model)[70]. A climate model (MAGICC) is used to compute climate variables from GHG emission levels and an air pollution model (FASST) is linked to compute air pollutant concentrations. While for this exercise WITCH is used for cost-effective mitigation analysis, the model supports climate feedback on the economy to determine the optimal adaptation strategy, accounting for both proactive and reactive adaptation expenditures.

Supplementary Text 2 *Model differences*

An important feature of our study is the use of multiple models to address uncertainties and ambiguities related to different methods of representing energy-economy systems. For example, should investment decisions be represented as based on information about the future (as they most commonly are in perfect foresight models), or should they be represented as based only on present information (as they most commonly are in simulation models)? In the real world, investors are informed by both the future and present, but in models, one approach is usually emphasized over the other. A common way to overcome the limitations which a single modeling approach imposes is to compare the results of models with fundamentally different characteristics, as we have done in this study to ensure that the results are robust against what is commonly known as model uncertainty. Supplementary Table 1 summarizes key characteristics of the models in this study. For this study, we selected models that differ in their representation of the economy (equilibrium type), modeling approach, and in the key model characteristics of *flexibility of supply* and *flexibility of demand* (explained in the next paragraph).

The results which we report are robust for all models, but there are certain variations in the projected effects of subsidy removals on emission reductions, energy demand and the energy mix, explained by different assumptions and model characteristics. One of the most important model differences for our study is whether or not price changes have a stronger effect on energy demand (model flexibility of demand) or whether price changes more readily induce changes in the energy mix (model flexibility of supply)[41]. This characteristic is determined by earlier work on diagnostic indicators which measure an IAMs response to a carbon price[41]. The first indicator measures the *Flexibility of supply* compared to other models. It quantifies the response in transformation primary energy supply (TI-p) relative to other models: a high TI-p will show relatively larger changes in the primary energy mix from a given carbon price compared to one with a low TI-p. The second indicator measures the *Flexibility of demand* or how much the energy intensity changes from a given carbon price. This indicator – Carbon Intensity over Energy Intensity (CoEI) measures how the carbon intensity of an energy system changes (as a proportion of Baseline carbon intensity) compared to the overall energy intensity changes (also as a proportion of Baseline energy intensity) under a given carbon price. A model with a high CoEI value shows relatively higher energy intensity (and demand) response than a model with low CoEI. The CoEI and TI-p indicate how the model balances energy demand changes with energy supply changes not only in response to a climate policy but also in response to other changes in energy pricing, such as subsidy removal, as investigated in our study.

WITCH and GEM-E3 are comparatively more flexible on demand than on supply and therefore show a higher drop in demand response to subsidy removal (Figure 4), which also translates into a larger drop in emissions in these models (Figure 3). In particular, emission reductions in WITCH become comparable to the NDCs in India$^+$ (Supplementary Figure 5 and 6). In contrast, MESSAGE and REMIND have higher flexibility of supply and therefore model substitution of oil or natural gas with coal. This can lead to lower emission reductions or even emission increases following removal of oil and natural gas subsidies in some regions in these models (Figure 3). IMAGE has low flexibility of demand and therefore shows the smallest demand and emissions drop from subsidy removal (Figures 3 and 4). In contrast to the other models, natural gas in IMAGE remains competitive even after subsidy removal, so its use does not decrease, even in MENA and Russia$^+$ (Figure 5 and Supplementary Figure 11). As already mentioned, the flexibility of global energy trade, which may lead to an effect similar to carbon leakage following subsidy removal, also differs across models. Finally, models also have slightly different regional definitions (Supplementary Tables 10-14), which can explain certain variations in regional results. For example, the 'Rest of Asia' region in GEM-E3 is dominated by Indonesia with its high subsidies for coal-fired electricity which results in the highest projected emissions reductions compared to other models and which are comparable to the NDCs under both low and high oil prices (Figure 3 and Supplementary Figure 6).

Supplementary Text 3 *Fuel price and income elasticity*

The impact of subsidy removal on emissions and energy systems depends on the response of fuel demand to price changes or the fuel price elasticity. For the models used in this study, fuel price elasticities are not an exogenous parameter but rather inherent characteristics of each model which reflect the response of the energy-economy system to changes in prices. In Supplementary Table 2 we report the range of implicit oil price elasticities in our scenarios, as well as the transport energy demand price and income elasticities from earlier work[42]. For the former, we calculated the elasticity using the difference in the oil price and demand in transport between the scenarios with and without subsidies under both low and high oil prices in regions which show at least a 5% difference in the oil price in the transport sector in 2030 from subsidy removal. The range in each model represents the different availability of alternative options for switching away from oil or reducing demand in the transport sector. The estimate of implicit transport energy demand price elasticity which we report is from Edelenbosch et al.[42] who used a set of price shock scenarios to calculate the implicit transport energy demand price elasticity. The oil price elasticity of the transport sector for the models used in this study is between 0.01 and -1.27 while the transport energy demand price elasticity ranges from -0.01 to -0.4 (Supplementary Table 2).

Consistent with earlier work[42,52,54,71], we find that the implicit elasticities in the different models in this study fall within the empirical range observed in the literature[72,73] (for long-term elasticity which generally relates to time periods of longer than 10 years[74]). Empirical estimates of long-term elasticity of fuel consumption in the transport sector range from -0.01 to -1.81 by dynamic estimation methods and -0.11 to -1.12 by cross-sectional estimation methods[72]. This is consistent with earlier estimates of long-run price elasticity of gasoline which ranged from 0 to -2.72[73].

While fuel price elasticity reflects a change in demand in response to price changes, income elasticity reflects a change in demand in response to change in income. It is an important characteristic of any future scenario where energy demand increases following economic growth. The implicit income elasticity of transportation energy demand in the participating models is between 0.38 and 0.98 (Supplementary Table 2). This is well within empirical estimates, which range from 0.27 to 1.71 for long-term dynamic estimation and from 0.02 to 1.4 for static model estimation[72]. These ranges are also consistent with earlier estimates which ranged from 0.05 to 2.73[73].

Supplementary Text 4 *Scaling fossil fuel subsidy data*

The low oil scenario is based primarily on subsidy rates from the IEA for subsidies for the year 2015[3] (also available at: http://www.iea.org/statistics/resources/energysubsidies/.). This dataset accounts for approximately 80% of the bulk subsidies in our subsidy dataset. For the remaining 20% of subsidies in our dataset, the most recent subsidy estimate we have is from subsidies under high oil prices. However, historically, fossil fuel subsidies have generally followed the oil price (Supplementary Figure 1) so using the 2014 rates would likely overestimate the subsidies. Thus, we used historical subsidy rates, their correlation to the oil price, and the change in oil price from 2014 to 2015 to project subsidy rates under low prices.

To do this analysis, we relied on historical subsidy from the OECD[4] and the IEA[2,3,39,40,75] and energy data from the IEA for the year 2014 (which was the most recent year available)[44]. We calculated the weighted average of consumption subsidies for oil, gas and electricity for OECD countries, non-OECD oil and gas importers and non-OECD oil and gas exporters (Supplementary Figure 2). These three groups follow the three archetypal regions in our paper, but they also have different practical relationships with the oil price. For non-OECD oil and gas exporters, the correlation between fossil fuel subsidies and oil prices should be the strongest; this is because in these countries, it's not only that the need for fossil fuel subsidies is lower when the oil price falls but also that the funding mechanism for it is also depressed since for these countries, the government budgets relies on oil prices to fund fossil fuel subsidies[76]. For non-

OECD oil and gas importers, the need for fossil fuel subsidies is lower when the oil price falls. In OECD countries, where 'subsidies' are primarily reduced taxes, the link should be the weakest. In fact we found, that in OECD countries, the weighted average subsidy rate does not correlate with the oil price so we did not scale the subsidy rate in OECD countries from the 2014 for the low oil price world. For non-OECD countries, we used the linear regressions in panels (b), (d), and (f) in Supplementary Figure 2 and scaled the subsidy rate based on the difference in the oil price from 2014 and 2015. (For GIZ data, we used the difference in the oil price from 2012 to 2015 since the GIZ data came from 2012.)

For production subsidies, we performed a similar analysis for OECD and non-OECD countries (Supplementary Figure 3). What we found was that in OECD countries, production subsidies do not follow the oil price whereas in non-OECD countries they do. Thus, we scaled production subsidies down for non-OECD countries for the low oil price scenario but not for OECD countries using the same method described in the paragraph above.

Supplementary Text 5 *OECD dataset*

The OECD dataset[4] includes approximately 140 billion USD_{2005} in 2014 of 'budgetary support measures' to fossil fuels. In our analysis, we include approximately 90% of all consumer, producer and "general services" support measures (both budgetary transfers and tax expenditure mechanisms). We exclude measures which are already counted in the IEA dataset on consumer fossil fuel subsidies or are particularly small and not represented in our models. When in doubt we included a subsidy. In this section we list the cases which we excluded. In all cases of exclusion, the subsidy values are small and as a result would not affect our results.

We exclude subsidies related to "Labor" or "Stockholding" which are not specifically represented in our models. (Labor accounts for about a half a billion USD_{2005} in 2014 and there are only a couple of stockholding measures reported which amount to under 0.2 billion USD_{2005}. While we included measures related to "Knowledge" that were focused on exploration and development of new fossil resources, we excluded those focused on research and development. (These R&D measures amounted to less than 1 billion USD_{2005} in 2014). We also excluded tax breaks on natural gas in transportation (which amounted to less than 0.09 billion USD_{2005}) since we do not represent the tax regime in the transport sector. Additionally, we excluded the scant electricity generation subsidies in OECD countries since these usually go to subsidize cleaner production technologies such as cogeneration plant, combined heat and power, or in the case of Korea even for renewables generation. These subsidies amounted to about half a billion dollars in 2014. The electricity generation subsidies in non-OECD countries are captured in the IEA dataset except for Brazil. For Brazil, for all models except MESSAGE, we allocate these subsidies to the end-use electricity use based on 2013 consumption levels.

Supplementary Text 6 *Carbon price discussion*

The 'average carbon price' is a common metric to measure how expensive mitigation is in a given scenario (see ref. 77). The reason it is useful to take an average carbon price is that carbon prices change over time; this metric averages out the effort needed to reach a given stabilization target. We follow the methodology from the IPCC WGIII[77] and measure the average carbon price in our study period (2020-2050) using a 5% discount rate. All five models in our study ran a 550 ppm CO_2eq stabilization target by 2100 with and without subsidies under low oil prices. We report this range in the main paper and the model results in Supplementary Table 16. In addition, using the MESSAGE and REMIND model, we ran a set of scenarios with the 550 ppm CO_2eq stabilization target under high oil prices (Supplementary Table 17). Under high oil prices, the absolute effect of subsidy removal on the carbon price would be comparable but the relative decrease would be larger since the required carbon tax is generally lower under high oil prices. Using MESSAGE, we tested the sensitivity of the results impact to a more stringent concentration target (450 ppm CO_2eq by 2100). The absolute decrease in the carbon tax in these scenarios is larger because there are more subsidized fossil fuels (oil and gas) vis-à-vis less subsidized fossil fuels (coal) in the system. Under the 450 ppm stabilization target, there is actually more oil and gas relative to coal compared to in the 550 ppm stabilization target. However, in the 450 ppm stabilization target since the carbon tax is so much higher, it results in a lower relative decrease in the necessary carbon tax (Supplementary Table 17).

Supplementary Text 7 *Different Baseline assumptions*

One question is would our results hold up under different assumptions about Baseline developments namely different trends in GDP, technological developments, and demographic, economic, technological and resource availability assumptions. To test this, we used the shared socio-economic pathways (SSPs) designed to reflect a wide range of uncertainties in long-term climate scenarios[78-81]. The SSP scenario design relies on the principle of "internally-consistent" scenarios meaning that assumptions should be varied in a way that makes sense with how other variables change[82]. For example, a scenario with resource scarcity would have higher rates of technological development.

We modelled the effect of subsidy removal in WITCH and IMAGE for three SSPs: SSP1 ('Sustainability World' – with lower energy demand, fossil fuel use and emissions), SSP2 ('Middle of the Road') and SSP3 ('The Regional Rivalry' – with higher energy demand, fossil fuel use and emissions). The results reported in this paper are in agreement with the ones obtained in SSP2. This set of assumptions represents the biggest challenge for climate change mitigation (SSP3), the most optimistic developments for climate change mitigations (SSP1) and an intermediate path (SSP2). SSP3, or the 'Regional Rivalry – Rocky road' scenario is characterized by high energy demand and fossil-fuel use with a material-intensive economy, low GDP growth and slow technological change. In contrast, the SSP1, or the 'Sustainability' scenario is characterized by lower fossil fuel use and energy demand through rapid improvements in low-carbon technologies and dematerialization of the economy and higher GDP growth. In the middle of these two extremes is the SSP2 scenario, or 'Middle of the Road' scenario which represents a continuation of current trends (and is comparable to the assumptions we use in the core set of scenarios in the paper). The reason these three scenarios are useful to test the robustness of the findings in our paper is that they allow us to explore if our emissions and energy findings are robust under scenarios with significantly higher emissions and energy demand (SSP3) and significantly lower emissions and energy demand (SSP1)[83]. Since we can compare them to various SSP implementations of the NDC scenarios[36], we can also use this scenario set-up to investigate relationship between the impact of subsidy removal and the NDCs.

The emissions and energy system impacts of subsidy removal in SSP1 and SSP3 are very similar to the ones reported in SSP2 (Supplementary Figures 14-17). However, the projected emission reductions from implementing the NDCs are different which in some cases changes the relationship between the NDCs and the effects of subsidy removal (Supplementary Text 7). In particular, the effects of implementing NDCs in India$^+$ and in the Rest of Asia region become comparable to the effects of subsidy removal. In SSP3, the effect of implementing the NDCs becomes comparable to the effect of subsidy removal in India$^+$, but in Latin America and Russia$^+$ the NDCs would deliver stronger emission reductions than subsidy removal

We find that at the global level, varying the SSP assumptions has a minimal effect on the emissions impacts of subsidy removal (Supplementary Figure 14). Varying the SSP assumptions, however does change the emission impact of NDCs relative to the relevant SSP Baseline. This is because many of the NDC commitments are relative to 2005 emission levels. In SSP1, the projected emission reduction from implementing the NDCs is lower and therefore fossil fuel subsidy removal achieves an effect closer to the lower estimate of the NDCs (Supplementary Figure 14). In this case, subsidy removal would deliver 1.9 Gt of CO_2 emissions reductions from fossil fuels and industry compared to 2.4 Gt reductions of the minimum level from the unconditional NDCs. However, an SSP1 world would represent a distinct departure from historical trends with lower fossil fuel resource use and rapid improvements in technological development and energy intensity[83]. If, on the other hand, we are actually moving towards an SSP3 world, which is characterized by very high emissions from high fossil fuel use and low technological development, the difference between fossil fuel subsidy removal and NDCs would be even greater.

At the regional level, varying the SSP assumptions has a very small impact on the emissions effect of subsidy removal (Supplementary Figure 14). However, in a few regions, varying the SSP assumptions can change the NDC impact enough to change the relationship between subsidy removal and NDCs. The most prominent example of this effect is in India+ whose main NDC target emission intensity. Under SSP1 in India+, the emission reduction from NDCs is lower than in SSP2 because it is primarily defined in terms of emissions intensity reduction relative to the 2005 level. In contrast, under the SSP3 scenario in India+, under the NDC scenario, emissions actually increase because fossil fuels become cheaper globally which leads to carbon leakage (see also Methods). In Russia+ and Latin America, NDCs have the largest impacts under SSP3 assumptions because they are largely defined in terms of historical emission levels (e.g. 1990 levels for Russia and 2005 for Brazil) so subsidy removal may have a smaller effect on emissions than NDCs under this type of a Baseline. The final region which can change the qualitative results is for the Rest of Asia which sees lower emission reductions from NDCs under SSP1 which would be comparable to those achieved from subsidy removal.

Varying the SSP assumptions changes the quantitative results of effect of subsidy removal on final energy demand and the energy mix but not the qualitative results (Supplementary Figure 15 – Supplementary Figure 17). The biggest effect is the larger decrease in demand from subsidy removal in WITCH, which has flexible demand and inflexible supply, under SSP3 assumptions (compared to the core scenario with SSP2 assumptions). This is due to the relatively higher energy demand assumptions under SSP3 and the relatively higher demand to supply flexibility in WITCH (see Supplementary Text 2). Note that we did not test the robustness of the full model range under different Baseline assumptions thus the full range of impacts was not explored with this sensitivity (in particular, the models/regions which have a positive emission impact from subsidy removal – see main text for more discussion).

Supplementary Text 8 *Decoupling oil and gas prices*

One of the assumptions in our scenarios is the coupling of oil and gas prices in all world regions except North America. This is to reflect the fact that since the shale gas revolution, natural gas and oil prices in the U.S. have sharply de-coupled while remaining coupled elsewhere[84-87] where natural gas contracts continue to be pegged to oil prices[88,89]. However, there is intense debate as to whether or not the de-coupling of oil and natural gas prices will continue and spread globally[90-97].

Given the uncertainty about the relationship between the oil and natural gas prices, the question naturally arises, how would our results hold up under oil and natural gas de-coupling? Our findings remain valid if gas prices do not rise with oil prices in the future. Globally, the emissions effect of subsidy removal under de-coupled oil and gas prices is minimal (Supplementary Figure 17). De-coupling of oil and gas prices is likely to have more noticeable (but still modest) effects in oil and gas exporting regions (Supplementary Figure 18 – Supplementary Figure 21). Similar to the core scenarios, emission and energy demand effects of subsidy removal in MENA and Russia+ remain lower in IMAGE than in other models as gas remains competitive even without subsidies. In Russia+ with high oil and low gas prices, final energy demand remains essentially un-changed after subsidy removal (Supplementary Figure 19).

In MESSAGE, the emissions and energy effects of subsidy removal are somewhat higher in most world regions in this scenario under the decoupling scenario as compared to the standard subsidized scenario under high oil prices (and high gas prices) but they are still lower than the NDCs and generally within the range of values from the other models. This is because with lower gas prices there is more subsidized gas in the system. As a result, subsidy removal generally leads to a greater (Supplementary Figure 20 and Supplementary Figure 21). While in most regions, this leads to more emission reductions, in MENA, MESSAGE models slightly lower emission impacts of subsidy removal under decoupled oil and gas prices, which are still higher than the non-conditional NDC of that region and are within the range of values provided by other models; because the gas is replaced by coal following subsidy removal under low gas prices (Supplementary Figure 18 and Supplementary Figure 20).

Supplementary Text 9 *Higher production subsidies*

We used the WITCH model to run a third sensitivity with higher production subsidies based on a dataset from the non-profit organizations Overseas Development Institute (ODI) and International Institute for Sustainable Development (IISD)[5,6]. These references cover only G20 countries, but they include measures which the OECD does not include as subsidies and thus arrive at much larger estimate for production subsidies. In ref. 5, the authors report subsidies for each of the G20 countries; extrapolating this to the world (using average subsidy rates for each fuel and global production amounts), they estimate global production subsidies to be about 92 billion USD_{2005} in 2013[98]. Using these global averages and a systems dynamic model with a single global region, ref. 5 estimates that removing all production subsidies would lead to a reduction of about 1.1 Gt CO_2 emissions per year. The results in our paper are not directly comparable to their work because our results include consumer subsidies (which are three to five times larger depending on the oil price) and are based on an energy-economy model with distinct regions rather than a single-region systems dynamic model.

In order to use a comparable set of assumptions, we first took a weighted average of the national data from ref. 5 for the WITCH regions. For the Middle East region, there was no nationally-available data. So we started with the subsidy rate available for Russia and adjusted it until the total global subsidies matched the total global production subsidies for 2013 which ref. 98 report. We then ran two sets of scenarios with higher production subsidies (under both high and low oil prices). In these scenarios, production subsidies are about 96 billion USD_{2005} in the base year compared to 21 billion in the core scenarios USD_{2005}. We didn't scale production subsidies down as we do in the core scenarios since this is a sensitivity and since we don't have historical data for this dataset to establish such a scaling relationship.

We find that the higher production subsidy assumptions have a minimal impact on our results (Supplementary Figure 22 – Supplementary Figure 25). Higher production subsidies lead to slightly lower CO_2 emissions from fossil fuels and industry and lower final energy demand (Supplementary Figure 22). The decrease in demand from subsidy removal is somewhat larger than our core scenario under low oil prices (Supplementary Figure 23) where the production subsidies are about nine times higher than our core scenario (Supplementary Table 18).

Supplementary Text 10 *Distribution of poor in subsidizing countries*

Fossil fuel subsidy removal in oil and gas exporting regions would not only be likely to have the biggest emissions effect but it may affect fewer poor people than in other middle- and low-income regions. Our analysis shows that both the absolute number and the relative share in population of those living under $3.10/day is significantly smaller in the regions which are the highest subsidizers (MENA, Russia$^+$, Latin America) and where removing fossil fuel subsidies would have the largest emission impacts (Supplementary Table 19). These regions, where only 4% of those living under $3.10/day live, account for about 2/3 of global subsidies. In most countries, energy subsidies account for larger shares of poor people's incomes[76] even though they are criticized for 'leaking' benefits to higher income groups[99,100]. The distributional impacts of subsidy removal is influenced by the specific allocation of subsidies[99,101] and the approach to their reform[102], which is out of scope of this study. Nevertheless, a first order analysis clearly shows that fewer poor are likely to be affected by subsidy removal in energy exporting regions than in other lower- and middle-income regions.

Supplementary References

1. International Energy Agency. *World Energy Outlook 2011*. (Organization for Economic, 2011).
2. International Energy Agency. *World Energy Outlook 2014*. (OECD/IEA, 2014).
3. International Energy Agency. *World Energy Outlook 2016*. (OECD/IEA, 2016).
4. OECD. *OECD Companion to the Inventory of Support Measures for Fossil Fuels 2015*. 1–66 (OECD, 2015).
5. Gerasimchuk, I. *et al. Zombie Energy*. 1–111 (IISD, 2017).
6. Bast, E., Doukas, A., Pickard, S., van der Burg, L. & Whitley, S. *Empty promises*. (ODI, 2015).
7. IMF. *Energy subsidy reform*. 1–68 (International Monetary Fund, 2013).
8. Coady, D., Parry, I., Sears, L. & Shang, B. *How large are global energy subsidies?* 1–42 (International Monetary Fund, 2015).
9. Coady, D., Parry, I., Sears, L. & Shang, B. How Large Are Global Fossil Fuel Subsidies? *World Dev* **91,** 11–27 (2017).
10. G20. *Joint report by IEA, OPEC, OECD and World Bank on fossil-fuel and other energy subsidies: An update of the G20 Pittsburgh and Toronto Commitments*. 1–14 (2011).
11. Skovgaard, J. The devil lies in the definition: competing approaches to fossil fuel subsidies at the IMF and the OECD. *Int Environ Agreements* **17,** 341–353 (2017).
12. *The Political Economy of Energy Subsidy Reform*. 1–273 (World Bank, 2017).
13. Victor, D. G. *The Politics of Fossil-Fuel Subsidies*. (Global Subsidies Initiative and International Institute for Sustainable Development, 2009). doi:10.2139/ssrn.1520984
14. Lockwood, M. Fossil Fuel Subsidy Reform, Rent Management and Political Fragmentation in Developing Countries. *New Political Economy* **20,** 475–494 (2015).
15. Aidt, T. S. Political internalization of economic externalities and environmental policy. *Journal of Public Economics* (1998). doi:10.2307/23606123?ref=search-gateway:b42e7841f03120b66dfeb323570c5fb2
16. Binder, S. & Neumayer, E. Environmental pressure group strength and air pollution: An empirical analysis. *Ecological Economics* **55,** 527–538 (2005).
17. Fredriksson, P. G., List, J. A. & Millimet, D. L. Bureaucratic corruption, environmental policy and inbound US FDI: theory and evidence. *Journal of Public Economics* **87,** 1407–1430 (2003).
18. Schwanitz, J., Piontek, F., Bertram, C. & Luderer, G. Long-term climate policy implications of phasing out fossil fuel subsidies. *Energy Policy* **67,** 1–13 (2014).
19. Burniaux, J.-M. & Chateau, J. *Mitigation Potential of Removing Fossil Fuel Subsidies*. **853,** (2011).
20. Jewell, J. *et al. DELIVERABLE No 3.1Report on improving the representation of existing energypolicies (taxes and*

subsidies) in IAMs. 1–46 (2015).
21. British Petroleum. *BP Statistical Review of World Energy June 2013*. 1–48 (British Petroleum, 2013).
22. Enerdata. *Energy prices*. (Enerdata intelligence and consulting, 2014).
23. International Energy Agency. *Energy prices and taxes*. 1–422 (OECD/IEA, 2013).
24. Wagner, A. *International Fuel Prices 2012/2013*. (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 2014).
25. IFC. *Solar Lighting for the Base of the Pyramid - Overview of an Emerging Market* . 1–80 (International Finance Corporation, 2010).
26. Pachauri, S. *et al.* Pathways to achieve universal household access to modern energy by 2030. *Environ. Res. Lett.* **8,** 024015 (2013).
27. International Energy Agency. *Natural Gas in India*. 1–56 (OECD/IEA, 2010).
28. LBNL. *Key China Energy Statistics: 2012*. 1–68 (Lawrence Berkeley National Laboratory, 2012).
29. Mahangar. Mahangar gas website. (2014). Available at: http://www.mahanagargas.com/Content.aspx?Mkey=Mjk=&lKey=Mw==. (Accessed: 17 March 2014)
30. International Energy Agency. *International Energy Agency energy statistics*. (IEA, 2013).
31. World Bank. World bank databank. (2014).
32. International Energy Agency. Energy Subsidies. *iea.org* (2017). Available at: http://www.iea.org/statistics/resources/energysubsidies/. (Accessed: 2nd May 2017)
33. Bauer, N. *et al.* Global fossil energy markets and climate change mitigation – an analysis with REMIND. *Climatic Change* (2013). doi:10.1007/s10584-013-0901-6
34. UNFCCC. *FCCC/CP/2015/7: Synthesis Report on the Aggregate Effect of the Intended Nationally Determined Contributions*. (UNFCCC, 2015).
35. Rogelj, J. *et al.* Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* **534,** 631–639 (2016).
36. Rogelj, J. *et al.* Understanding the origin of Paris Agreement emission uncertainties. *Nature Communications* **8,** ncomms15748 (2017).
37. Fricko, O. *et al.* SSP2: A middle of the road scenario for the 21st century. *Global Environmental Change* (2016).
38. Terton, A., Gass, P., Merrill, L., Wagner, A. & Meyer, E. *Fiscal Instruments in INDCs*. (International Institute for Sustainable Development, 2015).
39. International Energy Agency. Online Database for Energy Subsidy Data. (2013).
40. International Energy Agency. *World Energy Outlook 2015*. 1–718 (OECD/IEA, 2015).
41. Kriegler, E. *et al.* Diagnostic indicators for integrated assessment models of climate policy. *Technological Forecasting & Social Change* **90,** 45–61 (2014).
42. Edelenbosch, O. Y. *et al.* Transport fuel demand responses to fuel price and income projections: Comparison of integrated assessment models. *Transportation Research Part D* 1–12 (2017). doi:10.1016/j.trd.2017.03.005
43. IMF. *World Economic Outlook database*. (International Monetary Fund, 2016).
44. International Energy Agency. World Energy Statistics and Balances. (2016).
45. WRI. *CAIT Climate Data Explorer: Paris Contributions Map*. (World Resources Institute, 2015).
46. JRC/PBL. *EDGAR version 4.2 FT2012*. (Joint Research Centre of the European Commission/PBL Netherlands Environmental Assessment Agency, 2014).
47. Gütschow, J., Jeffery, M. L., Gieseke, R. & Gebel, R. The PRIMAP-hist national historical emissions time series. *Earth System Science Data* **8,** 571–603 (2016).
48. Grubler, A. *et al.* in *Global Energy Assessment - Toward a Sustainable Future* 99–150 (2012).
49. Pachauri, S. *et al.* in *Global Energy Assessment - Toward a Sustainable Future* 1401–1458 (2012).
50. World Bank. *World Bank Databank*. (World Bank Group, 2017).
51. Supple, D. *Units & Conversions Fact Sheet*. 1–2 (MIT Energy Club, 2007).
52. Capros, P. *et al. The GEM-E3 Reference Manual*. (E3M Lab Institute of Communications and Computer Systems National Technical University of Athens, 2013).
53. Institute of Communication Computer Systems (ICCS). *GEM-E3*. (ADVANCE IAM Wiki, 2013).
54. Karkatsoulis, P., Siskos, P., Paroussos, L. & Capros, P. Simulating deep CO2 emission reduction in transport in a general equilibrium framework: The GEM-E3T model. *Transportation Research Part D* 1–16 (2016). doi:10.1016/j.trd.2016.11.026
55. van Vuuren, D. P. Energy systems and climate policy-long-term scenarios for an uncertain future. (PhD Thesis, Utrecht University, 2007).
56. Stehfest, E. *et al. Integrated Assessment of Global Environmental Change with IMAGE 3.0*. (PBL The Netherlands Environmental Assessment Agency, 2014).
57. Messner, S. & Strubegger, M. *User's guide for MESSAGE III, Working Pater WP-95-069*. (International Institute for Applied Systems Analysis (IIASA), 1995).

58. Riahi, K., Grubler, A. & Nakicenovic, N. Scenarios of long-term socio-economic and environmental development under climate stabilization. **74,** 887–935 (2007).
59. Riahi, K. *et al.* in *Global Energy Assessment: Toward a More Sustainable Future* 1203–1306 (Cambridge University Press, 2012).
60. IIASA. *MESSAGE.* (ADVANCE IAM Wiki, 2013).
61. Keppo, I. J. & Strubegger, M. Short term decisions for long term problems - The effect of foresight on model based energy systems analysis. *Energy* **35,** 2033–2042 (2010).
62. Wilson, C., Grubler, A., Bauer, N., Krey, V. & Riahi, K. Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Climatic Change* (2012). doi:10.1007/s10584-012-0618-y
63. Amann, M. *et al.* Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. *Environmental Modelling and Software* **26,** 1489–1501 (2011).
64. Rafaj, P., Rao, S., Klimont, Z., Kolp, P. & Schöpp, W. *Emissions of air pollutants implied by global long-term energy scenarios.* 1–34 (International Institute for Applied Systems Analysis, 2010).
65. Messner, S. & Schrattenholzer, L. MESSAGE-MACRO. **25,** 267–282 (2000).
66. Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmos. Chem. Phys.* **11,** 1417–1456 (2011).
67. Luderer, G. *et al.* Description of the REMIND Model (Version 1.6). 1–44 (2015).
68. Bosetti, V., Carraro, C., Galeotti, M., Massetti, E. & Tavoni, M. WITCH: A World Induced Technical Change Hybrid Model. *Environmental Modelling & Software* **27,** 13–37 (2006).
69. Emmerling, J. *et al. The WITCH 2016 Model.* (Fondazione Eni Enrico Mattei (FEEM) and Centro Euromediterraneo sui Cambiamenti Climatici (CMMC), 2016).
70. Havlík, P. *et al.* Global land-use implications of first and second generation biofuel targets. *Energy Policy* **39,** 5690–5702 (2011).
71. Schäfer, A., Kyle, P. & Pietzcker, R. Exploring the use of dynamic linear panel data models for evaluating energy/economy/environment models — an application for the transportation sector. *Climatic Change* **136,** 141–154 (2014).
72. Goodwin, P., Dargay, J. & Hanly, M. Elasticities of road traffic and fuel consumption with respect to price and income: a review. *Transport reviews* (2004). doi:10.1080/0144164042000181725
73. Espey, M. Gasoline demand revisited: an international meta-analysis of elasticities. *Energy Economics* **20,** 273–295 (1998).
74. Dargay, J. & Gately, D. The demand for transportation fuels: Imperfect price-reversibility? *Transportation Research Part B: Methodological* **31,** 71–82 (1997).
75. International Energy Agency. *World Energy Outlook 2013.* 1–708 (OECD/IEA, 2013).
76. Inchauste, G. & Victor, D. G. in *The Political Economy of Energy Subsidy Reform* (eds. Inchauste, G. & Victor, D. G.) 1–44 (World Bank, 2017).
77. Clarke, L. *et al.* in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Edenhofer, O. et al.) 413–510 (Cambridge University Press, 2014).
78. van Vuuren, D. P. *et al.* The Shared Socio-economic Pathways: Trajectories for human development and global environmental change. *Global Environmental Change* **42,** 148–152 (2017).
79. Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* **42,** 153–168 (2017).
80. O'Neill, B. C. *et al.* A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change* **122,** 387–400 (2013).
81. Kriegler, E. *et al.* A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Climatic Change* **122,** 401–414 (2014).
82. Schoemaker, P. Scenario planning: a tool for strategic thinking. *Sloan management review* (1995).
83. Bauer, N. *et al.* Shared Socio-Economic Pathways of the Energy Sector. *Global Environmental Change* **42,** 316–330 (2017).
84. Ji, Q., Geng, J.-B. & Fan, Y. Separated influence of crude oil prices on regional natural gas import prices. *Energy Policy* **70,** 96–105 (2014).
85. Geng, J.-B., Ji, Q. & Fan, Y. The impact of the North American shale gas revolution on regional natural gas markets_ Evidence from the regime-switching model. *Energy Policy* **96,** 167–178 (2016).
86. Wakamatsu, H. & Aruga, K. The impact of the shale gas revolution on the U.S. and Japanese natural gas markets. *Energy Policy* **62,** 1002–1009 (2013).
87. De Bock, R. & Gijon, J. G. *Will Natural Gas Prices Decouple from Oil Prices Across the Pond?* (International Monetary Fund, 2011).
88. Stern, J. International gas pricing in Europe and Asia_ A crisis of fundamentals. *Energy Policy* **64,** 43–48 (2014).

89. Choi, G. & Heo, E. Estimating the price premium of LNG in Korea and Japan_ The price formula approach. *Energy Policy* **109,** 676–684 (2017).
90. Asche, F., Oglend, A. & Osmundsen, P. Gas versus oil prices the impact of shale gas. *Energy Policy* **47,** 117–124 (2012).
91. Erdős, P. Have oil and gas prices got separated? *Energy Policy* **49,** 707–718 (2012).
92. Villar, J. A. & Joutz, F. L. *The Relationship Between Crude Oil and Natural Gas Prices.* 1–43 (Energy Information Administration, 2006).
93. Caporin, M. & Fontini, F. The long-run oil-natural gas price relationship and the shale gas€revolution. *Energy Economics* **64,** 511–519 (2017).
94. Brown, S. & Yücel, M. K. What drives natural gas prices? *Environmental Modelling & Software* (2008).
95. Batten, J. A., Ciner, C. & Lucey, B. M. The dynamic linkages between crude oil and natural gas markets. *Energy Economics* **62,** 155–170 (2017).
96. Brigida, M. The switching relationship between natural gas and crude oil prices. *Energy Economics* **43,** 48–55 (2014).
97. Hartley, P. R., suffix, K. B. M. S. I. & Rosthal, J. E. The Relationship of Natural Gas to Oil Prices. *Environmental Modelling & Software* **29,** 47–65 (2008).
98. Bassi, A. M. & Gerasimchuk, I. Zombie energy subsidies bulk amount.
99. del Granado, F., Coady, D. & Gillingham, R. The unequal benefits of fuel subsidies: A review of evidence for developing countries. *World Dev* **40,** 2234–2248 (2012).
100. Koplow, D. in *Energy Poverty: Global Challenges and Local Solutions* (eds. Halff, A., Sovacool, B. K. & Rozhon, J.) 316–337 (Oxford University Press, 2014).
101. Rao, N. D. Kerosene subsidies in India: When energy policy fails as social policy. *Energy for Sustainable Development* **16,** 35–43 (2012).
102. Durand-Lasserve, O., Campagnolo, L. & Chateau, J. Modelling of distributional impacts of energy subsidy reforms. (2015). doi:10.2307/20797986?ref=search-gateway:8097e513643b18ca0b889c6f014adc9f