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Report on improving the representation of existing energy policies (taxes and subsidies) in IAMs

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1. Introduction

Achieving a sustainable energy transition requires a rapid phase out of today's fossil fuels and rapid introduction of clean energy technologies. However, achieving such a change means overcoming interests and policies which are embedded in and support existing energy systems. Arguably, one of the main policy instruments supporting fossil fuels today is subsidies. End-use subsidies to fossil fuels and electricity consumption amount to some $500 billion or about 0.7% of global GDP (IMF 2013; International Energy Agency 2013b). Can a sustainable transition be achieved in the face of these distortionary policy measures supporting the status quo?

In the last five years there has been an increasing policy focus on phasing out fossil fuel subsidies. In 2009, G20 leaders committed to "rationalize and phase-out ... fossil fuel subsidies" (G20 2011). In the wake of this commitment, there has been increasing scientific attention and resources on understanding the fossil fuel subsidy landscape as well as the role these policies play in hindering growth in renewable energy and improvement in energy efficiency and what impact subsidy removal would have on the energy system.

For the most part, current-generation integrated assessment models do not depict energy subsidies (or taxes). However, these policies have major implications on the perceived cost of greenhouse gas abatement. Thus, Task 3.2 in ADVANCE aims to contribute to the understanding of the impact that energy taxes and subsidies have on the cost of climate change mitigation and what the climate impact would be of removing energy subsidies. We build on two recently-published databases of energy subsidies (International Energy Agency 2013b; OECD 2013) and three recent modelling papers on the energy, cost and climate impacts of subsidy removal (Schwanitz et al. 2014; International Energy Agency 2012b; Burniaux and Chateau 2011). From a scientific perspective, the current study goes beyond these recent advances by preparing subsidy and tax data in such a way that will enable a multi-model comparison of the impacts of subsidy removal.

The focus of Task 3.2 has been on model development and integrating the empirical and modelling advances into the participating integrated assessment models. So far, this task has included three main activities: data compilation and processing; pioneering implementation in the MESSAGE model; and initial experimentation in successor models. Section 2.1 documents the data compilation. Section 2.2 describes the methodology for the pioneering implementation in MESSAGE, as well as strategies for implementation in successor models.[1] Section 3 then discusses initial scenario results from implementation in the pioneering model, MESSAGE. Section 4 presents conclusions and the next steps for this ongoing project.

[1] The collaborative working paradigm adopted within all tasks of the ADVANCE project is one of initial experimentation and analysis with a single, "pioneering" model, followed by adoption, adaptation and potential improvement in successor models.

2. Methodology

2.1 Data set comprising energy prices, taxes and subsidies

The ADVANCE data set is a compilation of data from three main sources: Enerdata on energy prices and taxes; IEA data on energy prices, subsidies, energy production and energy use; BP data on primary energy prices for globally traded fuels; GIZ on pump prices for gasoline and diesel and national level data on energy prices. The compilation aimed for **global** coverage (i.e., all countries), which represents a novel contribution of this project. Where multiple data sources were identified for a given value, the most comprehensive data source (generally Enerdata) was used, and any gaps were filled in by less comprehensive data sources (e.g. IEA price data for Member countries, sector-specific reports and finally national data sources to fill in any remaining gaps). Wherever possible, price data used the average price from 2006 to 2010, whereas for the subsidy and tax data the most recent year was used (generally 2012 or 2011). 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 (weighted averaging). In all cases, the data were converted to USD2005/GJ using the World Bank Inflation index[2] and the energy conversion factors listed in the supporting material to this document (Appendix A.1).

2.1.1 Price data

In order to be able to effectively model subsidy removal, the prices in the model have to approximate prices which are seen in reality. This section discusses the data sources and methods for estimating current primary energy prices globally as well as end-use prices in different regions and sectors. These data are then used to calibrate the model for the subsidy removal runs.

Primary energy prices

The primary energy price data comes from the BP Statistical Review of World Energy 2013[3]. All prices were converted to USD2005. Primary energy prices were calibrated using the average price from 2006-2010 corresponding to the benchmark listed in Table 1.

[2] Available at: http://data.worldbank.org/indicator/FP.CPI.TOTL.ZG/countries/1W?display=graph.
[3] British Petroleum. 2013. *BP Statistical Review of World Energy* June 2013. London: British Petroleum. Original data can be downloaded here: http://www.bp.com/content/dam/bp/excel/Energy-Economics/statistical-review-2014/BP-Statistical_Review_of_world_energy_2014_workbook.xlsx

Table 1 Benchmark prices for primary energy price calibration

Fuel in model	Benchmark	Notes
crude oil	Average spot price of Brent (2006-2010)	The Brent and WTI prices are the two most important oil prices in the market. Brent represents sour crude and WTI represents sweet. The difference between these two spot prices over our time period is ≤3%, below our level of precision.
natural gas (piped)	Average price of German natural gas imports (2006-2010)	Most of today's bilateral gas trade primarily goes from Russia (or Former Soviet Union) to Eastern and Western Europe. This price best represents the piped gas market. Additionally, with greater market liberalization Eastern Europe will most likely converge on the Western European price.
natural gas (LNG for non-US)	Average price of Japan's LNG imports (2006-2010)	There are really two LNG markets in the World: the US one and everything else. Most recently, these two markets have been diverging with the shale gas development in the US.
natural gas (LNG for US)	Average price of US LNG (2006-2010)	see above
coal	Average of Northwest European Market	This is the most liquid coal market by far in the world. The IEA uses an "OECD coal price index" in their World Energy Outlook, but their coal expert has said that this index tracks very well with the Northwest European market price.

End-use prices

This section describes the data sources and compilation procedure for the end-use prices which are also summarized in Table 2. Wherever possible, end-use prices represent the average price from 2006-2010, except in cases in which we only had data for a single year or one of the years was missing.

Table 2 Summary of primary data sources and volumetric averages where appropriate for end-use price data. See text for more details

	Residential/Commercial	Industrial	Transportation
Oil	Volumetric average between LPG and light fuel oil: - LPG from IEA and Pachauri et al. (2013) - Light fuel oil price for residential from IEA, Pachauri et al. (2013) and heating oil price from Enerdata	Volumetric average between heavy and light fuel oil: - Light fuel oil and heavy fuel oil for industry from IEA - Light fuel oil and heavy fuel oil price from Enerdata	Volumetric average for gasoline (95-octane) and diesel: - Prices are compiled from Enerdata, the IEA and the GIZ dataset
Coal	Enerdata for "Households" and IEA residential price	Enerdata for "Industry" and IEA industrial price	–
Natural gas	Enerdata for "Households" and IEA residential price	Enerdata price for "Industry" and IEA industrial price	–
Electricity	Enerdata for "Households" and IEA residential price	Enerdata price for "Industry" and IEA industrial price	–

Residential/Commercial (R/C)

The two main oil products used in the Residential/Commercial sector are liquefied petroleum gases (LPG) and light fuel oil (what the IEA calls gas/diesel oil and Enerdata calls heating oil). In fact over 80% of global oil product demand in the sector comes from these two products alone (about 40% from each). Thus, the oil price which we use to calibrate the R/C sector is a volumetric average of LPG prices and light fuel oil prices using energy data from the IEA for the residential and commercial sectors. LPG prices are reported by the IEA for IEA Member Countries. Additionally, we used LPG prices from Pachauri et al. (2013) for a representative African price of LPG from Ghana as well as a price for India, China and Indonesia. Light fuel oil prices were compiled from the IEA for IEA Member Countries, from Pachauri et al. (2013) for the same four countries (Ghana, India, China, and Indonesia), from IFC (2010) for over 40 sub-Saharan African countries and finally from Enerdata for any remaining countries which Enerdata covers.

The coal, natural gas and electricity prices for the R/C sector were compiled from two data sources: from Enerdata and the IEA for any remaining IEA Member Countries for the corresponding product's price (including taxes) in the "Household" category. There were two big gaps which we also filled using national data for coal and natural gas prices in the R/C sector: the coal price for China was taken from LBNL (2012) and the natural gas price for residential use in India was taken from the Mahangar gas website (2014), which is one of the main suppliers of residential gas use in India.

Industrial

The two main oil products in the Industrial sector are light and heavy fuel oil accounting for 41% and 25%, respectively, of oil demand in this sector globally. Thus, the oil price for the Industrial sector is a volumetric weighted average of heavy fuel oil prices and light fuel oil prices using energy data from the IEA for the industrial sector. The prices for both heavy and light fuel oil categories are compiled from the IEA for IEA Member Countries and from Enerdata for other countries.

The coal, natural gas and electricity prices for the Industrial sector compiled data from two data sources: Enerdata and the IEA for the corresponding product's price in the "Industry" sector. Additionally, the coal price for China was taken from LBNL (2012). And the natural gas for India was taken from an International Energy Agency report on natural gas in India (2010).

Transportation

The transportation oil product price represents the oil price for road transportation, which accounts for about three-quarters of oil product demand in the transport sector. The oil price in the road-transport sector is a volumetric weighted average of the gasoline (95-octane) price and diesel price. Prices for gasoline and diesel are compiled from Enerdata, the IEA, and GIZ.

2.1.2 Taxes and subsidies

This section discusses the data for tax and subsidy calculations. The tax and subsidy data represents the most recent year for which data were available at the time of data compilation (generally 2011 or 2012). The tax and subsidy data are compiled from the IEA, OECD, Enerdata, and GIZ. The following sections discuss in detail the data compilation process for each type of data.

Subsidies

Energy is subsidized by countries at both the primary (resource extraction) and final (end-use) energy levels. The ADVANCE data set compiles information for both.

Primary energy

The production subsidies come from OECD (2013) and are classified as "producer support" for coal, crude oil and natural gas extraction. The subsidy rate for a given fuel in a particular region is calculated by dividing the sum of all producer support for the most recent year (in billion USD2005) by the total energy that the country produced in that same year (in EJ).

End-use subsidies

End-use subsidies ("consumer support") are compiled from two different data sources: the IEA end-use subsidy database[4] and the OECD's Inventory of Estimated Budgetary Support and Tax Expenditures for Fossil Fuels for OECD countries (OECD 2013).

For OECD countries, the end-use subsidy was calculated using the "consumer support" category in the OECD database. In each case, the consumer support was allocated to R/C, Industry, Transport, Agriculture, Electricity or some combination thereof. Using these bulk subsidy levels for all the sectors and the energy use of each fuel in each sector in a given country, a subsidy rate was calculated for each sector/fuel/country combination. Agricultural subsidies were allocated to the R/C sector.

The subsidy rate for non-OECD countries built on the IEA database which reports subsidy rates for about 40 developing countries. This database only reports the bulk end-use subsidies (in billion USD2005) for oil, gas, coal and electricity so we calculated the subsidy rate as described below. For natural gas, coal and electricity we allocated the bulk subsidy between R/C and Industry using the difference in prices between the two sectors by calculating a "theoretical unsubsidized price" (across both sectors) using the following formula:

$$unsubsidized\ price_f = \frac{Bulk\ subsidy_f + \ Price_{f_I} * Energy_{f_I} \ + (Price_{f_{RC}} * Energy_{f_{RC}})}{Energy_I + Energy_{RC}}$$

where:

f is fuel or carrier (natural gas, coal or electricity)

I is the Industrial sector

RC is the Residential/Commercial sector.

Then for each sector, the fuel-specific subsidy rate was calculated using the difference between the theoretical price and the actual observed price:

$$subsidy\ rate_{f_S} = \ Price_{f_S} - unsubsidized\ price_f$$

where:

S is a sector (either Industrial or Residential/Commercial).

Note that where the theoretical unsubsidized price was higher than the actual price in only one of the sectors, the whole subsidy was allocated to the sector with the actual price lower than the theoretical price.

For oil, the subsidy rate for the transport sector was calculated using the price differential between the GIZ (2011) pump price for gasoline (95-octane) and diesel in a given country and the oil product spot price from the IEA for gasoline and diesel in the United States of America. (We also considered using the price in Rotterdam, but the

[4] Available here: http://www.iea.org/subsidy/index.html.

average difference in the two prices is under 5%, which is below our level of precision.) The oil subsidy for other sectors takes into account these transport subsidies and was calculated using the following formula:

$$oil\ subsidy\ rate_{I-RC} = \frac{Bulk\ subsidy_o - (subsidy\ rate_T * Energy_{o_T})}{Energy_{o_I} + Energy_{RC}}$$

where:

$oil\ subsidy\ rate_{I-RC}$ is the subsidy rate for oil in the Industry and Residential/Commercial sectors,

$subsidy\ rate_T$ is the subsidy rate in the transport sector calculated from GIZ database, and

$Energy_{o_S}$ is the total quantity of oil used in the Transport, Industrial and Residential/Commercial sectors.

This calculation resulted in some subsidy rates for oil which were unrealistically high and exceeded the global price of crude oil. Thus, in addition we capped the oil subsidy at 25$/GJ because this is approximately the maximum subsidy rate for other sector/fuel combinations which have less uncertainty than oil subsidy rates. The most likely cause for this disparity is that the oil subsidies are being applied to more sectors then we are taking into account (for example, oil in electricity generation in oil-producing countries). We are currently digging deeper into this disparity and have been in touch with the team which compiled this dataset in order to identify the root of the problem and address it.

Taxes

The tax rate data are a compilation of three data sources: the IEA[5], Enerdata and GIZ.

For coal and electricity in R/C and Industry, the tax rate is compiled from Enerdata and IEA. The tax rate from Enerdata is calculated as the difference between Constant price (taxes incl.) and Constant price (taxes excl.) for "Industry" and "Households", corresponding to Industrial and the R/C sectors, respectively. The IEA tax rate for coal and electricity in R/C and Industry is taken from the "Total tax" for Household and Industry use, respectively. Enerdata does not report any tax rates for natural gas, so for natural gas the IEA database was used.

The tax rate for oil products in transport is a volumetric weighted-average of the tax rates for gasoline and diesel in the road transport sector using the energy use for gasoline and diesel in the transport sector. The tax rates are from Enerdata (the difference between Constant price incl. and Constant price excl. taxes); from the IEA database (total tax for Automotive diesel fuel and Premium Unleaded 95 RON), and finally, from the GIZ database of pump prices for gasoline and diesel and the difference with the spot price for gasoline and diesel in the United States market.

[5] In this case, the IEA data are from International Energy Agency (2013a).

2.1.3 Regional aggregation and energy data

All price, tax and subsidy data are collected at the national level and then aggregated to the regional level for modelling purposes. Regional aggregation is done by volumetrically weighting the national data (in $/GJ) for each sector-fuel combination using energy data (GJ) from the IEA for 2010. The volumetric mean is calculated only using the data for countries for which there is data. In other words, if a region has twelve countries but we only have price data for five of those countries for a given fuel and sector, the volumetric mean is calculated on the basis of those five countries. Mathematically, the volumetric mean for each price, tax or subsidy value v is calculated as follows:

$$v_{f_{S_R}} = \frac{v_{f_{S_c}} * e_{f_{S_c}}}{e_{f_{S_R}}}$$

where:

$v_{f_{S_R}}$ is the price, tax or subsidy value for fuel f in sector S in region R,

$v_{f_{S_c}}$ is the price, tax or subsidy value for fuel f in sector S in country c for each applicable country in region R,

$e_{f_{S_c}}$ is the energy use of fuel f in sector S in country c for each applicable country in region R, and

$e_{f_{S_R}}$ is the total energy use of fuel f in sector S in region R.

Regionally-aggregated price, tax and subsidy data are listed in Appendix A.1 in Tables 5-8. For these purposes, the regional aggregation of the MESSAGE model has been used; see Appendix A.2 for those regional definitions.

2.2 Model implementation of energy price, tax and subsidy data

The initial Section 2.2.1 describes the methodology for the pioneering model implementation in MESSAGE – see Appendix A.2 for a brief description of the model – as well as the scenario design that is the basis of the results that are being presented in Section 3. The MESSAGE implementation can serve as an example for models that are based on the same modelling paradigm, i.e., an energy-engineering type optimization framework (which is soft-linked with a macro-economic model), but may need to be significantly adapted for other modelling paradigms. Therefore, Section 2.2.2 outlines strategies for implementation of energy taxes and subsidies in successor models, which in some cases rely on quite different modelling paradigms than MESSAGE (e.g., system dynamics based simulation models, computable general equilibrium models, endogenous growth models).

2.2.1 Pioneering model implementation in MESSAGE and scenario design

Modelling approach

To carry out a meaningful analysis of energy tax/subsidy policies in MESSAGE, the first step was to ensure that the energy prices (historical) calculated endogenously by the model are consistent with those that have been observed in reality. This needed to be done for the different fuels, regions and sectors of the model. Moreover, price calibration at the primary and final energy levels was handled differently and is discussed in turn below. In all cases, historical price data (meant to reflect the year 2010) was pegged to the 2020 prices calculated within MESSAGE, because due to calibration constraints 2010 prices are not always meaningful.

Historical prices for primary energy commodities (coal, crude oil and natural gas) were compiled from different sources as discussed in Section 2.1. For both oil and coal, there is a single global price, which is meant to reflect the fact that these fuels are globally traded and, thus, there is a global market for each of them. For natural gas, three separate prices were given, reflecting that there is as yet no global market for gas; rather there are fragmented regional markets. From a modelling perspective, this required that we choose which of the three prices/markets are applicable to which of the 11 MESSAGE regions (see Appendix A.2 for a detailed definition of regions in MESSAGE). For the North America and Pacific OECD (largely Japan), Western Europe, and Eastern Europe regions of MESSAGE, this was a fairly straightforward choice, as the three prices are taken from those regions. Then, since much of the gas consumed in Europe originates in Russia and the Caspian region, we chose to benchmark the gas price in the Former Soviet Union (FSU) region of MESSAGE to the historical price for the European market. Then, because they are on the same landmass (and can therefore connected by pipeline infrastructure), we made a simplifying assumption that the gas prices in South Asia and China (Centrally Planned Asia in MESSAGE) could also be benchmarked to the European/FSU gas price. For the other regions of MESSAGE (Sub-Saharan Africa, Latin America, Southeast Asia, and the Middle East and North Africa), we simply assumed that the historical spot market price of LNG is the most representative benchmark – in other words, the same price used for the Pacific OECD region.

The strategy for getting the endogenous MESSAGE prices to be consistent with the historical data relies on the use of "price adjustment factors". Their application is fairly simple. To provide a hypothetical example, if the model calculates the price of a given fuel commodity (say, oil) to be 8 $/GJ within a region, but we know the price to be 12 $/GJ, then a price adjustment factor of +4 $/GJ (= 12 - 8 $/GJ) needs to be applied in order to increase the endogenous MESSAGE price to the observed. In MESSAGE, for the primary energy commodities, we apply these price adjustment factors at the level of the energy extraction (i.e., coal mining, oil and natural gas drilling).[6] More specifically,

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[6] This is akin to saying that as soon as these commodities reach the surface of the Earth, their prices reflect that of the prevailing market (again, global for coal and oil, regional for natural gas). While there are of course exceptions to this paradigm in reality (e.g., factories and power plants built at the site of a

the price adjustment factors feed into the processes as additional variable O&M costs on the respective technologies. We assume that the adjustment factors apply in the base-year (in our case 2020) and then remain constant throughout the entire modelling horizon. Procedurally, we start by running a baseline (no climate policy) scenario with MESSAGE that does not have any price adjustment factors embedded. After the run has finished, we compare the primary energy prices for coal, oil and gas (across each of the 11 MESSAGE regions) to the observed prices that they are being benchmarked against (as mentioned above). Price differences are calculated in all cases (for all fuels within all regions), and these difference are used as the first set of price adjustment factors. Then, a new baseline scenario is run, this time with the price adjustment factors included. Inevitably, the adjustment factors have an impact on the energy system (i.e., the fuels and technologies chosen at all stages of the energy supply chain), and therefore the price dynamics in the model are also different from the previous run. This means that the price adjustment factors need to be revised – in some cases upward, in other cases downward. New price differentials are calculated, and these are added to the price adjustment factors from before. (For example, if the calculated price difference is 0 $/GJ, then the price adjustment factor remains exactly the same. But if it is now -1 $/GJ, then this -1 must be added to the previous adjustment factor to arrive at the new factor.) A third scenario is then run with the newer set of adjustment factors, and the iterative process begins again[7]. With MESSAGE it took a handful of scenario runs before these prices converged.

In addition to benchmarking the model's endogenously calculated primary energy prices to historical data, the same procedure was used for prices at the final energy level (though not at the secondary level). While the procedure is largely identical to the one described above for primary energy prices, there are, however, some important differences when considering final energy consumption in the end-use sectors. The first key difference is that there are many more fuels at the end-use level than at the level of resource extraction – both in terms of model representation and in the historical price data included in the data compilation. Historical data exists for coal, natural gas, electricity and oil products in both the Industry and Residential/Commercial sectors, and for oil products in Transport. The data is regionally disaggregated. Noticeably absent for this list of fuels, for obvious reasons, are "future fuels", such as hydrogen, biofuels, fossil synfuels (CTL/GTL), electricity in transport, etc. To avoid distortions in the competition between established and future fuels it is, based on our experience, also important to consider these fuels when doing the price adjustment (see below). In general, the iterative procedure described above for primary energy prices applies to final energy prices as well. Importantly, the price adjustment factors that are already in the model feed through the system and have an effect on final energy prices, such that

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coal mine or gas field), from the model's point of view this is a straightforward way to capture the dynamics of supply and demand for fuels.

[7] Note also that we have carried out the iterative process described above using some Excel spreadsheets outside the model. This made sense for testing, but other modelers might consider automating the procedure through scripting (either inside or outside the model). Such automation seems entirely possible from our point of view.

the final energy prices calculated by the model are no longer the same as those from a scenario that was run without the adjustment factors. But it is likely the case that further price adjustments are needed. In regions with high taxes on end-use fuels (e.g., oil products in transport in Europe), a highly positive price adjustment factor will still be needed. By contrast, in regions with high subsidies (natural gas in the residential/commercial sector in South Asia), a strongly negative adjustment factor may be needed. Irrespective of the tax/subsidy levels of individual countries/regions, we find occurrences in MESSAGE where the model slightly over- or under-estimates the cost of energy conversion and transmission/distribution at the secondary level (e.g., large industrial consumers will be connected to the high voltage power grid while residential consumers are connected to the low-voltage distribution network for which grid tariffs are substantially different). The price adjustment factors at the final energy level also capture these differences from real-world price dynamics. As before, in MESSAGE we are able to get the endogenously calculated final energy prices of the model to converge to those from the observed data after a handful of iterations. Note that application of the adjustment factors at the final level also has feedback effects on those applied at the primary level.

As alluded to above, it is important that those fuels that are not used in heavy quantities today but that may be in the future (e.g., electricity or natural gas in transport, biofuels or hydrogen in industry or buildings) also have price adjustment factors applied to them. Without including them into the procedure, these "future fuels" will in many cases be dramatically under-priced relative to their competitors. A prime example is electricity for transport in Europe. If the price adjustment factors were only applied to oil products but no effort was made to somehow adjust the prices of electricity, then electricity-based transport would likely be much cheaper than oil-based transport, and the model would move to electricity even in a baseline scenario without climate policy, which happened in MESSAGE. In order to avoid these kind of model artefacts, we use certain "current" fuels as proxies for "future" fuels. For instance, we take the price adjustment factor for oil products in transport (by region) and apply it directly to biofuels, fossil synfuels, and natural gas. Meanwhile, we take the price adjustment factor for electricity in res/com and apply it directly to electricity and hydrogen in transport. Similar decisions have been made to use different fuels as proxies in the industry and res/com sectors (e.g., coal as a proxy for biomass, natural gas as a proxy for hydrogen used for thermal operations, etc.)[8]. One important caveat here is that with MESSAGE, when applying the price adjustment factors from one fuel to another, we have opted not to carry over any subsidies embedded in the adjustment factor. Taxes we do bring over, but not subsidies – they are simply subtracted out of the price adjustment factor. The argument is that future fuels like hydrogen will not be subsidized in the same way that, for example, natural gas is today. This subsidy caveat only applies to a limited number of fuels in particular regions, however.

[8] There are, of course, different arguments to using different fuels as proxies, and modelers should definitely feel free to choose the fuel-mapping that makes the most sense to them and their modeling framework.

Because the MESSAGE framework includes an aggregated macro-economic model, we have also been forced to consider the question of what happens with the savings that accrue from not paying out subsidies to firms. MESSAGE and MACRO iteratively exchange energy service prices and quantities (six categories) and in addition, MESSAGE passes the entire energy system costs of the solution to MACRO (Messner and Schrattenholzer 2000). This enables MACRO to estimate the objective function value of the MESSAGE optimization problem and therefore in its demand response calculate the influence on the energy system costs as calculated by MESSAGE.

Two adjustments of MACRO were necessary when switching to the MESSAGE version with a representation of taxes and subsidies:

1. MACRO had to be re-calibrated to the new MESSAGE baseline scenarios which included adjustments of base year reference prices for the energy service demands and autonomous energy efficiency improvement (AEEI) factors to reproduce the new baseline energy demand trends.
2. While including the impact of taxes and subsidies on prices is important to adequately reflect price information in MACRO as seen by consumers, the energy tax revenues had to be removed from the energy system cost estimate to account for the fact that these are not “real costs”, but rather a redistribution mechanism within the economy. On the other hand, subsidies are taken into account in the cost information passed on to MACRO as they need to be generated from other sources of income. Alternative accounting methods of taxes and subsidies in MESSAGE and MACRO are still subject to research and may affect the magnitude of, for example, the economic impacts of subsidy removal, as shown in Sections 3.1.3 and 3.2.2.

After these adjustments to MACRO, the full model MESSAGE-MACRO is now operational, including the energy tax and subsidy representation.

Scenario design

For the pioneering implementation with MESSAGE, four scenarios were run: one baseline case and one climate policy scenario (stabilization at 550 ppm in 2100), each with and without subsidies. (A pair of 450 ppm scenarios has also been run, but these are discussed only briefly in this report.) Since the modelling approach involved first matching the endogenously calculated prices with the observed data, subsidies are removed (at the primary and final level) by stripping out the subsidy component of the price adjustment factors and then re-running the model. The changes exhibited by the model then represent the impact of removing subsidies.

Table 3 Scenarios in the pioneering implementation discussed in Section 3

Subsidies	Baseline (no climate policy)	550 ppm stabilization	450 ppm stabilization
With subsidies	Baseline	550 ppm	450 ppm
Without subsidies	Baseline w/o subsidies	550 ppm w/o subsidies	450 ppm w/o subsidies

2.2.2 Successor model implementation strategies

The text in this section has been contributed from each of the other modelling teams participating in this work task of ADVANCE (Task 3.2). These teams have already begun working with the data set described in Section 2.1, but scenario results are still forthcoming.

GEM-E3

The precise representation of taxation in CGE models is important since together with the production costs they determine the relative price system that coordinates agents' actions. The GEM-E3 model is calibrated on the GTAP database (v8.1.), which identifies three main categories of taxes/subsidies: (i) factor taxes and subsidies, (ii) trade taxes and subsidies (duties and export subsidies) and (iii) net taxes on production and sales. In GEM-E3 a reconciliation of these taxes with EUROSTAT data on VAT and other indirect taxes is performed in order to maintain consistency with EUROSTAT while ensuring that the national public budget suggested by the GTAP database is unchanged. Owing to data limitations, this action is only performed for the EU28 member states, not for other countries. The energy prices of the model are calibrated based on the energy volumes from the GTAP-E database and the energy transactions from the GTAP monetary input-output (IO) tables[9].

The representation of energy prices, subsidies and taxes will be further improved in GEM-E3 using the output of this ongoing task within ADVANCE (Task 3.2). Our objective is to ensure that energy prices calculated by the model adequately represent the formation of prices in energy markets both at the global level for crude oil, coal and gas and at the country/regional level for all fuels used in final demand sectors (industry, households, services, transport, non-energy uses) and in power generation. At the same time we need to verify that the tax and subsidy rates compiled in the database from IIASA result in plausible revenues/expenditures for the public budget of each country. The energy prices and associated tax system from IIASA will be included in the model ensuring consistency with the GTAP dataset and the overall General Equilibrium framework.

The work of Task 3.2 on energy prices, taxes and subsidies will be complemented by the work on Task 2.3 that regards the "Integration of bottom-up elements in macro-economic models". The objective of Task 2.3 is to split the monetary values of the IO

[9] This calibration procedure is being improved within the ADVANCE project under task 3 of WP2.

tables regarding final energy demand quantities (measured in tonnes of oil-equivalent, TOE) and in energy prices (for fossil fuels and electricity). For the monetary IO tables the GTAP database is used, and the IEA database is used for the derivation of energy quantities for each fuel, sector and country represented in GEM-E3. Ideally these derived energy prices should be broken down in their main constituting parts: i) the cost of production ii) mark-up rates reflecting market power and iii) taxes or subsidies

A first step is to combine the energy prices as derived from the analysis in Task 2.3 with the price/tax/subsidy information compiled in Task 3.2 for the base year (2007 or 2010). Then the following checks will be made:

- Whether the new set of prices lead to consistent energy volumes as compared to the energy balances
- Whether the new set of taxes/subsidies is consistent with the public fiscal revenues and expenditures by country
- How the new set of relative energy prices is formulated
- Whether the implicit tax rates are plausible and consistent with available data

The results on these checks will be communicated to the IIASA team in order to facilitate the computation of taxes/subsidies and ensure overall consistency of the tax system, tax base and public budget. A balancing routine will be used so that prices, energy volumes and taxes will be consistent with the monetary IO tables.

Our focus will be on large tax revenue categories regarding energy taxation or subsidization, e.g. taxation of transport fuels in the EU and Japan, fossil fuel subsidization in Russia and MENA countries, coal prices in China etc. One has also to consider the subsidy equivalent of various hidden subsidies, like tax expenditures, write-offs, bail-outs, preferential interest rates, cross-subsidization.

Once the tax system of the model is updated, a new reference scenario will be implemented with the enhanced GEM-E3 model. The Reference scenario will naturally take a cautious view with regard to future developments of energy taxes/subsidies. We suggest that, the level of energy taxes should remain stable in the base year levels, while a gradual (but not complete by 2050) reduction of energy subsidies will be implemented reflecting current efforts for removal of fossil fuel subsidies in developing regions. The exact definition of alternative harmonized subsidy removal scenarios will be discussed and agreed with the rest working group.

We propose to perform, in addition to the subsidy removal scenarios, alternative simulations to quantify the macro-economic and sectoral implications of policies related with: i) changes in energy price taxation, i.e. change in the level of tax on energy products in developed economies, ii) alternative uses of the public revenues generated from energy subsidies removal (i.e. reduce employers social security contributions, reduction of indirect taxes etc). This will enable us to illustrate the impacts from increasing the precision on computing energy prices.

IMAGE

IMAGE is a recursive-dynamic, simulation model that starts in 1970 and is calibrated on the basis of various IEA data regarding energy demand and supply, sectoral activity levels and estimated primary and secondary fuel prices. Final energy demand per fuel (FE_{ec}) is simulated on the basis of activity levels (Act), structural change (SC) and efficiency parameters (Eff) and secondary fuel prices (p) and, as well as exogenously specified "preference factors" (pf). This latter reflects non-price factors such as environmental policies, strategic considerations of firms/nations or consumer inconvenience.

$$FE_{ec} = \mu * Act * Eff * SC$$

$$\mu = \frac{e^{\lambda * p * pf}}{{}_{ec}\, e^{\lambda * p * pf}}$$

The sectoral energy price of each energy carrier itself at the end-use level (coal, oil, gas, bio-energy, electricity, hydrogen) is calculated based on the primary energy price, energy taxes, the costs of energy conversion throughout the energy supply chain and a correction factor (to calibrate to observed fuel prices).

$$p = p_{prim} + Tax + Conv + Corr1$$

In turn, the resulting demand for primary energy carriers drives the primary fuel prices on the basis of depletion, technology learning and a second calibration factor to correct for price influences other than production costs, such as periods of geopolitical discord.

$$p_{prim} = p_{prim,0} * depl * learn + Corr2$$

In other words: IMAGE has already estimates of energy taxes and prices at the end-use sector level. The calculations of IMAGE start in 1970. This means that also tax and subsidy data is needed for the 1970-2010 period.

In this list we have formulated our implementation plan on the basis of subsequent decisions.

For subsidies, we will add these to the model explicitly, as they are only programmed implicitly as of now as part of the correction factor. Similarly, we will explicitly add the primary energy tax to the primary energy price. And for taxes at the secondary level, we will first compare the existing tax rate levels in IMAGE with those contained in the dataset compiled by IIASA. In terms of implementation strategy, we can more easily absorb the data in case of small differences than in the case of large differences.

Based on our findings, we will then have several options for proceeding further. The preferable option depends on the implementation time-frame, the data and impact on the model outcomes (they are listed in terms of increasing difficulty; decisions on exact implementation will be made during the implementation phases).

- A first option would be to implement and update the tax and subsidy rates without historic re-calibration of existing prices in IMAGE. The analysis would focus on the difference between the old and new model set-ups and the impact of the changes on e.g. the market shares of the different fuels (as a result market shares and prices would no longer match the historical observed one – and the model can only be used to compare two different cases in terms of dynamics).

- A second option is to implement and update the tax and subsidy rates in such a way that we subtract the difference from the correction factor on the final energy level and from correction factor on the primary energy level so that the sum remains the same (i.e., so that the historical prices in IMAGE match those from historical data sets). While this does not require a total re-calibration of the energy demand model, it does, however, pose a problem for the 1970-2005 period, because no tax and subsidy data is provided in the IIASA data set. One way to create the a historical set, is to assume that the current IMAGE data is correct for the historical trend (1970-2005) and we scale all values to match the data in the new tax/subsidy dataset (which represent averages of the 2006-2010 period).
- A third option is to implement the new data as a new estimate in the model. This option is the most involved as it would require re-calibration of the energy demand model on the primary and final energy level through the correction values for the 1970-2010 period. Once the simulated market shares reflect that of the historic data, we can once again fix the preference factors throughout the entire modelling horizon.

The tax/subsidy data is available on a per-country basis, and the pioneering model (MESSAGE) aggregated this information to its native 11 regions. IMAGE calculates with 26 regions and therefore a new aggregation will be done on the basis of a weighted tax/subsidy price per country by total energy use. For new energy carriers such as bio-energy (at the primary and final level), hydrogen and electricity (and the end-use/final level), price correction factors assumptions need to be consistent with those for the other carriers for which data is available.

The implementation plan greatly depends on the data and its impact on the model, but once we have improved the representation of taxes and subsidies in the model, we will be able to run new scenarios with and without subsidies. This would mean removing the subsidy component in the price calculations at either the primary of final level. Assessing the effect of subsidies in both baseline and climate policy scenarios is scheduled to be part of the ADVANCE Work Package 3, with first results by January 2015.

REMIND

The REMIND model since its model version 1.4 includes a representation of final energy taxes and subsidies that we plan to improve within Task 3.2 of the ADVANCE project.

Existing taxes and subsidies representation in REMIND

The existing representation of taxes and subsidies in REMIND, as well as an exploration of the implications of a subsidy phase-out in baseline and climate policy scenarios are documented in the article Schwanitz et al. (2014).

Subsidy rates on four different fuel categories are considered differentiated by region: solid fuels, gaseous fuels, stationary use of electricity and liquids, both stationary and for transport. For taxes, the same fuels are covered in general. Due to data availability issues, we so far consider only transport fuel taxes in all regions and furthermore include taxes for stationary fuels in the USA and EUR regions. Unlike in the case of subsidies, taxes for liquids are therefore differentiated by stationary and transport use, respectively, with much higher rates for transport use. While not being important for the first few time steps, we decided to tax transport electricity at the same rate that liquid transport fuels are taxed in the respective region[10]. As electricity has a better tank-to-wheel efficiency than liquid fuels - about factor 3 - this implies that the taxation on the useful energy level still favours electricity.

In a few instances, the negative net of tax and subsidy rates as calculated from the historical data exceeded the models initial positive fuel supply price, leading to a negative consumer price. In these cases, the subsidy rate was lowered so that the effective supply price was not below 25% of the one we had in the model before the implementation of taxes and subsidies.

With the existing representation of taxes, subsidies, system inertias we achieve a reasonable, albeit not perfect match between modelled and real-world prices. We so far have not adjusted our endogenous prices for primary and final energies with constant mark-ups to exactly match historic prices. We instead tried to identify drivers for the higher prices observed in real markets and subsequently tried to represent those in the model, so that prices closer to the historic record emerge endogenously. For example, fossil fuels are binned into different quality grades, each with specific extraction costs. Implementing a bound on the maximum rate of increase and decrease of yield per grade causes the earlier start of exploration of lower grades, so that prices rise. While this approach brought prices in REMIND closer to the observed market prices, prices in general are still lower (especially for oil).

Our tax/subsidy implementation is budget-neutral. Technically, we achieve this by an iterative procedure. In each iteration, each region gets a lump-sum payment (fixed

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[10] We decided so, because we only had fuel taxes available for all regions. With the new more comprehensive dataset also covering electricity taxes globally, we will consider changing that tax level to that of household electricity use, as it will technically be very difficult to apply different electricity tax rates to households' stationary and transport uses.

during each solution) that exactly offsets the loss due to paid taxes as in the previous iteration. The difference between the lump-sum rebate and the positive taxes paid quickly converges to zero, as the overall size of the tax/subsidy payments is in the order of a few percent of total output. This way, the solution takes the marginal of the tax/subsidy rate into account while being budget-neutral.

Planned improvements of the representation in the course of the ADVANCE project

The ADVANCE project Task 3.2 offers a great opportunity for our team to review and improve on the representation of taxes and subsidies.

The first step we will take is to compare the tax and subsidy rates as compiled and implemented for the previous work in REMIND with the respective rates in the dataset compiled by IIASA. We will then update the rates used in REMIND where appropriate. To this end, we will both use the spreadsheet calculations for regional aggregation as provided by IIASA, as well as using the full country information and redoing the regional aggregation as part of our input data handling. In order to be able to run the model with different regional settings, we are currently in the process of aggregating all regional data from original country data with harmonized scripts. The added benefit of having the regional aggregation done twice is that this offers a comparison of the two aggregation calculations.

We currently still have to aggregate the disaggregated rates for industry on the one hand and residential and commercial (R&C) on the other for the one generic stationary sector represented in REMIND. At the same time, and related to ADVANCE WPs 2 and 3, we are working on separating the stationary sector into industry and R&C in the REMIND model. After this is finished (probably not yet in 01/2015), we can use the more disaggregated tax and subsidy information. The question of whether or not to implement end-use specific mark-ups to match historic final energy prices will also become more relevant, once the separation is completed.

Parallel to the work on splitting the stationary sector, we will already experiment with adjustment mark-ups on primary and final energy prices in the current version of the REMIND model. We will first compare the endogenous prices in REMIND in the model time step 2010 with the data provided by IIASA. In the REMIND model, initialized with time step 2005, we can run the model without constraints in the time step 2010, so that meaningful prices emerge. In usual policy runs, we however fix the model behaviour until 2010 to a reference scenario with certain constraints in 2010 (like e.g. the Kyoto targets) but without further climate policy constraints beyond 2010.

We will then identify the fuels, sectors and regions, where the difference between historic and model endogenous prices is highest and therefore mark-ups are most relevant. The reason why we currently cannot adjust all prices with mark-ups at the same time is that we so far don't have an automated routine for calibrating the final energy demands over time [11]. This is due to the hard-link between the macro-economy

[11] Similar to the energy demand in MACRO, energy demand in REMIND is directly coupled to assumptions about the temporal evolution of efficiency parameters in the CES production functions. As

and the energy system in REMIND, that makes the calibration of final energy trajectories a much more complicated procedure than in soft-coupled models like MESSAGE, where separate supply prices can be extracted. In markets with strong strategic behaviour, such as crude oil, we are looking into ways of representing resulting price mark-ups via royalties or export taxes in major resource exporting regions (e.g., Middle East, Russia).

In case that we see that there is a high need for price correction but we still don’t have the infrastructure to implement universal adjustment mark-ups, an alternative could be to scale the tax and subsidy rates accordingly. The absolute amount of subsidies paid/taxes received is no important quantity in our model, as we anyway only look at one representative household per region, for which taxes and subsidies are budget-neutral. Therefore, having lower or higher absolute tax rates than observed is less of an issue, if at the same time the relative importance of the tax/subsidy vis-à-vis the supply price is correct.

TIAM-UCL

Taxes and subsidies have been successfully implemented in MESSAGE with an iterative, calibration approach to primary and end-use energy prices, using the database of global prices, taxes and subsidies developed at IIASA for ADVANCE WP3, Task 3.2.

The implementation procedure in MESSAGE has some inherent difficulties and uncertainties, because of the nature of the optimisation model: Every time a price is adjusted between model runs (using a mark-up factor), this changes the balance of the model and so can change the solution (potentially dramatically). When many prices are changed simultaneously, this could change the results at every step to such an extent that the iterations would not converge. The IIASA/MESSAGE implementation has overcome this difficulty by not calibrating the price of all primary energy commodities, not “over constraining” the problem.

Therefore, we propose to test the feasibility of this strategy with a model of similar formulation: TIAM-UCL is a bottom-up partial-equilibrium optimisation model, similar in principal to MESSAGE. We will test whether the procedure undertaken for MESSAGE is replicable for other optimisation-type integrated assessment models. We will also attempt to calibrate all prices and examine the level of coverage that leads to non-convergence and is therefore not possible to calibrate.

Calibrating prices to real-world data throughout the model is likely to lead to baseline scenario results that are different from before, as it has in MESSAGE. We will analyse these results in comparison with MESSAGE and attempt to interpret the change in light of the adjusted prices.

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there is no good way to project these parameters many decades out, for REMIND – just like for the MESSAGE-MACRO model – these parameters are calibrated such that final energy demand trajectories emerge that fulfill certain expectations about future demand levels. Mostly, we assume that at similar per-capita GDP levels, similar per-capita final energy demands have to be fulfilled.

The purpose of calibrating prices and implementing taxes and subsidies is to evaluate the impact of tax/subsidy policies on energy transition pathways and the cost of reaching climate targets. In TIAM-UCL we will specify explicitly what the value of subsidies are in the objective function and, by calculating the difference between objective function values (excluding subsidies) when subsidies are present and removed, we can report total cost of global subsidies to the energy system. We will do this with and without global climate targets, and will examine policy scenarios which phase out subsidies, rather than simply representing their binary inclusion or not.

WITCH

To implement observed taxes and subsidies on energy prices in the WITCH model, we first reconsider the calibration process meant to meet observed quantities and prices of different energy sources. In the original procedure, net prices have been used to calibrate to model. The main idea is thus to revise this procedure taking into account fiscal instruments to better reflect real observed prices after taxes and subsidies. However, for instruments and tax bases that are significant, we find that it is important to take into account the fiscal burden or revenues and thus the recycling of the tax/subsidy. Therefore we explore **two methods** of implementing them in the model depending on the characteristics on the tax base and instruments used.

The regional tax and subsidies are computed as regional averages aggregating over countries weighted by the respective energy consumption. For policies on Energy Production, we use the data directly for oil, coal, and natural gas. For policies on final energy demand, given that the residential, commercial, and industrial sector (with the exception of electricity production and personal transportation) are summarized in one single non-electric energy demand sector in WITCH, we compute the weighted average tax or subsidy rate of residential and industrial demand (first we aggregate the final demand across sectors for each countries and second across countries according to the WITH region definition). For transportation, we apply the averaged tax (or subsidy in the case of the middle east) on gasoline and diesel on all oil products used in the transportation sector in WITCH. This comprises use in conventional combustion engine cars as well as hybrid and plugin-hybrid cars.

Getting the prices right in WITCH

In the WITCH model as of 2014, regional differences in primary energy prices are already taken into account to reflect transportation costs and regional markets (e.g., for the markets of natural gas and (to a lesser extent) coal. Moreover, inter-regional price differences are accounted for. This is done in the static calibration of the CES production function nest based on observed quantities and prices in the calibration year 2005 where regional adjustments are accounted for. The global prices of fossil fuels that are computed by the WITCH model (for 2010, 5.4$/GW for Natural Gas, 9.1$/GW for Oil, and 2.5$/GW for Coal)[12]. To account for transportation cost and regionally

[12] When comparing these prices with the data compiled by IIASA (as an average over 2006-2010), the values are in line for coal and oil (2.9 $/GJ and 11.7 $/GJ respectively), whereas for Natural gas our price

fragmented markets, they are adjusted across regions according to time-invariant mark-ups that are added or subtracted from the global market price.

Prices and Subsidies are not accounted for in this adjustment. Therefore, our **first approach** is to adjust the regional price mark-ups according to the data collected and aggregated according to the regional structure of WITCH. During the static calibration procedure of the model, which aims at calibrating the model parameters of the nested production function in order to replicate price and quantity data in the base year (2005), resulting prices are iteratively updated as to match observed prices of the current WITCH model across regions from the WITCH team's own model calibration. Given that the sectorial disaggregation is focusing mostly on the supply side, we consider fiscal instruments on the demand side as acting on the fuels fed into the power system and non-electric sector, which covers both industrial and residential demands. However, in order to avoid negative prices, we have to adjust the empirical values found in some regions and sectors.[13]

In particular for regions with high subsidy rates and energy demand such as some countries in the Middle East, the fiscal burden from subsidies (or revenues from taxation in other cases) can be significant. The revenue recycling of those taxes and subsidies can be substantial and should be considered in a General Equilibrium type of model. Therefore we also implement a **second approach** where we introduce the estimated taxes and subsidies in the model in a similar fashion as e.g., a carbon tax: The revenue (or amount spent) is considered at the budget constraint of the representative household in each region. The budget constraint in WITCH thus comprises the aggregate production via the nested production function minus costs of energy, emission reductions, and investments and equalizes the level of consumption in each region. Thus, the resulting level of taxes/subsidies is again added/subtracted to/from the budget constraint. This way, within the inter-temporal optimization of regional consumption, the taxes and subsidies are automatically considered in the fuel choice, and the wedge driven between net prices and prices considering taxes and subsidies will reflect the prices net of taxes and subsidies. This seems in particular relevant for the taxation of gasoline and diesel where the tax rates are highest and adjusting only prices would lead to a loss of GDP without accounting for tax revenues.

For the final implementation we thus consider using a hybrid approach considering primary energy taxes and subsidies on the level of price mark-ups in the calibration of the model and the second approach for transport and final energy demand.

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is comparably lower (5.4$/GJ compared to the proxies of the three regional markets US (6.0 $/GJ), East-Asia (9.1$/GJ) and Europe (8.5$/GJ) as reported by IIASA.

[13] Doing some preliminary test runs, we found that the data for electricity and coal subsidies on final energy could be used directly. However, for subsidies on oil and gas, the comparably high values led to infeasibilities in the model due to implicit negative prices in some regions/sectors. Therefore, we applied a maximum subsidy of 2 $/GJ for those two fuels. For the final runs, a careful check of the data will provide useful information of the cause of this issue.

Subsidy removal scenarios

Additionally, and in particular to study the effect of subsidies, we run the model under different scenarios about the phasing out of subsidies over time in concordance with the other models.

3. Scenario results and discussion: Initial analyses with the MESSAGE model

As the model within the ADVANCE project tasked with the pioneering implementation of energy taxes and subsidies, initial analyses have been carried out with the MESSAGE-MACRO integrated assessment framework. The scenario results discussed in this section therefore focus entirely on insights generated thus far using MESSAGE. Future collaborative work within ADVANCE will rely more on the involvement of the other modelling teams (REMIND, IMAGE, GEM-E3, TIAM-UCL and WITCH). As exhibited in Section 2.2.2, this work is already underway.

To showcase the impacts of subsidy-removal policies on energy supply and demand, greenhouse gas emissions and climate change, and the wider economy, model analyses have up to this point primarily focused on two scenario pairings, for a total of four scenarios: two baselines and two 550 ppm CO2-eq cases. (The 450 ppm scenarios, which have also been run, are discussed only briefly.) In both cases, we explore scenarios where present-day subsidy rates are retained throughout the century, as well as cases where they are fully removed in 2020 and kept that way until 2100. All four scenarios assume the same energy system development path through 2020, a path based on the “reference baseline.” Only after 2020 do the subsidy-removal and/or climate policies take effect.

3.1 Baseline scenarios

The reference scenario in the current analysis is a counterfactual baseline without any climate policies whatsoever from 2010 onward. This essentially assumes the failed implementation of countries’ energy and climate policies that are currently on the books or in the early stages of implementation (i.e., lack of success in translating Copenhagen pledges into actions and measures). The reference baseline does, however, preserve all current energy subsidy policies (i.e., rates at their current levels; see Section 2.1) in all countries throughout the entire time horizon of the model (until 2100).

In terms of the socio-economic assumptions driving energy service demand growth in the modelling (e.g., for mobility, lighting, heating, etc.), the reference baseline can be considered a “middle-of-the-road” scenario, wherein median projections for both population growth and gross domestic product are used (Figure 1). Further explanation can be found in the Global Energy Assessment (Riahi et al. 2012), the scenarios for which share the same underlying drivers of energy demand growth that are assumed here.

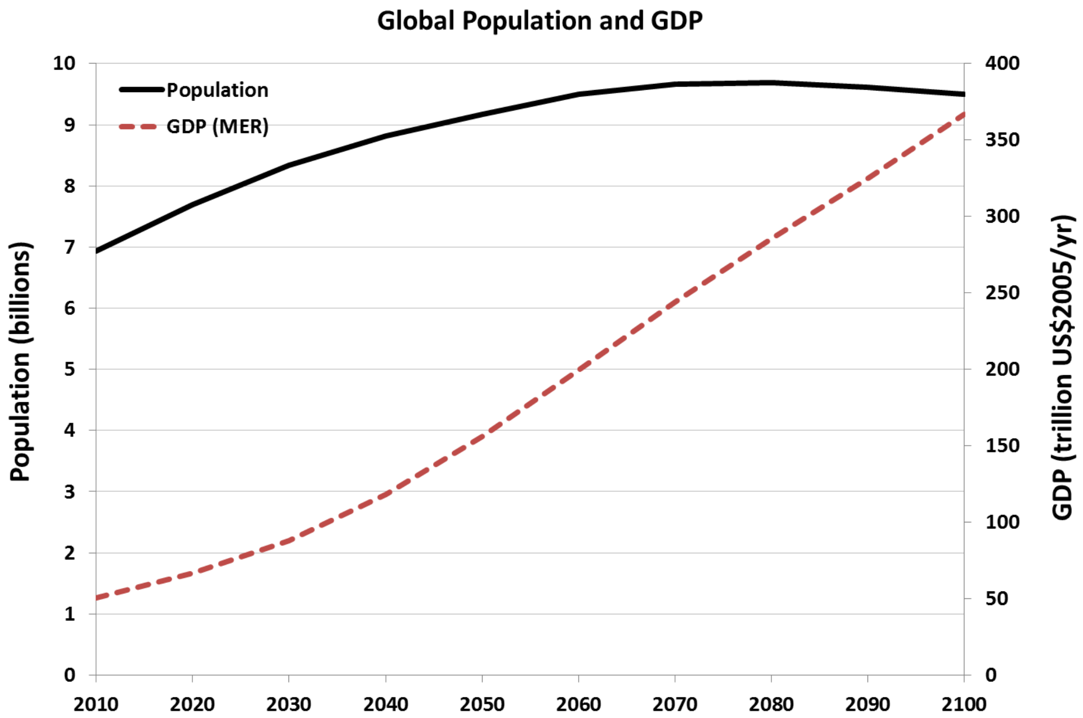

Figure 1. Global population and gross domestic product (GDP) trajectories in the reference baseline. GDP is measured in terms of market exchange rates (MER) across countries.

3.1.1 Energy system development in a future where current subsidy rates are preserved (reference baseline)

In the reference baseline, the energy system develops in a way one would typically expect, with the current mix of fuels and technologies remaining largely the same going forward. This implies the continued dominance – and considerable growth – of fossil fuels (coal, oil and natural gas; all without carbon capture and storage). Meanwhile, nuclear power declines by mid-century; and renewables (mainly biomass, solar and wind), although increasingly considerably from their small base today, still comprise a minority share of primary energy supply for decades to come. These trends, which are shown in Figure 2, are not surprising, given that fossil fuels are the least expensive option for producing energy in the future, according to the assumptions embedded in the model. In the absence of a carbon price, and moreover due to the depressed prices of fossil fuels in certain regions (because of subsidies), coal, oil and gas are likely to remain dominant for the foreseeable future.

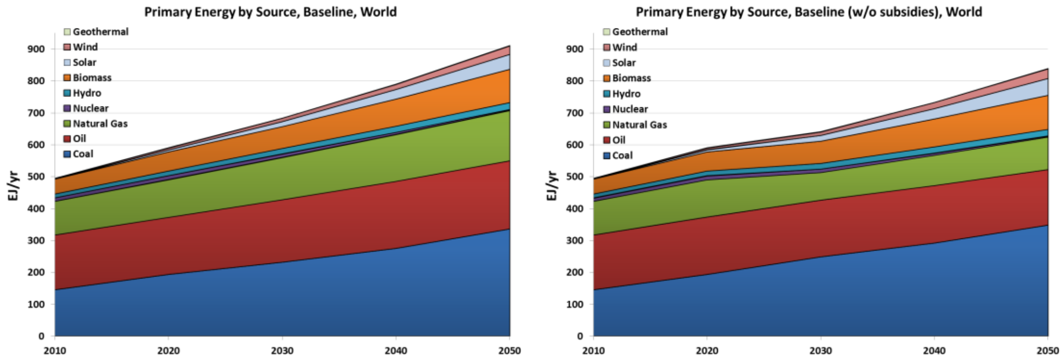

Figure 2. Global primary energy by source in the reference baseline and in the baseline where subsidies are removed.

A similar story can be told for fuels consumed at the final energy level by end-use devices (e.g., cars, trucks, consumer appliances, industrial boilers, etc.). Coal, oil products and gases continue to dominate, though there are some noticeable developments by mid-century (Figure 3). For instance, electricity consumption grows significantly, while both biofuels and synthetic fuels produced with coal or natural gas ("fossil synfuels") increase considerably from their presently low base.

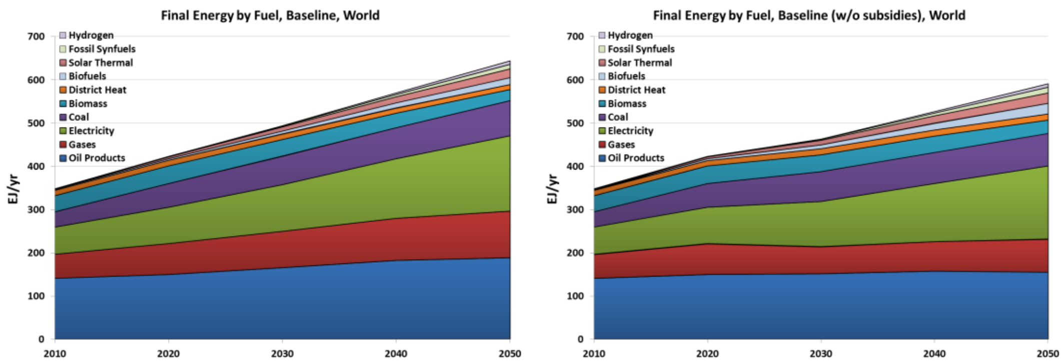

Figure 3. Global final energy by fuel type in the reference baseline and in the baseline where subsidies are removed.

Owing to the continued reliance on fossil-based energy forms to meet growing service demands, the reference baseline sees emissions of carbon dioxide continuing their steep upward trajectory for long into the future (Figure 4). The long-term (by 2100), global warming impacts of such high emissions growth paths would be sizeable: atmospheric concentrations of CO2 (including all forcing agents) climbing to 990 ppm CO2-eq, total radiative forcing (globally averaged) increasing to 7.0 W/m2, and around a 4 °C rise in surface temperatures (globally averaged) relative to pre-industrial levels. (For reference, CO2 concentrations and radiative forcing levels in 2010 have been estimated at around 420 ppm CO2-eq and 2.18 W/m2, respectively.[14]) The climate change impacts of such warming would be significant (IPCC 2013).

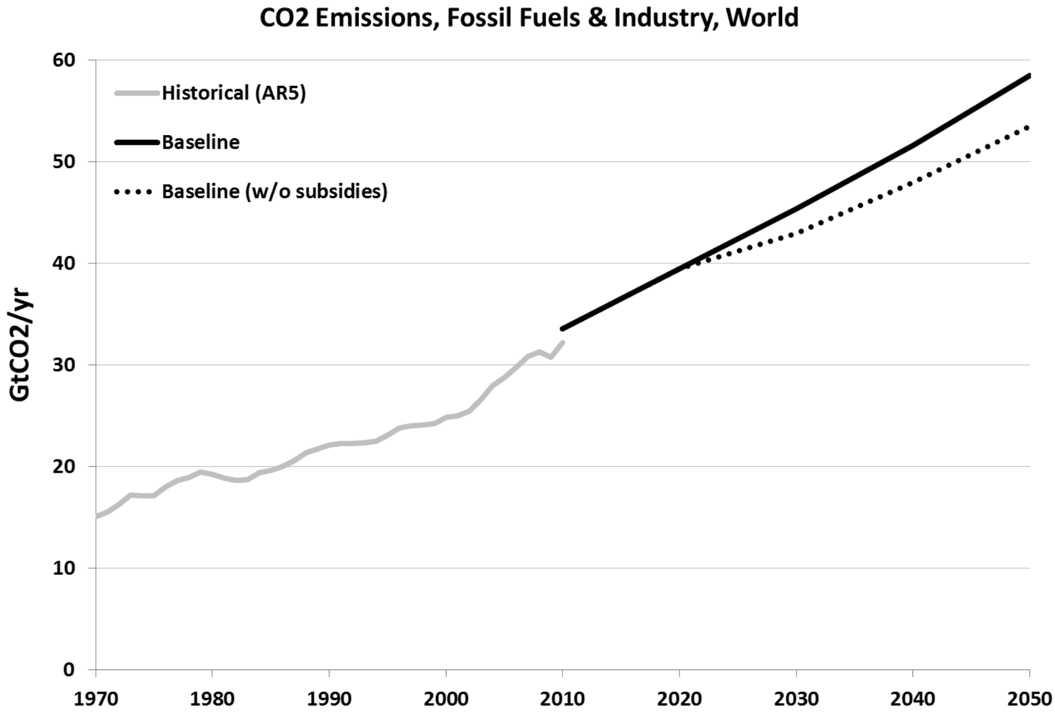

Figure 4. Global CO2 emissions from fossil fuels combustion in energy and industry (FF&I) in the reference baseline and in the baseline where subsidies are removed. Historical CO2 emissions (FF&I) are also shown for reference; source: IEA (2012a) and JRC/PBL (2013).

3.1.2 Impacts of subsidy-removal policies on energy supply and demand

Compared to the counterfactual reference baseline described above, the imposition of policies to remove energy subsidies can have important, non-trivial impacts on energy supply and demand. This is illustrated in Figure 2 (primary energy) and Figure 3 (final energy), where, in addition to results for the reference baseline, global energy system developments are also shown for a baseline scenario in which subsidies are fully removed in 2020 and kept that way until 2100.

At the primary level, subsidy-removal primarily leads to lower use of crude oil and natural gas globally (Figure 5). This is to be expected since these are the two most heavily subsidized fuels today – by way of both producer and consumer subsidies on crude oil, oil products and natural gas. Filling the void left behind by reduced consumption of oil and gas, renewables (biomass, solar, wind) and nuclear experience a small increase in use. The bigger changes, however, are found on the end-use side of the energy system. Because certain consumers in regions with currently high subsidies

[14] Based on the authors' own calculations using the MAGICC6 model, which is integrated with MESSAGE.

begin to pay market prices for their fuels, there is a much greater incentive to slow energy demand growth through efficiency and conservation efforts. The results are especially pronounced in countries of (i) Russia & other Reforming Economies, and (ii) the Middle East & North Africa (Figure 5).[15]

Results at the final energy level are consistent with the above-described changes in the primary energy mix. Subsidy-removal leads to lower use of oil products and gases globally (Figure 6), while alternatives like biomass and biofuels, fossil synfuels and solar thermal contribute modestly to the void left behind. In addition, a clear impact of subsidy-removal policies appears to be a marked increase in energy efficiency and conservation, resulting from consumer responses to higher prices. On this point, however, the model results tend to be quite region-specific. In regions where subsidy rates are relatively high today (e.g., Russia & other Reforming Economies and the Middle East & North Africa), we see large reductions in the use oil products, gases and even electricity (Figure 6), as all three energy carriers are heavily subsidized today. In North America, by contrast, where subsidies on energy are extremely small and consumers already pay market prices, there are essentially no changes in the final energy mix. China finds itself somewhere in between these two extremes: the country subsidizes end-use energy at non-trivial levels but not so much that subsidy-removal policies have a dramatic impact on the energy mix. It should be mentioned that these results for China are also representative of countries in Latin America, South Asia, Southeast Asia and Africa, whereas the North America results are representative for countries in Europe and the Pacific OECD (Japan, Australia and New Zealand).

An additional finding from this scenario exercise relates to the impact that subsidy-removal policies have on coal consumption. Because current subsidies for coal are relatively small compared to those for oil, gas and electricity, an across-the-board removal of subsidies further increases coal's economic attractiveness. Add to this the fact that extraction costs for coal are inherently cheaper than for oil and gas, and the scenarios point to greater future coal demand in regions where it is not used heavily today (e.g., Middle East). In certain instances, this would imply increasing imports of coal from abroad, which could have important political ramifications.

[15] Price-induced reductions in energy demand come about through two mechanisms in MESSAGE: (i) increasing efficiency through technology-switching, and (ii) service demand feedbacks from an aggregated macro-economic model. For an explanation of these methodologies, as well as of the regional definitions used in MESSAGE, see Riahi et al. (2012).

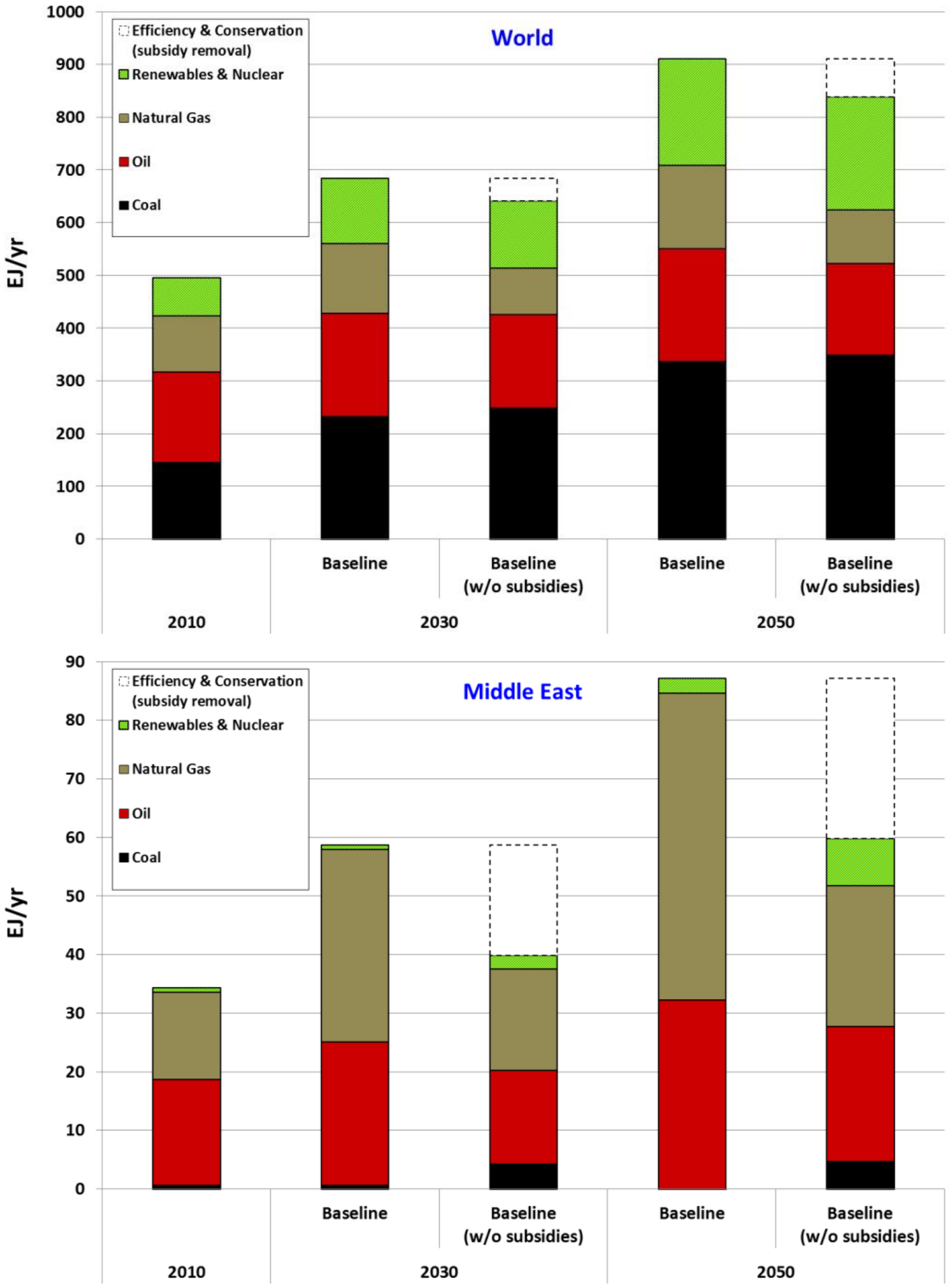

Figure 5. Primary energy by category in 2030 and 2050 in the reference baseline and in the baseline where subsidies are removed. Results for both the world and the Middle East (including North Africa) are shown. The energy mix in 2010 is also displayed for reference. Empty, white blocks in the bars represent the demand reduction effect of removing subsidies and exposing consumers to higher energy prices.

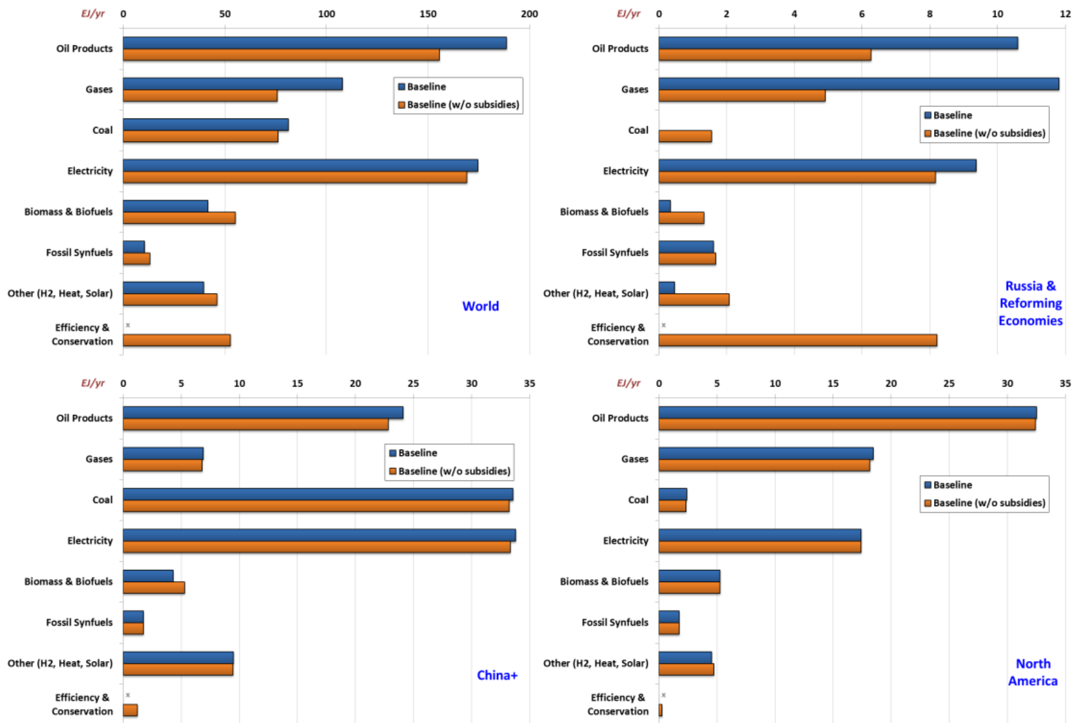

Figure 6. Final energy by category in 2050 in the reference baseline and in the baseline where subsidies are removed. Aggregated results for the world and for several macro-regions are shown. Demand reduction effects of removing subsidies and exposing consumers to higher energy prices are calculated relative to the reference baseline.

3.1.3 Impacts of subsidy-removal policies on the economy

The scenarios modelled with MESSAGE indicate that there are two principal effects of removing energy subsidies in countries where they are today the highest. The net effect of these two determines the overall economic impact (or net welfare impact) of the subsidy-removal policies. On one hand, removing subsidies increases energy prices as seen by consumers; and while this leads to a certain amount of demand reduction, as discussed previously, it may also result in a less expensive energy system. The second effect relates to large sums of money saved by national governments when they are no longer paying out subsidies. How these funds are recycled into the broader economy can significantly influence the overall economic impact of the subsidy-removal policy.

The macro-economic module of MESSAGE is an aggregated single-sector model (see Appendix A.2), which does not allow assessing tax revenue and/or subsidy saving and recycling schemes in detail (e.g., redirecting funds to infrastructure projects, lowering income taxes, etc.)[16]. As discussed in Section 2.2.1, the accounting of taxes and

[16] Note that in a later phase of the ADVANCE project, the computable general equilibrium (CGE) model GEM-E3, with its detailed representation of the global macro-economy, will be used to analyse different revenue recycling schemes.

subsidies in MESSAGE-MACRO is still subject to research and may influence the magnitude of the economic impacts of subsidy removal as shown below.

Initial findings from MESSAGE indicate that the immediate and full removal of energy subsidies in 2020 and thereafter leads to non-trivial *gains* in economic welfare relative to the reference baseline. More specifically, subsidy-removal leads to an increase in consumption (one major component of GDP) on the order of 1.5 to 2.2% in the years between 2030 and 2050. As illustrated in Figure 7, the gains are largest in earlier time periods but then decrease over time. (Although not yet modelled, it is plausible that a more gradual phase-out of subsidies would result in consumption gains that vary less over time.) Cumulative consumption gains over the period 2020-2050 amount to 1.5% (relative to the reference baseline; discounted back to 2010 at 5% interest). Incidentally, this finding is consistent with previous scenario studies that have analysed subsidy-removal policies using alternative methodologies (see Schwanitz et al., 2014). It is also of a similar magnitude as the consumption *losses* that are often reported by integrated assessment models when analysing stringent climate change mitigation policies, e.g., to stay below the 2 °C target (see Clarke et al. (2014)).

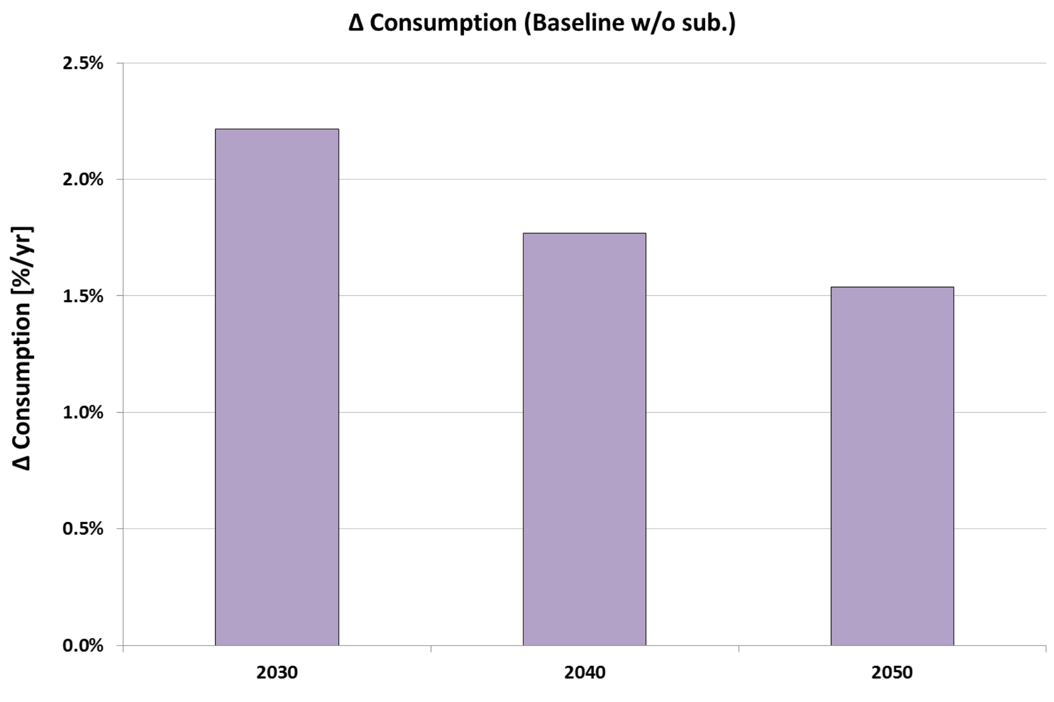

Figure 7. Consumption change in the baseline where subsidies are removed, relative to the reference baseline. Aggregated results for the world are shown. Positive values represent consumption gains; negative values represent losses. Consumption changes for 2020 are not shown because all scenarios are identical up to that year.

3.1.4 Impacts of subsidy-removal policies on carbon emissions and climate

The aforementioned changes in energy supply and demand motivated by subsidy-removal policies have a modest, but noticeable, impact on carbon emissions and, by extension, the global climate. For instance, subsidy-removal leads to global annual CO2 emissions levels in 2050 that are ~11% lower than in the reference baseline (Figure 4). Emissions would still be considerably higher than today, however. The long-term (by 2100), global warming impacts of such high emissions growth paths would be sizeable, albeit somewhat reduced from the reference baseline: atmospheric concentrations of CO2 of 940 ppm CO2-eq (compared to 990 ppm in the reference baseline) and total radiative forcing of 6.7 W/m2 (compared to 7.0 W/m2).

3.2 Climate change mitigation scenarios

As illustrated above, subsidy-removal policies will need to be complemented by stringent climate policies if low-temperature targets, such as 2 or 2.5 °C, are to be achieved in the long term. The question thus becomes: what are the impacts of subsidy-removal policies in a policy environment where mitigation is also a high priority. We attempt to answer this question in MESSAGE by running two alternate versions of a scenario leading to atmospheric CO2 concentrations of 550 ppm CO2-eq by the year 2100. One of these cases preserves all current subsidy rates at today's levels throughout the modelling time horizon while another fully removes these subsidies immediately in 2020.

We find that subsidy-removal leads to only a small reduction in emissions in the 550 ppm case (Figure 8). The reductions up to 2050 are much smaller than in the corresponding pair of baseline scenarios, both in absolute and relative terms. This dynamic is partly due to the way the overarching climate policy is modelled: as a century-long, cumulative budget on all greenhouse gas emissions. (Notably, the impact does show up in reduced carbon prices; see later section.)

As expected, our analyses suggest that stringent climate policies at global scale have a more dominant influence on the future composition of the energy system than subsidy-removal policies (which are concentrated in only a few regions). As exhibited in Figure 8, the more stringent the climate policies, the greater the influence (i.e., the more similar the cases with and without subsidies). Therefore, in the discussion below we only focus on the 550 ppm mitigation scenario, as there still remains a noticeable signal from the subsidy-removal policies under this climate policy framework. In the 450 ppm scenario, the signal largely disappears.

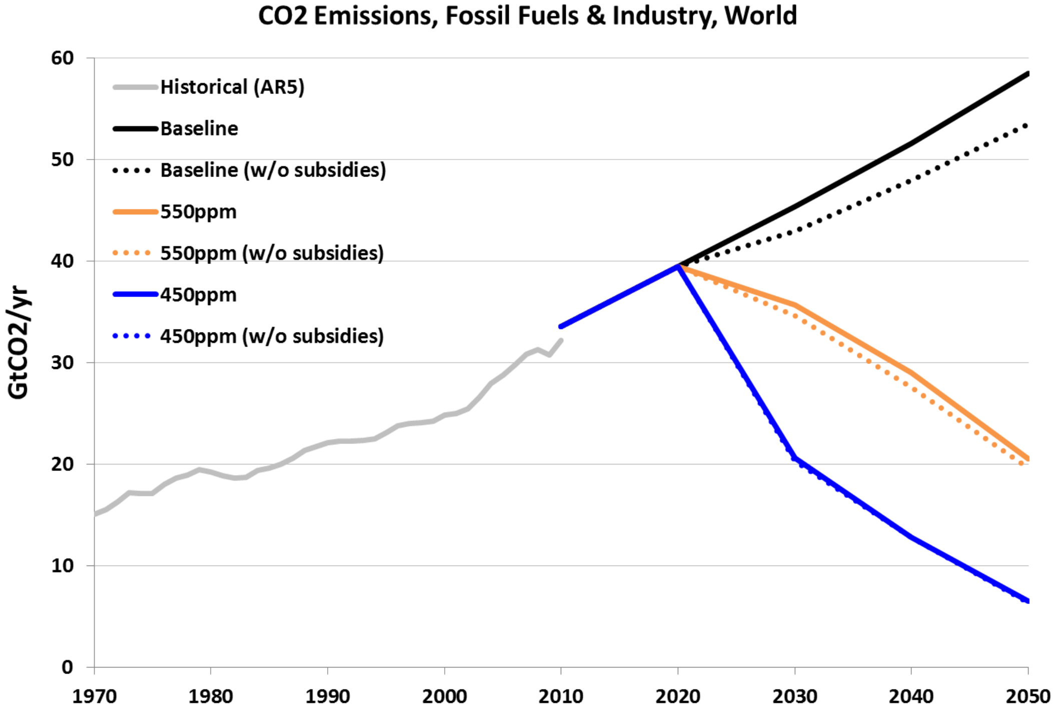

Figure 8. Global CO2 emissions from fossil fuels combustion in energy and industry (FF&I) in the reference baseline and in climate change mitigation scenarios resulting in atmospheric concentrations of CO2 (including all forcing agents) of either 550 or 450 ppm CO2-eq in the year 2100. The emissions impact of removing subsidies is similarly shown for each case. Historical CO2 emissions (FF&I) are also displayed for reference; source: IEA (2012a) and JRC/PBL (2013).

3.2.1 Impacts of subsidy-removal policies on the mitigation portfolio

Although the total additional emission reductions motivated by subsidy-removal policies may be modest in the 550 ppm climate policy scenario, where those reductions come from – in other words, the composition of the mitigation portfolio – does provide useful insights for policy. The MESSAGE scenarios show that subsidy-removal leads to a certain amount of fuel-switching on both the supply and demand sides of the energy system, namely less oil and gas and more renewables and nuclear (Figure 9). These swings indicate that subsidy-removal policies can provide an incremental boost to climate policy efforts, if integrated in an effective way. At the same time, subsidy-removal motivates additional energy efficiency and conservation efforts at the end-use level, on top of those already induced by stringent climate policy measures. In short, because consumers in certain regions (those with large subsidies) now see higher prices for their energy, subsidy-removal policies appear to shift some mitigation from the upstream/conversion sectors to the downstream/demand sectors (transport, buildings and industry). Figure 10 illustrates this for the pair of 550 ppm cases.

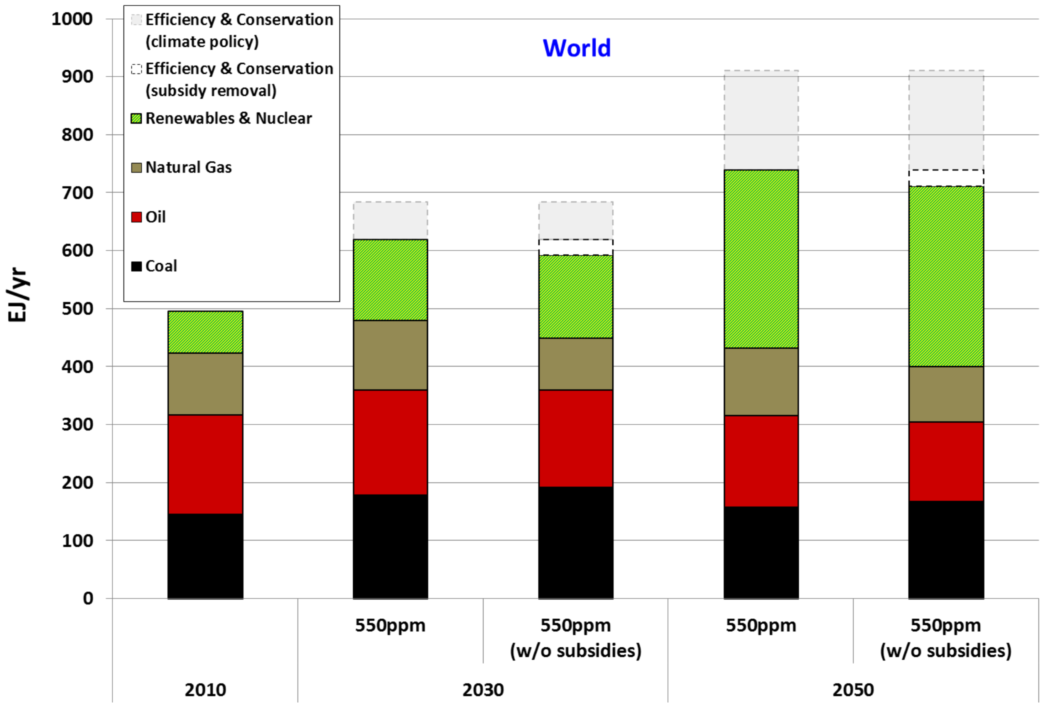

Figure 9. Primary energy by category in 2030 and 2050 in the 550 ppm CO2-eq scenarios (both with and without subsidies applied). Aggregated results for the world are shown. The energy mix in 2010 is also displayed for reference. Empty, white blocks in the bars represent the demand reduction effect of removing subsidies and exposing consumers to higher energy prices. Grey, transparent blocks represent demand reduction effect of climate policies and exposing consumers to a carbon price.

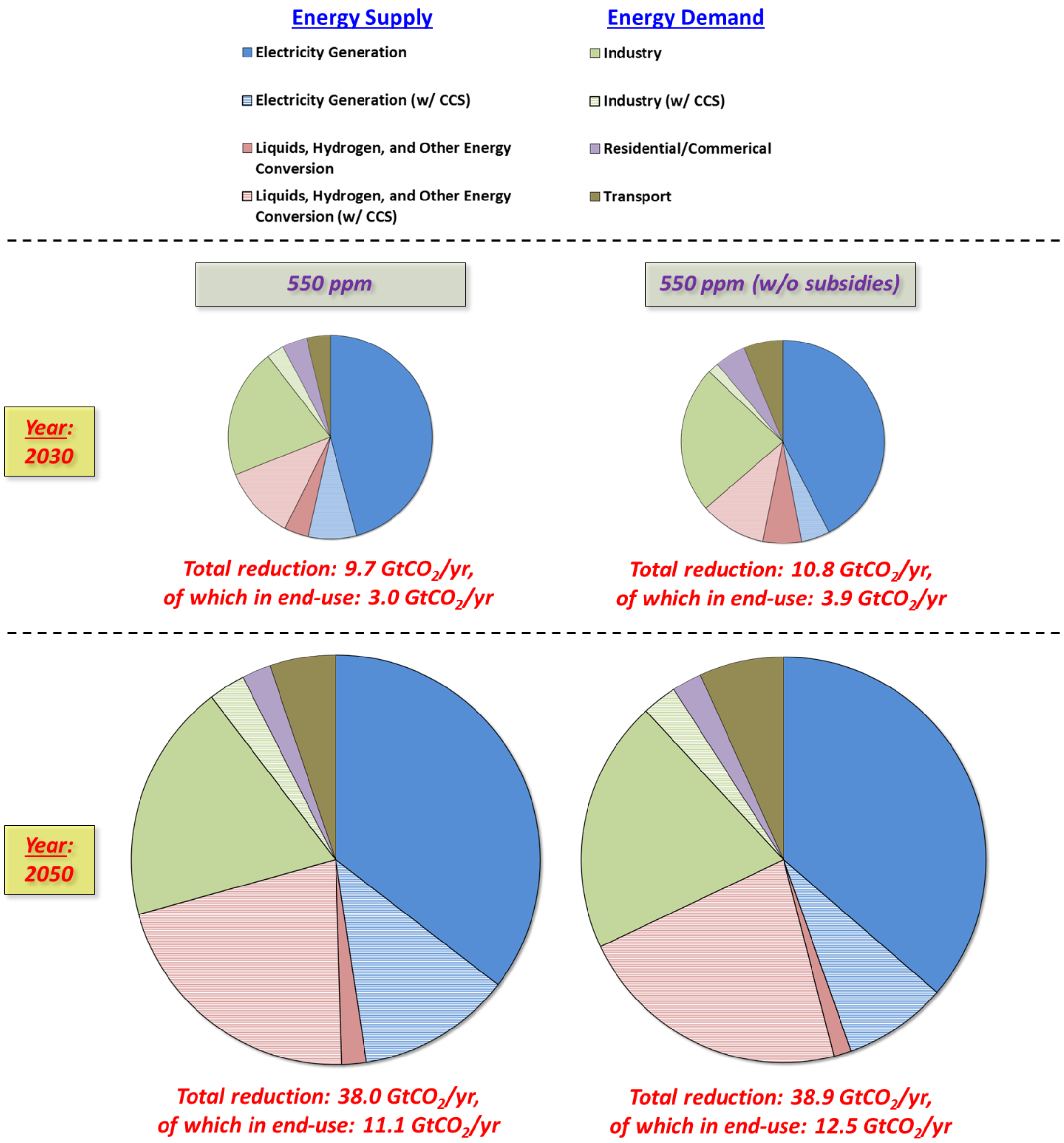

Figure 10. Emissions reductions by sector in 2030 and 2050 in the 550 ppm CO2-eq scenarios (both with and without subsidies applied). Aggregated results for the world are shown. All reductions are calculated relative to the reference baseline (with subsidies still included).

3.2.2 Impacts of subsidy-removal policies on mitigation costs

The impacts of subsidy-removal policies on the overall costs of mitigation can be measured by their effect on two metrics: (i) carbon prices, a marginal measure, and (ii) consumption changes, a cumulative measure.

Firstly, subsidy-removal policies are found to modestly reduce carbon prices in the 550 ppm scenario. Specifically, the price in 2020 is lowered from 21 $/tCO2 in the standard 550 ppm case (with subsidies) to 18 $/tCO2 in the case where subsidies are removed

(Figure 11), i.e., by around 15%. One explanation for this dynamic is that when subsidies are removed and consumers see higher prices for energy (in addition to the price-wedge already created by the carbon price), the incentives to reduce demand increase. Then, with demand being lower, the carbon price does not need to be as high in order to motivate the same level of emissions reduction through technological changes on the energy supply side. In other words, the additional energy efficiency and conservation efforts at the end-use level that are induced by subsidy-removal policies slightly relax the stringency of mitigation on the supply side of the system.

Secondly, subsidy-removal policies are found reduce the consumption losses associated with mitigating climate change. In the standard 550 ppm case (with subsidies), cumulative consumption *losses* over the period 2020-2050 amount to 0.3% (relative to the reference baseline; discounted back to 2010 at 5% interest), while yearly losses grow from 0.2% in 2030 to 1.0% in 2050 (Figure 11). When subsidies are removed, however, these losses turn to *gains*: approximately 1.0% greater cumulative consumption than in the reference baseline (with subsidies). In other words, the economic impact of the subsidy-removal policies outweighs the impact of the climate policies – at least over the first half of the century and under a climate target of this stringency – and the net effect is a consumption gain. Under more stringent climate policies (e.g., a 450 ppm scenario, which was also run in this study, although not discussed at length here), the lowering of consumption losses is also found; yet, in those cases the net effect may be a loss, as mitigation costs are likely to outweigh the benefits of subsidy-removal in more stringent climate policy scenarios. Regardless, that the impact of subsidy-removal and revenue recycling within the broader economy has such a pronounced impact on mitigation costs is quite insightful, even if these policies do not appear to lead to marked changes in energy supply and demand or in the portfolio of mitigation measures undertaken.

A final noteworthy observation from our modelling of climate policy scenarios here is that the carbon prices needed to induce a change in the energy system have risen, relative to earlier scenario analyses (also with MESSAGE) that analysed climate targets of similar stringency. The primary reason for these increases relates to the generally higher levels of energy prices that now characterize the model (because the model is now more closely calibrated to base-year price levels). Simply put, higher energy prices require higher carbon prices in order to induce the same level of emission reductions. This is because relative fuel price changes are what is important from the point of view of a firm or consumer (both in the model and in reality).

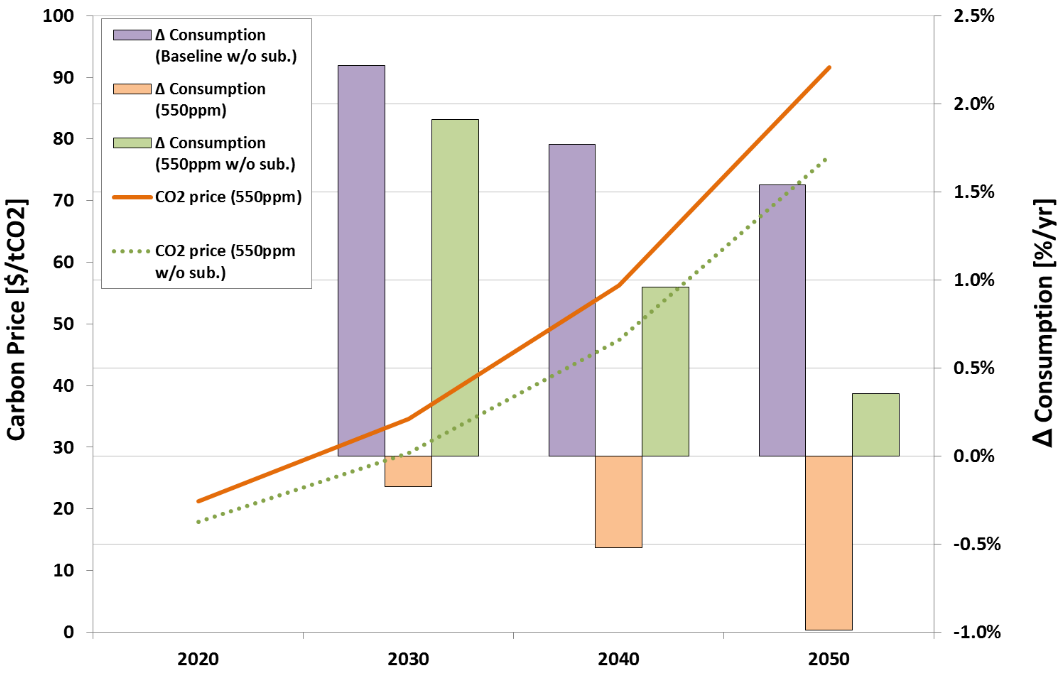

Figure 11. Carbon prices (left axis) and consumption change (right axis) in the baseline where subsidies are removed and both 550 ppm scenarios (with and without subsidies), in all cases relative to the reference baseline (with subsidies included). Aggregated results for the world are shown. Positive values represent consumption gains; negative values represent losses. Consumption changes for 2020 are not shown because the all scenarios are identical up to that year.

4. Conclusions and next steps

Better capturing real energy prices, subsidies and taxes in integrated assessment models is crucial for more accurately depicting the cost of climate mitigation and contributing to the policy debate surrounding subsidy removal. Two policy-relevant questions are at the centre of this debate: What would be the energy system and GHG emissions effects of subsidy removal? And conversely, how does the cost of climate change mitigation change with subsidy removal?

Two recently published databases make answering these questions possible. Task 3.2 in ADVANCE builds on these two databases and three recent papers to conduct the first multi-model comparison on the climate impacts and cost of climate mitigation of subsidy removal. To date, and by design, this task has focused on model development. The ADVANCE consortium has undertaken three main activities: compilation of a database energy price, subsidy rate and tax data; pioneering implementation of four basic scenarios in the MESSAGE-MACRO model; and development of implementation plans for all successor models.

While we have made significant progress on this task until now, work still remains. First, we will use what we have learned from the pioneering implementation to refine the database for the modelling exercise. This will involve cross-checking the model results from MESSAGE with the empirical data to ensure that the total subsidy estimates from the modelling work agree with empirical estimates and refining the modelling to match today's subsidy landscape as closely as possible. The second big task is implementation in all successor models. Third, which is closely related to the first two tasks, we will check if the swing from consumption losses to gains with subsidy removal under climate policies is a robust modelling insight. It could be the result of overestimating total subsidy levels (in dollars per year), as those values have a big impact on the economic conclusions. But it could also be the result of recycling all saved expenditures from subsidy removal, as opposed to only a fraction of them. These three tasks will enable both better depiction of real energy prices in some of the leading integrated assessment models as well as the first multi-modelling exercise on the interaction between energy subsidies and climate objectives.

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A. Appendix with supporting material

A.1 Additional information related to the data set of energy prices, taxes and subsidies (Section 2.1)

Table 4 lists the conversion factors used in the data analysis and conversion.

Table 4 Summary of conversion factors from energy content to volume, with reference

Energy conversion	Value	Reference
LPG GJ/l	0.02	MIT Energy club units conversion (Supple 2007)
Crude oil GJ/bl	6.1	MIT Energy club units conversion (Supple 2007)
Fuel oil GJ/kg	39.3	From IEA B2020 used light fuel oil for "all other countries" (International Energy Agency 2013a)
Heating oil GJ/kl	39.2	From IEA B2020 used heavy fuel oil average (International Energy Agency 2013a)
95 gasoline GJ/l	0.03	MIT Energy club units conversion (Supple 2007)
diesel GJ/l	0.04	MIT Energy club units conversion (Supple 2007)
coal GJ/t	30	MIT Energy club units conversion (Supple 2007)
natural gas MJ/SCM	0.0382	MIT Energy club units conversion (Supple 2007)

Table 5 Summary of end-use prices

End-use prices (2005USD/GJ)									
	Residential sector				Industrial Sector				Trans.
	Natural gas	Oil	Coal	Elect.	Natural gas	Oil	Coal	Elect.	Oil
AFR		18.4		17.8	9.3	10.0		8.1	26.6
CPA	6.4	11.9	0.7	17.2	7.7		0.7	21.4	27.6
EEU	12.0	25.7	5.7	34.8	8.3	19.8	1.7	25.8	41.7
FSU	1.0	9.4	1.0	13.0	1.5	5.9	0.6	8.8	25.0
LAM	4.6	19.6		31.9	4.6	10.3	1.3	25.7	26.1
MEA	1.3	7.7		7.3	1.6	4.2		9.1	9.8
NAM	10.7	22.0		27.7	5.9	16.0	2.0	16.7	21.2
PAO	28.3	23.6		48.9	7.0	16.9	3.1	31.6	37.5
PAS	14.8	19.8		22.2	10.6	15.8	1.7	17.5	27.1
SAS	9.9	9.3	3.2	11.5	2.9	4.6	1.1	24.4	28.2
WEU	18.9	27.4	7.1	51.1	10.2	22.3	3.4	30.9	47.9

Table 6 Summary of regional end-use tax rates

End-use tax rates (2005USD/GJ)									
	Residential sector				Industrial Sector				Trans.
	Natural gas	Oil	Coal	Elect.	Natural gas	Oil	Coal	Elect.	Oil
AFR									9.8
CPA									15.0
EEU	4.6	8.2	1.2	7.7	0.4	5.0	0.0	1.7	19.7
FSU				1.2				1.6	5.9
LAM	1.9	2.9		3.6	0.0	2.9		2.5	10.4
MEA		19.9		4.3	0.0	15.2		0.0	11.8
NAM	0.0	1.1	0.0	1.2	0.0	0.9	0.0	0.9	4.0
PAO	0.0	2.4	0.0	3.1	0.0	1.3	0.4	2.2	14.3
PAS	0.0	9.9	0.0	0.2	0.0	6.8	0.0	0.2	17.1
SAS		2.8				2.8			8.0
WEU	4.3	7.8	0.6	16.2	1.0	4.9	0.3	7.0	27.7

Table 7 Summary of end-use subsidy rates

End-use subsidy rates (2005USD/GJ)									
	Residential sector				Industrial Sector				Trans.
	Natural gas	Oil	Coal	Elect.	Natural gas	Oil	Coal	Elect.	Oil
AFR		-8.2	0.0	-2.4	0.0	-6.3	0.0	-3.3	-5.8
CPA	-0.4	-2.4	-0.1	-3.5	-0.3	-2.4	-0.1	-0.2	
EEU	-4.5	-0.2	0.0		-0.1	0.0	-0.1		
FSU	-7.7	-2.6	-0.9	-6.1	-6.7	-2.8	-1.5	-10.0	-10.2
LAM	-4.8	-5.2	0.0	-5.0	-3.3	-11.0	-2.0	-4.2	-20.6
MEA	-8.5	-24.0	0.0	-19.3	-8.9	-24.2	0.0	-18.9	-17.1
NAM	-0.6	-0.4	0.0		0.0	-0.2	-0.1		
PAO	0.0	0.0	0.0		0.0	0.0	-0.5		
PAS	-2.7	-13.3	0.0	-2.4	-1.5	-16.2	-0.5	-2.2	-10.0
SAS	-13.4	-11.9	0.0	-9.2	-13.9	-11.7	0.0	-1.7	
WEU	-3.6	0.0	0.0		-0.5	-0.6	-0.9		

Note: End-use subsidy rates marked in blue cells are impacted by the assumption that no subsidy rate exceeds $25/GJ as explained in the section on End-use subsidies.

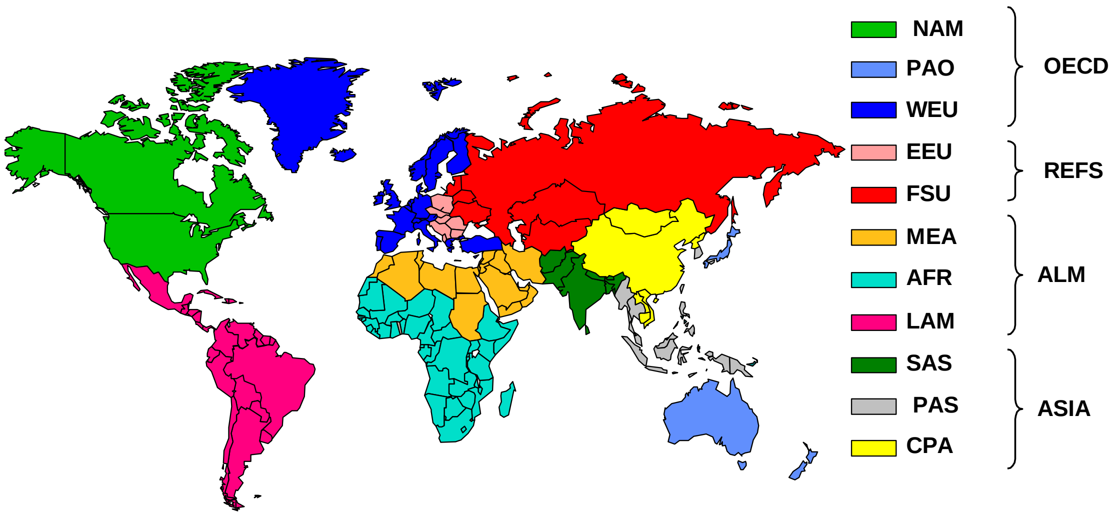
Table 8 Summary of production subsidy rates

Production subsidy rates (2005USD/GJ)			
	Natural gas	Oil	Coal
AFR			
CPA			
EEU	0.0	0.0	-0.2
FSU			
LAM	0.0	0.0	0.0
MEA	-0.2	0.0	0.0
NAM	-0.1	-0.2	0.0
PAO	0.0	-0.6	0.0
PAS	0.0	0.0	-2.5
SAS			
WEU	0.0	-0.1	-0.8

A.2 Brief description of the MESSAGE-MACRO integrated assessment modelling framework

The MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) integrated assessment model (IAM) is a global systems engineering optimization model used for medium- to long-term energy system planning, energy policy analysis, and scenario development (Messner and Strubegger 1995; Riahi et al. 2012; van Vliet et al. 2012). Developed at the International Institute for Applied Systems Analysis (IIASA) for more than two decades, MESSAGE is an evolving framework that, like other global IAMs in its class (e.g., MERGE, ReMIND, IMAGE, WITCH, GCAM, etc.), has gained wide recognition over time through its repeated utilization in developing global energy and emissions scenarios (e.g., Nakicenovic and Swart (2000)).

The MESSAGE model divides the world up into eleven (11) regions (Figure 12, Table 9) in an attempt to represent the global energy system in a simplified way, yet with many of its complex interdependencies, from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. Trade flows (imports and exports) between regions are monitored, capital investments and retirements are made, fuels are consumed, and emissions are generated. In addition to the energy system, the model includes also the other main greenhouse-gas emitting sectors, agriculture and forestry. MESSAGE tracks a full basket of greenhouse gases and other radiatively active gases – CO_2 , CH_4 , N_2O , NO_x , volatile organic compounds (VOCs), CO, SO_2, PM, BC, OC, NH_3, CF_4, C_2F_6, HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca, and SF_6 – from both the energy and non-energy sectors (e.g., deforestation, livestock, municipal solid waste, manure management, rice cultivation, wastewater, and crop residue burning). In other words, all Kyoto gases plus several others are accounted for.



1 NAM North America
2 LAM Latin America & The Caribbean
3 WEU Western Europe
4 EEU Central & Eastern Europe
5 FSU Former Soviet Union
6 MEA Middle East & North Africa
7 AFR Sub-Saharan Africa
8 CPA Centrally Planned Asia & China
9 SAS South Asia
10 PAS Other Pacific Asia
11 PAO Pacific OECD

Figure 12. Map of 11 regions in MESSAGE model

Table 9 Listing of 11 MESSAGE regions by country

MESSAGE regions	Definition (list of countries)
NAM	**North America** (Canada, Guam, Puerto Rico, United States of America, Virgin Islands)
WEU	**Western Europe** (Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom)
PAO	**Pacific OECD** (Australia, Japan, New Zealand)
EEU	**Central and Eastern Europe** (Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Estonia, Latvia, Lithuania)
FSU	**Former Soviet Union** (Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan)
CPA	**Centrally Planned Asia and China** (Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam)
SAS	**South Asia** (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka)
PAS	**Other Pacific Asia** (American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa)
MEA	**Middle East and North Africa** (Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen)
LAC	**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 Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad

	and Tobago, Uruguay, Venezuela)
AFR	**Sub-Saharan Africa** (Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Democratic Republic of Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe)

A typical model application is constructed by specifying performance characteristics of a set of technologies and defining a Reference Energy System (RES) that includes all the possible energy chains that MESSAGE can make use of. In the course of a model run, MESSAGE determines how much of the available technologies and resources are actually used to satisfy a particular end-use demand, subject to various constraints (both technological and policy), while minimizing total discounted energy system costs over the entire model time horizon (1990-2110). It does this based on a linear programming, optimization solution algorithm. The representation of the energy system includes vintaging of the long-lived energy infrastructure, which allows for consideration of the timing of technology diffusion and substitution, the inertia of the system for replacing existing facilities with new generation systems, clustering effects (technological interdependence) and – in certain versions of the model – the phenomena of increasing returns (i.e., the more a technology is applied the more it improves and widens its market potentials). Combined, these factors can lead to “lock-in” effects (Arthur 1989; Arthur 1994) and path dependency (change occurs in a persistent direction based on an accumulation of past decisions). As a result, technological change can go in multiple directions, but once change is initiated in a particular direction, it becomes increasingly difficult to alter its course.

Important inputs for MESSAGE are technology costs and technology performance parameters (e.g., efficiencies and investment, variable, and O&M costs). For the scenarios included in this paper, technical, economic and environmental parameters for over 100 energy technologies are specified explicitly in the model. Costs of technologies are assumed to decrease over time as experience (measured as a function of cumulative output) is gained. For assumptions concerning the main energy conversion technologies see the following references: Riahi et al. (2007), Nakicenovic and Swart (2000), Riahi et al. (2012), and van Vliet et al. (2012) For information on carbon capture and storage technologies specifically, see Riahi et al. (2003).

MESSAGE is able to choose between both conventional and non-conventional technologies and fuels (e.g., advanced fossil, nuclear fission, biomass, and renewables), and in this respect the portfolio of technologies/fuels available to the model obviously has an important effect on the model result. In the version of the model used in this study, we consider a portfolio of technologies whose components are either in the early demonstration or commercialization phase (e.g., coal, natural gas, oil, nuclear, biomass, solar, wind, hydro, geothermal, carbon capture and storage, hydrogen, biofuels, and electrified transport, to name just a subset). Notably, this portfolio includes bio-CCS, a technology that can potentially lead to negative emissions (i.e., permanent underground storage of CO_2 which was originally pulled out of the atmosphere by photosynthesis). Exceedingly futuristic technological options, such as nuclear fusion and geo-engineering, are, however, not considered.

Other important input parameters for our modeling include fossil fuel resource estimates and potentials for renewable energy. For fossil fuel availability, the model distinguishes between conventional and unconventional resources for eight different categories of (oil, gas, coal) occurrences (Riahi et al. 2012; Rogner 1997). For renewable potentials we rely on spatially explicit analysis of biomass availability and adopt the assumptions discussed in Riahi et al. (2012).

Price-induced changes in energy demand (i.e., elastic demands) are also modeled in MESSAGE via an iterative link to MACRO, a top-down, macro-economic model of the global economy (Messner and Schrattenholzer 2000). Through an iterative solution process, MESSAGE and MACRO exchange information on energy prices, energy demands, and energy system costs until the demand responses are such (for each of the six end-use demand categories in the model: electric and thermal heat demands in the industrial, residential, commercial, and transportation sectors) that the two models have reached equilibrium. This process is parameterized off of a baseline scenario (which assumes some autonomous rate of energy efficiency improvement, AEEI) and is conducted for all eleven MESSAGE regions simultaneously. Therefore, the demand responses motivated by MACRO are meant to represent the additional (compared to the baseline) energy efficiency improvements and conservation that would occur in each region as a result of higher prices for energy services. The macro-economic response captures both technological and behavioral measures (at a high level of aggregation), while considering the substitutability of capital, labor, and energy as inputs to the production function at the macro level.

Further and more detailed information on the MESSAGE modeling framework is available, including documentation of model set-up and mathematical formulation (Messner and Strubegger 1995; Riahi et al. 2012) and the model's representation of technological change and learning (Rao, Keppo, and Riahi 2006; Riahi, Rubin, and Schrattenholzer 2003; Roehrl and Riahi 2000).