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Finn Roar Aune
Ann Christin Bøeng
Snorre Kverndokk
Lars Lindholt
Knut Einar Rosendahl

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Abstract

We study the interactions between fuel efficiency improvements in the transport sector and the oil market, where the efficiency improvements are policy-induced in certain regions of the world. We are especially interested in feedback mechanisms of fuel efficiency such as the rebound effect, carbon leakages and the “green paradox”, but also the distributional effects via oil price changes for different regions, sectors and oil producers. An intertemporal numerical model of the international oil market is introduced, where OPEC-Core producers have market power. We find that the rebound effect has a noticeable effect on the transport sector, but also on other sectors through lower oil prices in the regions that introduce the policy. There is a small green paradox effect in the sense that oil consumption increases initially when the fuel efficiency measures are gradually implemented. Finally, there will be significant carbon leakages if the policy is not implemented in all regions, with leakage rates of 35 per cent or higher. Non-OPEC producers will suffer more than OPEC producers by fuel efficiency policies due to high production costs.

JEL-Code: D420, Q540, R480.

Keywords: fuel efficiency, transport, oil market, market power, distribution, feedback mechanisms.

Finn Roar Aune
Statistics Norway
Research Department
fau@ssb.no

Ann Christin Bøeng
Statistics Norway
Research Department
abg@ssb.no

Snorre Kverndokk
Ragnar Frisch Centre for Economic Research / Norway
snorre.kverndokk@frisch.uio.no

Lars Lindholt
Statistics Norway
Research Department
lli@ssb.no

Knut Einar Rosendahl
Norwegian University of Life Sciences
Ås / Norway
knut.einar.rosendahl@nmbu.no

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1. Introduction

For several decades, policy makers in many OECD countries have tried to limit domestic oil consumption, for a variety of reasons. Oil is a non-renewable resource, and there have been worries about future availability and costs of oil (cf. e.g. the peak-oil debate). Further, security of supply has been a concern as most oil reserves are controlled by a few OPEC countries in the Middle East. Also, most OECD countries are oil importers, and are paying large import bills for the oil they consume. Finally, oil combustion leads to CO_2 emissions, and is an important contributor to climate change.

One of the main policy instruments to reduce oil consumption in most OECD countries has been fuel efficiency standards for new vehicles. In the United States, the CAFE (Corporate Average Fuel Economy) standards were first introduced in 1975, and have been regularly updated since. Japan introduced its fuel efficiency standards in 1979. In the EU, mandatory targets for new cars were implemented in 2007, after about ten years with a voluntary agreement with car manufactorers.[1] Fuel efficiency starndards have also been implemented in countries like China, Canada, Australia and Korea (IEA, 2008). Other policies to reduce oil consumption, such as fuel taxes and biofuels support, have also been introduced to a varying degree. However, efficiency standards seem to be politically easier to implement than price-based policies, e.g. because they may have less negative distributional effects than taxes, which are typically regressive (Kverndokk and Rose, 2008).

In this paper we investigate the effects in the oil market of fuel efficiency improvements in the transport sector, caused by stricter fuel efficiency standards.[2] We do not model an explicit policy instrument, but assume that the policy leads to enhanced fuel efficiency compared to a business as usual scenario. We examine the impacts on oil consumption, both in transport sector and in other sectors. Moreover, we are interested in the effects on oil prices, on the market shares of OPEC and Non-OPEC, and on the dynamic market effects. Although fuel efficiency improvements are valuable, they may have some feedback effects, i.e., second order effects in the market, and distributional impacts that are worth considering.

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[1] The targets are CO_2-intensity targets, not fuel efficiency targets, but the effects are quite similar for petrol and diesel cars (but not when considering biofuels and electrical vehicles).

[2] Fuel efficiency is usually measured as how many miles you can drive on a gallon of fuel, or alternatively how much fuel you need to drive a mile.

First of all, due to the so called rebound effect, energy efficiency measures may be less effective than expected if the aim is to reduce energy use (e.g. Frondel et al., 2012; Gillingham et al., 2014; Borenstein, 2015; Saunders, 2015). The rebound effect follows from the fact that energy services (e.g., miles driven) become cheaper, as less energy is required to produce the same service. Thus, the demand for energy services may increase and partly or totally mitigate the initial reduction in energy use required to produce the same energy service as before. However, according to Gillingham et al. (2014), the rebound effect will in most cases be significantly below 100 per cent.

A second feedback mechanism is carbon leakage, i.e., reduced demand for oil in a specific sector or country may lead to lower oil prices and correspondingly higher oil consumption in other sectors or countries (e.g., Felder and Rutherford, 1993; Böhringer et al., 2014; Habermacher, 2015). Policy measures that reduce the demand for oil products may have particularly large leakage effects as oil is a globally traded good, and not mainly traded in national or regional markets such as natural gas or coal. Thus, oil consumption in other regions and sectors will be stimulated by lower prices.

Another feedback mechanism is the "green paradox", i.e., fossil fuel suppliers might find it profitable to accelerate extraction if they foresee reduced demand in the future, e.g., due to gradual improvements in fuel efficiency (e.g., Sinn, 2008; van der Ploeg and Withagen, 2012). In addition, the distributional effects of changes in the oil price may differ among different regions, sectors and oil producers such as OPEC and Non-OPEC, as well as among consumers and producers (e.g., Kverndokk and Rose, 2008).

In this paper we study these feedback mechanisms and distributional effects of fuel efficiency in the transport sector, using a numerical model of the international oil market called Petro2. The model incorporates dynamic behavior by oil producers, and distinguishes between competitive producers and producers with market power. Oil demand and supply is divided into several regions and sectors. The model is described in more detail below.

There have been significant improvements in energy efficiency globally over the last decades,[3] e.g. in the transport sector, see IPCC (2014). However, many options for improved efficiency still remain, and targets for efficiency improvements have been implemented in future plans for large regions and countries such as the United States, China and the EU. For instance, in the goals for climate and

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[3] However, growth in energy use has shifted towards more energy-intensive countries, such as China. Thus, global energy intensity fell by 1.3 per cent per year in the 1990s, but only by 0.4 per cent per year in the 2000s (see IEA, 2013a, p 237).

energy policy towards 2030 by the EU,[4] improved energy efficiency is important to reach the target of reducing greenhouse gas (GHG) emissions by 40 per cent below the 1990 level. Further, in the 12th 5-year plan for China (2011-15), the aim is to reduce energy consumption per unit of gross domestic product (GDP) by 16 per cent and to reduce the carbon intensity in the economy by 17 per cent.[5]

The transport sector is particularly important when studying energy efficiency and its effects in the oil market. The sector currently accounts for 54 per cent of the world's fuel liquid consumption, and the share is expected to increase to 59 per cent in 2040 (IEA, 2014). According to IPCC (Sims et al., 2014), there are potential energy efficiency and vehicle improvements globally ranging from 30 to 50 per cent in 2030 compared to 2010.[6] There are, however, large differences in fuel efficiency in different countries in the world, and the highest potential is naturally in countries with relatively low fuel efficiency such as the US, Canada and Australia.[7]

Two characteristics of the oil market may be of particular importance when we study the feedback mechanisms and distributional effects of fuel efficiency, namely market power and the intertemporal setting. Kverndokk and Rosendahl (2013) show that the effects of policy instruments to reduce oil demand in the transport sector may be very dependent on the market structure in the oil market. They compare the effects on the oil price of different policy instruments such as a fuel tax, biofuel requirements and fuel efficiency standards. The different policies may have quite different effects on the oil price, in particular when there is market power. They show that improved fuel efficiency will lead to higher oil prices if the market power is sufficiently strong (e.g., under monopoly), as higher fuel efficiency makes the demand curve steeper, thereby giving the monopolist more incentives to cut back on its supply while increasing profits.

There is little consensus in the literature regarding OPEC's behavior in the oil market, except that most studies reject the hypothesis of competitive behavior (see e.g. Smith, 2005; Hansen and Lindholt, 2008; Kaufmann et al.,2008; Al-Qahtani et al., 2008; Huppmann and Holz, 2009; Huntington et al., 2013). We present a model where we assume Cournot behavior, which means that a core of countries within OPEC takes Non-OPEC's and non-Core OPEC's extraction path as given, but maximizes joint profits taking into account the price responsiveness on the demand side. Similar assumptions have

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[4] http://ec.europa.eu/clima/policies/2030/index_en.htm

[5] http://www.c2es.org/international/key-country-policies/china/energy-climate-goals-twelfth-five-year-plan

[6] Sims et al. (2014) refers to a ”substantial potential for improving internal combustion engines” for light duty vehicles, with up to 50 per cent improvements in vehicle fuel economy (litres/100 km) or 100 per cent when measured in miles per gallon.

[7] http://www.c2es.org/federal/executive/vehicle-standards/fuel-economy-comparison

been made in earlier simulation models of the oil market (e.g., Salant, 1982; Berg et al., 2002; Huppmann and Holz, 2009; Aune et al., 2010; Okullo and Reynès, 2011; Okullo et al., 2015), however, none of the studies analyze the effects of energy efficiency measures.

Another potentially important feature is the fact that oil is an exhaustible resource, i.e., extraction of oil has intertemporal effects as it reduces available resources in the future. This is important for the "green paradox" effect. As opposed to Kverndokk and Rosendahl (2013), we introduce a numerical intertemporal model with market power to discuss this effect.

There are many studies on regulations of the transport sector, but they often focus on the demand side (e.g. Parry and Small, 2005; West and Williams, 2005 and 2007; Fischer et al., 2007; Parry, 2009; Morrow et al., 2010; Liu et al. 2013), and calculate optimal fuel taxes, measure welfare effects of fuel economy regulations or the costs of meeting certain targets for gasoline consumption. Thus, our contribution is to study the implications on both the supply and demand for oil, when we take into account both market power and the intertemporal aspect of exhaustible resources.

The paper is organized in the following way. In the next section we describe the numerical model used. Then in section 3, the numerical results are presented. The final section concludes.

2. Model description

In this paper we introduce a new model, Petro2.[8] The model has seven regions: Western-Europe, United States, Rest-OECD, China, Russia, OPEC and Rest-of-World. On the supply side OPEC is divided into OPEC-Core (Saudi-Arabia, Kuwait, UAE and Qatar) and non-Core OPEC. Each region demands oil, natural gas, electricity, coal, biomass and biofuel. We are modeling the international markets for oil in a dynamic and intertemporal way. The oil price is endogenous, and we take OPEC-Core´s market power into consideration. The prices of the other energy goods are exogenous. We distinguish between seven end-users: Industry, household, electricity, road and rail transport, domestic/international aviation and domestic shipping, international shipping, and other sectors.

The global oil market clears in each period, i.e., total oil supply from all regions equals total demand over all regions. The time period in the model is one year, and the base year is 2007. A formal description of the model is given in the Appendix.

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[8] The first Petro model was introduced in Berg et al. (1997). The new model differs in several aspects.

2.1. Demand

In every region and sector there is demand for an energy aggregate. We assume that the price of the energy aggregate in a sector of a region is a weighted CES-aggregate of the prices of the various energy goods, where the initial budget shares are used as weights. The long-term demand for the energy aggregate in a sector/region is specified as log-linear functions of population, income (GDP) per capita, price of the energy aggregate and a parameter for autonomous energy efficiency improvements (AEEI).

All energy goods are bought at regional product prices. The end-user prices include costs of transportation, distribution and refining in addition to existing taxes/subsidies. End-user prices, regional product prices and taxes/subsidies are generally taken from IEA (2007, 2013b) and GTZ (2009). We do not have regional data on costs of transportation, distribution and refining. Hence, we measure these costs as residuals, which equal the end-user prices less the regional product prices and taxes/subsidies. The future regional product prices of all energy goods except oil are exogenous, and are generally taken from IEA (2013a). Costs of transportation, distribution and refining as well as taxes/subsidies are held constant (in 2007 USD) over the time horizon. Thus, future end-user prices move in tandem with future product prices.

The direct price elasticities are constant as we use log-linear demand functions for the energy aggregate. The price elasticities for energy are set to 0.5 in all sectors, based on, e.g., the discussion in Fæhn et al (2013)[9].

Growth rates of GDP and population are exogenous in the model. Population growth is based on United Nations (2011), while the annual GDP growth rates per capita are based on IMF (2012) until 2017 and the World Bank (2012) from 2018 until 2030. After 2030 we assume unchanged GDP per capita growth rate in the US (0.6 per cent p.a.), and that other countries gradually approach the US GDP per capita level by 2200.[10] The income elasticities are calibrated so that the energy demand in 2035 in the various regions/sectors are consistent with the New Policy Scenario (NPS) in IEA (2013a), given the price changes projected by the IEA. After 2035 we assume a gradual adjustment in energy demand per capita (for given energy prices) towards the OECD region with lowest energy use per

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[9] See the Appendix how the implicit price elasticity for oil is derived.

[10] We use nominal GDP levels, not PPP values, as most energy products are internationally traded goods, and thus exchange rates matter a lot. Due to the calibration of income elasticities (see below), this choice has little importance anyway.

capita in 2035 (this is done for each sector). Finally, the demand functions are calibrated to agree with consumption of the respective energy goods in 2007 given prices and taxes/subsidies this year.

Demand for a specific energy good in a sector and region is a function of the initial budget share, the demand for the energy aggregate as well as the end-user price of the energy aggregate relative to the end-user price of the energy good. The substitution possibilities determine how fast the demand for the energy good reacts to changes in relative prices. Our starting point is that the elasticities of substitution between the different energy goods are constant over time, and set to 0.5 in all sectors except the power sector where it is set to 2 (see, e.g., Serletis et al, 2011). As the share of oil used in the transport sectors is expected to decline during this century, not only due to relative price changes, we adjust the initial budget share parameters in the different regions/sectors exogenously over time. This is done in accordance with the expected share of oil in the respective sectors as described in IEA (2013a) up until 2035, and then as depicted in IPCC (2014) from 2035 to 2100[11].

For technical reasons, the AEEI-parameters are held constant equal to one in the reference scenario, as the income elasticities are calibrated based on IEA's (2013a) projections of future energy use in their NPS (see above). The IEA expects an annual improvement in energy efficiency of 1.6 per cent globally in this scenario. When the policy scenarios specify further improvements of fuel efficiency in the transport sectors, the AEEI-parameters are consequently reduced below one. However, due to the rebound effect, the AEEI-parameters are reduced by less than the efficiency improvements should indicate. Thus, if the efficiency improvement is x per cent, the AEEI-parameter is reduced from 1 to $(1-x/100)^{1+\alpha}$, where α is the direct price elasticity in that sector (e.g., to $0.5^{0.5} = 0.71$ in the Global_50 scenario where we consider 50 per cent additional improvements in fuel efficiency by 2050). This follows e.g. from eq. (3) in Kverndokk and Rosendahl (2013), see the Appendix for details.

2.2. Oil Supply

As oil is a non-renewable resource, its production allocation over time is important for the suppliers. Extracting one more unit today will change the supply conditions in the future. Hence, a rational producer will not only consider the current price or market condition before the optimal supply of oil today is chosen. We therefore model the supply of oil in an intertemporal way, where the producers maximize the present value of their oil wealth. A market interest rate of 10 per cent is used as a (real) discount rate in all regions except for OPEC which has a rate of 5 per cent, as they can be described as

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[11] The share of oil in the transport sectors declines to 80 per cent in 2050 and to 41 per cent in 2100.

more dependent on oil and thus attach more weight to long-term income. Their oil extraction is also to a larger extent than Non-OPEC countries undertaken by state-owned companies.

To analyze the importance of market power, the international oil market is modelled as a market with a cartel (corresponding to OPEC-Core) and seven competitive fringe producers (i.e. the Non-OPEC regions plus non-Core OPEC). The fringe producers always consider the oil price path as given, while the cartel regards the price as a function of its supply. Hence, the marginal revenue for the fringe is equal to the price, whereas for the cartel marginal revenue is in general less than the price. Both the fringe producers and the cartel take the supply of all other producers as given when deciding their own production profile (Salant, 1976). Hence, we have a Nash-Cournot model of a dominant firm. Production figures in 2007 are from IEA (2013a).

The initial cost level of the different producer groups differs, reflecting among other things that extraction costs in OPEC-countries are generally lower than in the rest of the world. The initial unit costs of oil production are calculated from Ministry of Petroleum and Energy (2011) and EIA (2012).

The cost functions of both the cartel and the fringe are assumed to be increasing functions of cumulative production, i.e. costs increase due to depletion. The scarcity rent of a producer then reflects that extracting one more unit today increases costs tomorrow. Hence, we focus on economic exhaustion where the long-term scarcity rent is zero. The depletion rate is calculated from EIA (2012), IEA (2013a) and Lindholt (2013) and varies from 0.004 for OPEC to 0.057 for Western Europe. Further, for some regions the depletion rate is calibrated so that the regional and total Non-OPEC production in 2040 is not far from the level in the NPS in IEA (2014).

Unit costs are reduced by a constant rate each year due to technological change, independent of production. This means that over time unit costs may be reduced or increased, depending on the production rate (depletion vs. technology effect). The future rates of technological change are very uncertain. We have generally assumed the rate of technological change in oil production to be 2 per cent for both the cartel and the fringe.

We assume that it is costly to alter production in the initial years for the fringe producers. This is modeled as increasing marginal costs also within a period (in addition to costs increasing in accumulated production). Hence, output from the fringe producers are quite rigid initially, but the effect is gradually reduced over time. This initial inflexibility is not modeled for the OPEC-Core producers as they have generally more spare capacity and lower capital costs (see the Appendix).

In equilibrium, the price in each period must be equal to marginal costs plus the scarcity rent for the fringe producers. The latter is the negative of the shadow costs associated with cumulative production which is equal to the alternative cost of producing one more unit today as it increases future costs. Similarly, for the cartel OPEC-Core the oil price must be equal to marginal costs plus the scarcity rent as well as the cartel rent.

3. The effects of improved fuel efficiency

3.1 Policy scenarios

We consider three policy scenarios with improved fuel efficiency in the transport sectors, see Table 1. These improvements could, e.g., be driven by strict fuel efficiency standards for new vehicles, ships and airplanes, or other policies that stimulate fuel efficiency. Improved fuel efficiency is implemented in the model by reducing the AEEI-parameters in the energy demand functions of the transport sectors, cf. Section 2. The policy scenarios are compared to a reference scenario, which to a large degree mimic the projections of the New Policy Scenario in IEA (2013a) until 2035, and then assume a gradual decline in the use of oil in all sectors of the economy (following, e.g., IPCC, 2014). Thus, the reference scenario itself incorporates substantial efficiency improvements in all sectors, so the fuel efficiency improvements in the policy scenarios come in addition to these. Note that the efficiency improvements are assumed to apply to all types of energy used in the transport sector, including biofuels and electric vehicles. Thus, strictly speaking fuel efficiency improvements should be interpreted as *energy* efficiency improvements in the transport sector.

Table 1. Scenarios with improved energy efficiency

Scenario name	**Scenario description**
Reference scenario	Follow the New Policy Scenario in IEA (2013a) until 2035. A gradual decline in the growth of oil demand thereafter.
Global_30	30 per cent improvement in fuel efficiency in all transport sectors in all regions (gradually over time)
Global_50	50 per cent improvement in fuel efficiency in all transport sectors in all regions
Regional	50 per cent improvement in fuel efficiency in all transport sectors in the U.S.; 40 per cent improvement in China; 30 per cent improvement in other OECD regions; no improvement in the three other regions

The first policy scenario assumes a 30 per cent improvement in fuel efficiency in all transport sectors and all regions, relative to the reference scenario. This improvement is gradually taking place towards 2050. As there is a significant efficiency improvement even in the reference scenario, a further 30 per cent improvement will likely require either substantial policies or much stronger technology improvements than anticipated over the next decades. The second policy scenario assumes an even larger fuel efficiency improvement, i.e., 50 per cent relative to the reference scenario. This is clearly ambitious, but according to IPCC (Sims et al., 2014) there is a potential for such an improvement.

The third policy scenario takes into account that different policies may be adapted in different regions, and that the potential for additional fuel efficiency improvements also differ across regions. Here we consider a scenario with 50 per cent improvement in the U.S., 40 per cent improvement in China, and 30 per cent improvement in Western Europe and Rest of OECD. No further improvements beyond what is included in the reference scenario are assumed for the other regions. In all our scenarios we do not take into consideration that energy efficiency improvements may affect the oil market, e.g. that new standards may lead to more expensive vehicles.

3.2 Simulation results

Figure 1 shows the development of the oil price towards 2050 in the reference scenario and the three policy scenarios. As the model assumes that oil producers have perfect foresight, and there are no adjustment costs in production for OPEC-Core, the oil price path shows a smooth increase over time also through the economic downturn after the financial crisis in 2008-9.

The price increase continues through 2050 even though the share of oil gradually declines over time in all sectors and regions.[12] The reason is that despite technological improvements in oil extraction, there is a gradual scarcity of oil pushing the oil price upwards.

The figure further shows that improved fuel efficiency globally will have noticeable but not dramatic impacts on the oil price. Even in the scenario Global_50, where fuel efficiency improves by 50 per cent in all transport sectors compared to the reference scenario, the price of oil is steadily increasing over time reaching almost $200 per barrel in 2050. As the transport sectors jointly account for almost 60 per cent of all oil consumption worldwide, the direct effect of this scenario is to reduce oil demand in 2050 by around 30 per cent.

One explanation for the somewhat moderate price effect is the *rebound effect*. As improved fuel efficiency makes transport services cheaper, for a given oil price, demand for such services increases. As explained above, this moderates (but not eliminates) the decline in oil demand. In addition, the oil price reduction itself stimulates oil demand, also moderating the decline in global oil consumption. Hence, whereas the direct fuel efficiency effect in the scenario Global_50 is to reduce oil consumption in the transport sectors by 50 per cent by 2050, the actual reduction is barely 25 per cent, cf. Figure 2. As oil consumption in the transport sector is around 60 per cent of global consumption, this is equal to a direct reduction in global oil consumption of 30 per cent and an actual global reduction of around 15 per cent[13]. Moreover, consumption of oil in the other sectors increases jointly by more than 10 per cent, which is mostly due to increased use of oil in power production but also modest increases in the other sectors. In total, global oil consumption in 2050 declines by 10 per cent in this scenario, cf. Figure 3.

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[12] In our reference scenario the oil price peaks at around $1250 per barrel in 2150.

[13] Hence, around half of the initial effect is reduced due to rebound. This is higher than Gillingham et al (2013), who claim that increased driving due to improved fuel economy reduces intended energy savings by around 30 per cent in the long-term.

Figure 1. The oil price towards 2050. $_{2007}$ per barrel

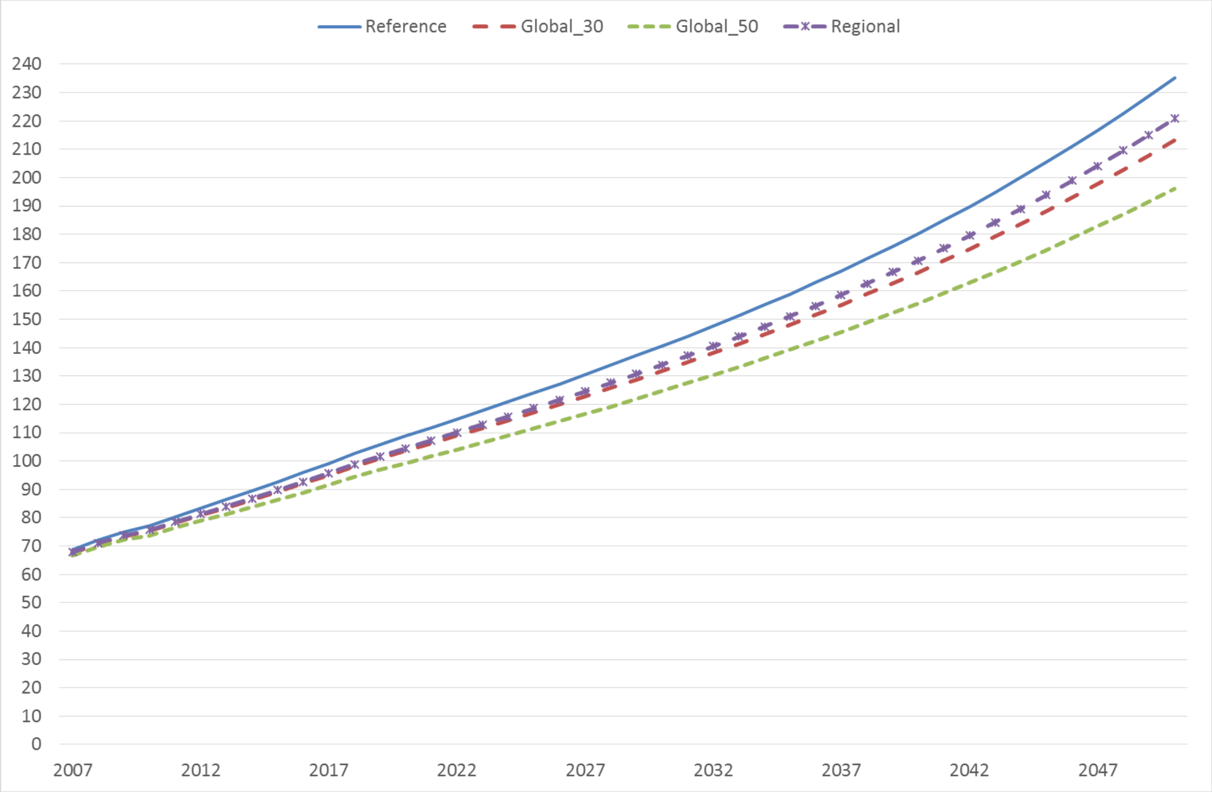


Figure 2. Global oil consumption in different sectors towards 2050 in the Global_50 scenario. Percentage change from the Reference scenario.

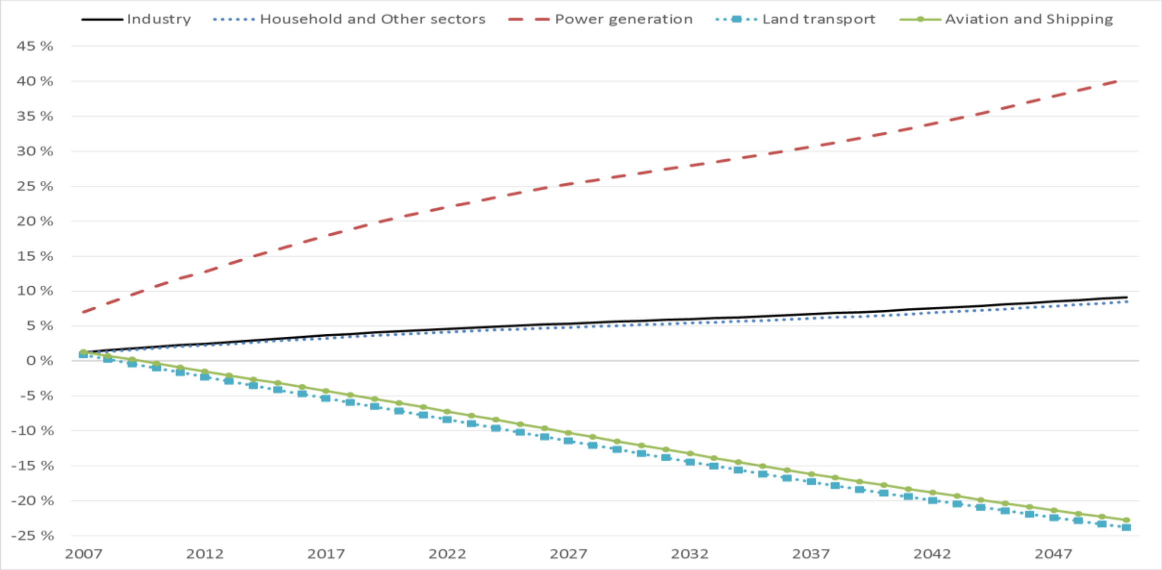
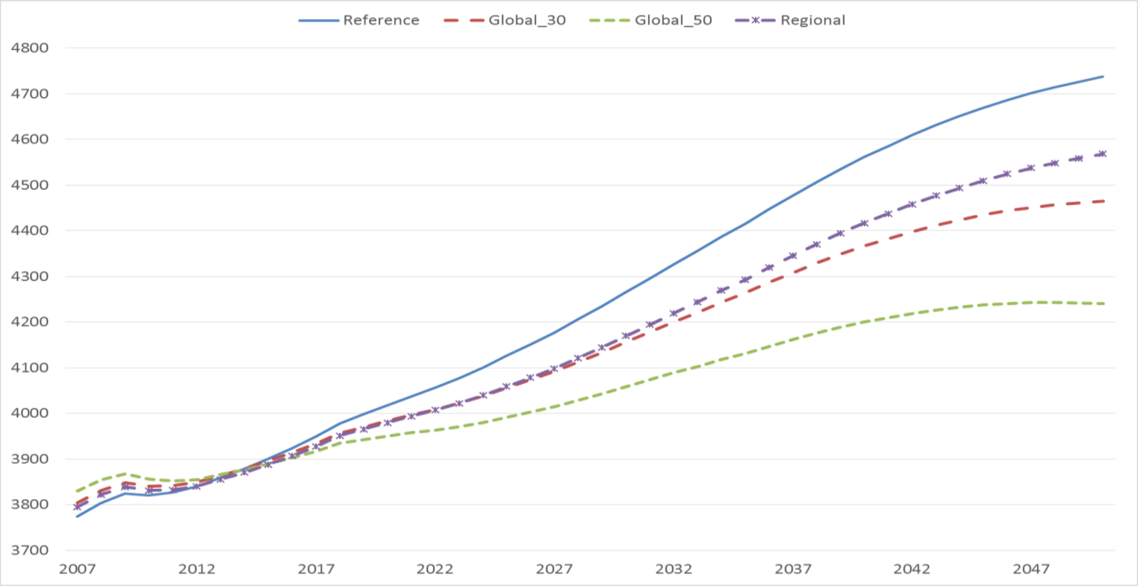


Figure 3. Global oil consumption towards 2050. Mtoe per year[14]



To further understand what happens in the oil market, it is useful to consider how OPEC and Non-OPEC producers respond. This is shown in Figures 4 and 5. First, we see that in the reference scenario OPEC increases its production somewhat towards 2045, before it slowly declines. We also notice that OPEC-Core's share of OPEC production is quite unchanged over this period. Although the largest producers with respect to reserves are in OPEC-Core, this group is by assumption holding back on production in order to have a higher price. Non-OPEC production also increases in this period, by 15 per cent from 2007 to 2050.[15] OPEC's market share increases from 43 per cent in 2007 to 48 per cent in 2050.

All oil producing regions cut back on their supply in the policy scenario. However, the policies will have different *distributional effects* for producers. The biggest production reductions are seen in Non-OPEC regions, especially in countries with relatively high costs of extraction and modest reserves such as Western Europe and Rest of OECD. In the Global_50 scenario, total Non-OPEC production decreases by 12 per cent in 2050. The non-Core OPEC countries reduce their production by 10 per cent, while production in OPEC-Core countries declines by 9 per cent. Thus, we notice that OPEC-Core finds it profitable to reduce its output slightly less than the competitive producers. One reason for this is the lower extraction costs in OPEC-Core – when the oil price declines a larger share of Non-

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[14] The volume of total oil production will differ from total consumption due to transformation etc.

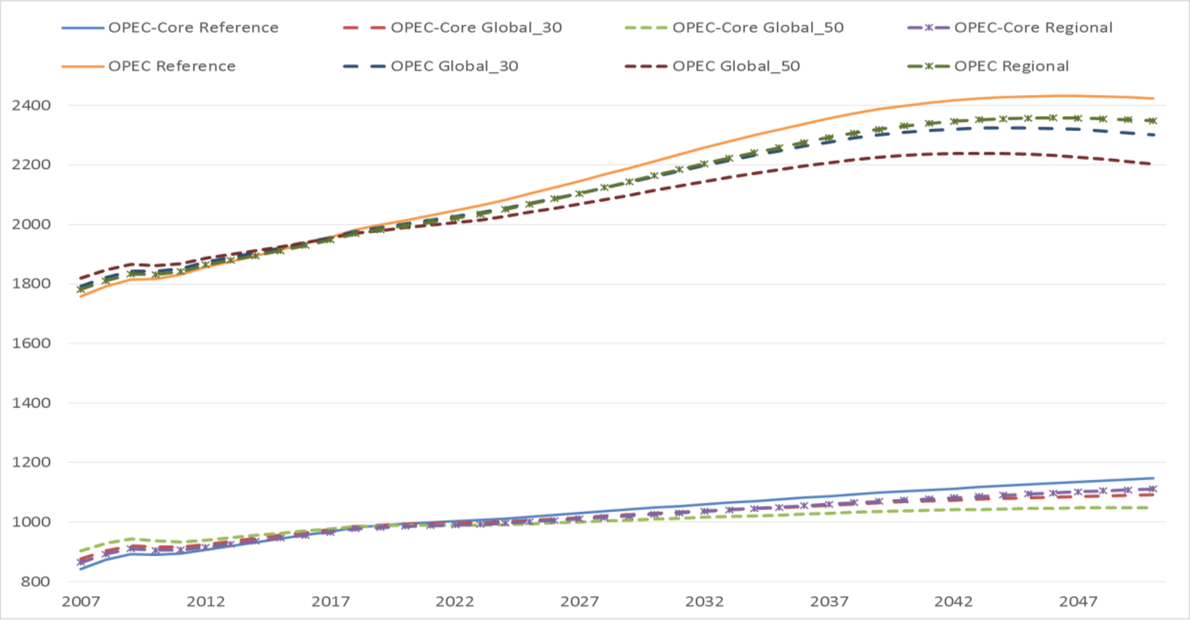
[15] While Non-OPEC production is around 9 per cent higher in 2040 than in 2020, the Non-OPEC production level in the NPS in IEA (2014) is 9 per cent lower. The IEA predicts a decline in unconventional oil production in the U.S as well as reductions in conventional oil production in Russia, Kazakhstan and China, above all after 2025.

OPEC and non-Core OPEC reserves become unprofitable to extract (and more profitable to postpone marginally profitable resources).

We further see from Figure 4 that production in OPEC-Core (and OPEC) increases somewhat in the policy scenarios in the first 8-13 years compared to the reference scenario. Remember that we assume a gradual increase in fuel efficiency over the period 2007-2050. Thus, although oil demand declines somewhat over the first years too (for a given oil price), the decline is much stronger after some decades. As the producers foresee this development, it is less advantageous to save resources for future extraction. Hence, it becomes profitable for OPEC-Core to produce more today. Similar logic applies to Non-OPEC regions, but since their initial extractions are assumed to be rather fixed (steep marginal cost curves in the first years), we do not see the same initial production increase for Non-OPEC in the policy scenarios, see Figure 5.

This intertemporal adjustment by OPEC implies that global oil consumption is initially increased in all policy scenarios, see Figure 3. Thus, even though fuel efficiency increases slightly, the use of oil actually increases over the first 6-8 years. The explanation is of course that the oil price declines (see Figure 1), mainly caused by OPEC-Core's decision to accelerate its extraction. This result is similar to the *"green paradox"* discussed in the introduction.

Figure 4. Oil production in OPEC and OPEC-Core towards 2050. Mtoe per year



As mentioned above, there are significant rebound effects when fuel efficiency is improved, both in the transport sectors where efficiency improves and indirectly in other sectors due to lower oil prices. One way of mitigating this rebound effect could be to simultaneously implement some sort of taxation on oil or energy use, either only in the transport sector or more economy-wide. Thus, we have run an additional simulation where we add a global CO_2-tax only in the transport sectors in the Global_50 scenario, sufficiently high to exactly eliminate the rebound effect in the transport sector in 2050. That is, global oil consumption in the transport sector drops by 50 per cent in 2050. The tax is assumed to rise exponentially over time, similarly to the gradual efficiency improvement in this scenario.

As a consequence of this tax, the oil price in 2050 drops by another 12 per cent relative to the Global_50 scenario, or 27 per cent relative to the Reference scenario. This leads to stronger rebound effects outside the transport sectors – still global oil consumption falls by 15 per cent compared to the Global_50 scenario in 2050. However, initially there is an even stronger green paradox effect than without the tax. Over the ten first years global oil consumption is higher than in the Reference scenario, and until 2030 consumption is higher than in the Global_50 scenario.

Figure 5. Oil production in Non-OPEC towards 2050. Mtoe per year

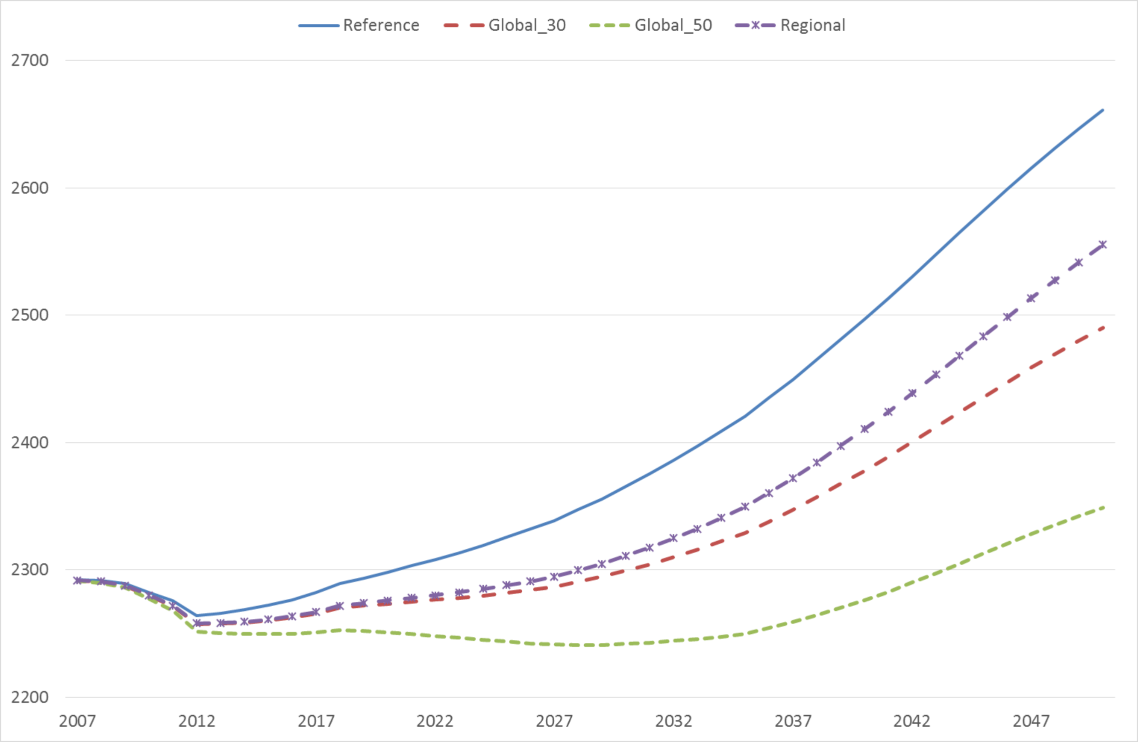
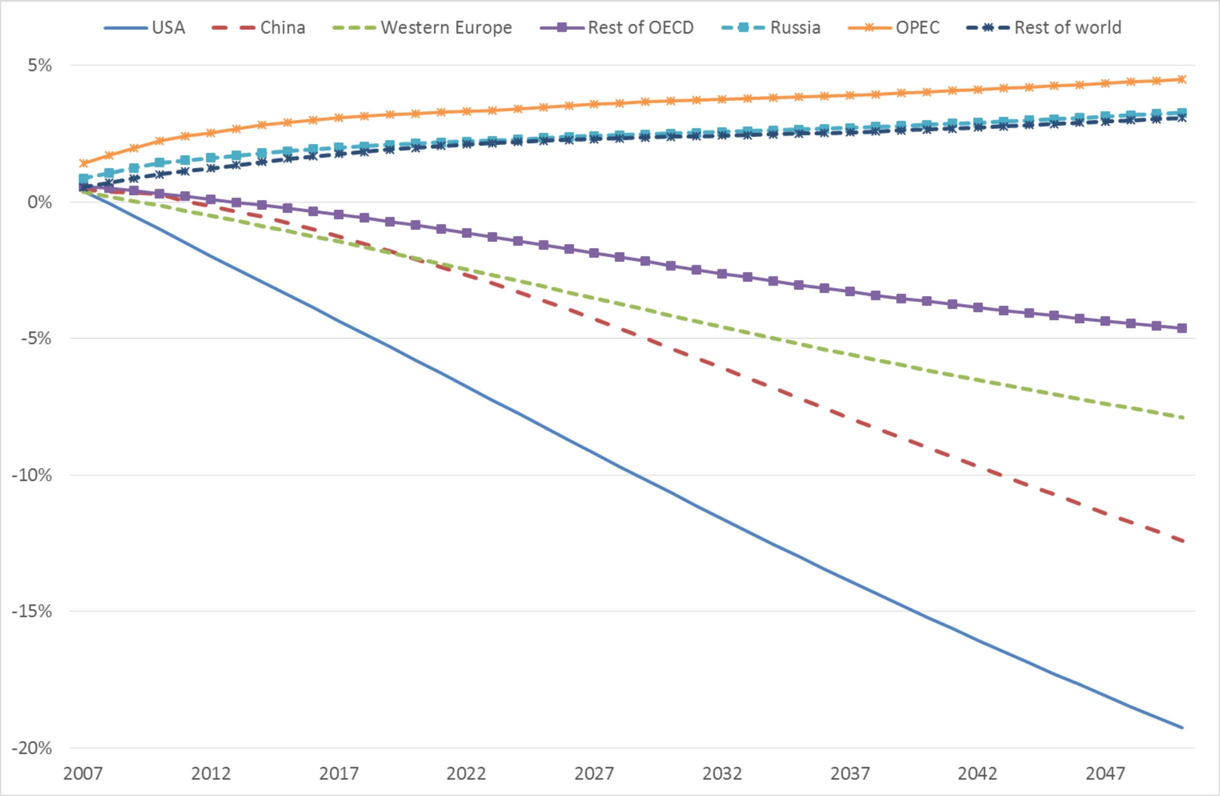


Figure 6 shows the impacts on oil consumption in different regions in the Regional scenario, where fuel efficiency increases only in four of the seven regions (see Table 1). As expected, oil consumption declines most rapidly in the U.S., where fuel efficiency in the transport sectors is assumed to improve by 50 per cent by 2050. Oil consumption declines significantly in China, too, where the efficiency increase is assumed to be 40 per cent, while the consumption decrease is more moderate in Western Europe and especially Rest of OECD, where we assume 30 per cent efficiency increase in 2050. The modest reduction in Rest of OECD is partly due to a lower share of oil being used in the transport sectors in this region – slightly below 50 per cent initially (versus 56 per cent globally).

Figure 6 further shows that oil consumption increases in the three regions that do not implement additional fuel efficiency policies. Again, this is due to the lower oil price seen in Figure 1. The biggest increase is seen for OPEC, where oil power production increases by 12 per cent compared to the Reference scenario. Oil power constitutes a large share of total power production in the OPEC countries. The overall *leakage rate*, calculated as the increased oil consumption in the three regions Russia, OPEC and Rest of World divided by the decreased oil consumption in the four other regions, is in the range 35-50 per cent in the period 2020-2050. Before 2020 the leakage rate is much higher, due to the “green paradox” discussed above. Thus, if fuel efficiency is stimulated mostly for the case of reducing CO_2-emissions, there is a strong unintended negative effect of increased emissions outside the policy regions. However, increased fuel efficiency may have other additional beneficial effects in the policy regions, such as reduced local air pollution and reduced dependence on imported oil.

Figure 6. Regional oil consumption towards 2050 in the Regional scenario. Percentage changes relative to the Reference scenario



4. Conclusions

In this paper we have looked into oil market effects of fuel efficiency improvements in the transport sector. We have focused on feedback mechanisms such as the rebound effect, carbon leakages and the “green paradox”, as well as distributional effects across regions and sectors. To study this, we have used a new intertemporal numerical model of the international oil market.

Our model simulations suggest that the rebound effect has a noticeable effect on the transport sector, but also on other sectors through lower oil prices. There is a small green paradox effect as oil consumption increases initially when fuel efficiency measures are implemented, as OPEC-Core finds it profitable to accelerate its extraction somewhat. Last but not least, there is significant carbon leakage if the policy is not implemented in all regions, with leakage rates of 35% or higher throughout 2050. The two first results show the importance of introducing fuel efficiency policies together with other policy measures such as carbon pricing, to mitigate some of the negative feedback effects. However, our simulations show that the CO_2-tax will reinforce the rebound effect in sectors not covered by the tax, and that the green paradox effect may be stronger if the tax is gradually increased. Moreover, carbon pricing in only some regions will not mitigate the leakage effects. Leakage through international energy markets are generally hard to avoid without having more countries implementing carbon policies (see Böhringer et al., 2014, for one exception though).

Finally, we find that Non-OPEC producers will suffer more than OPEC producers by fuel efficiency policies due to higher production costs. Still, Non-OPEC regions such as the U.S., Europe and China seem to be more willing to introduce fuel efficiency measures, which may be due to the relatively lower importance of the oil industry in their economy, as well as a shorter time horizon for their oil production.

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$_{s,i}$

Appendix: A formal description of the Petro2 model

Demand side

We have seven regions *i*, where both demand and production take place: OPEC, Western Europe (EU/EFTA), U.S., Rest-OECD, Russia, China and Rest of the World (on the supply side we can divide OPEC into OPEC-Core and Non-Core OPEC). Demand for final energy goods in each region is divided into six sectors *s*: Industry, Households, Other sectors (private and public services, defense, agriculture, fishing, other), Electricity, Road and rail transport, and Domestic and international aviation and domestic shipping. In addition, there is one global sector: International shipping. We have six energy commodities/fuels *f*: Oil (aggregate of different oil products), Gas, Electricity, Coal, Biomass and Biofuels for transport.

All variables are functions of time. However, we generally skip the time notation in the following. The functional forms and parameters are generally constant over time.

Table A1. List of regions, sectors and energy goods in the Petro2 model

Regions	Sectors	Energy goods
OPEC	Industry	Oil
Western Europe	Households	Gas
U.S.	Other sectors	Electricity
Rest-OECD	Electricity	Coal
Russia	Road and rail transport	Biomass
China	Domestic/International aviation and domestic shipping	Biofuels for transport
Rest of the World	International shipping*	

* International shipping is a global sector, whereas the other sectors are regional

List of symbols:

<u>Endogenous variables:</u>

$Q_{s,i}^{f}$	Demand for fuel *f* in sector *s* in region *i*
$Q_{s,i}$	Demand for energy aggregate in sector *s* in region *i* (index)

P_i^f	Producer price (node price) of fuel f in region i
$PP_{s,i}^f$	End-user price of fuel f in sector s in region i
$PI_{s,i}$	Price index for a fuel aggregate in sector s in region i

Exogenous variables and parameters:

$GDP_{s,i}$	Economic activity per capita index in sector s in region i
Pop_i	Population index in region i
$AEEI_{s,i}$	Autonomous improvements in energy efficiency index in sector s in region i
$\beta_{s,i}$	Long-term income per capita elasticity in sector s in region i
$\alpha_{s,i}$	Long-term price elasticity of the fuel aggregate in sector s in region i
$\varepsilon_{s,i}$	Long-term elasticity of population growth in sector s in region i
$b_{s,i}$	Short-term income per capita elasticity in sector s in region i
$a_{s,i}$	Short-term price elasticity of the fuel aggregate in sector s in region i
$e_{s,i}$	Short-term population elasticity in sector s in region i
$\sigma_{s,i}$	Elasticity of substitution in sector s in region i
$\theta_{s,i}^f$	Initial budget share of fuel f in sector s in region i
$\omega_{s,i}$	Constant in demand function in sector s in region i
$v_{s,i}^f$	Existing taxes/subsidies on fuel f in sector s in region i
$z_{s,i}^f$	Costs of transportation, distribution and refining on fuel f in sector s in region i
$\gamma_{s,i}$	Lag parameter in demand function in sector s in region i

The end-user price of fuel f in sector s in region i is equal to the regional producer price of the fuel (node price) plus costs of transportation, distribution and refining in addition to existing taxes/subsidies:

(A1) $PP_{s,i}^f = P_i^f + z_{s,i}^f + v_{s,i}^f$

We assume that demand for energy goods can be described through CES demand functions. Hence, we construct weighted aggregated fuel price index for each sector s and region i:

(A2) $$PI_{s,i} = \frac{\left[\sum_{f}\left\{\theta^{f}_{s,i}(PP^{f}_{s,i})^{(1-\sigma_{s,i})}\right\}\right]^{1/(1-\sigma_{s,i})}}{\left[\sum_{f}\left\{\bar{\theta}^{f}_{s,i}(\overline{PP}^{f}_{s,i})^{(1-\sigma_{s,i})}\right\}\right]^{1/(1-\sigma_{s,i})}}$$

where $\overline{PP}_{s,i,0}$ denotes the (exogenous) actual price levels in the initial data year 2007. The budget shares for fuel *f* in the base year are given by:

(A3) $$\bar{\theta}^{f}_{s,i} = \overline{PP}^{f}_{s,i,0} \cdot Q^{f}_{s,i} \Big/ \sum_{f \varepsilon f} \overline{PP}^{f}_{s,i} \cdot Q^{f}_{s,i}$$

where prices and quantities in (A3) are measured at $t = 0$. We allow for exogenous changes in $\theta^{f}_{s,i}$ to better model future changes in the composition of fuel consumption. So far we have only let oil as a share of total energy-use decline in the transport sector. Long-term demand for a fuel aggregate in sector *s* and region *i* is assumed to be on the following form:

(A4) $$Q_{s,i,t} = K_{s,i,t} \cdot Q_{s,i,t-1}{}^{\gamma_{s,i}} = \omega_{s,i,t} \cdot PI^{a_{s,i}}_{s,i,t} \cdot GDP^{b_{s,i}}_{s,i,t} \cdot Pop^{e_{s,i}}_{i,t} \cdot \left(AEEI_{s,i,t}\right)^{1+\alpha_{s,i}} \cdot Q_{s,i,t-1}{}^{\gamma_{s,i}}$$

where $K_{s,i}$ is an exogenous term representing other variables than price in the demand function, that is: $K_{s,i,t} = \omega_{s,i,t} \cdot GDP^{b_{s,i}}_{s,i,t} \cdot Pop^{e_{s,i}}_{i,t} \cdot \left(AEEI_{s,i,t}\right)^{1+\alpha_{s,i}}$.

Note that energy efficiency improvements beyond the reference level are modelled by reducing the *AEEI*-parameters. However, as efficiency improvements imply lower costs of energy services, there will be a rebound effect as long as the price elasticity is strictly negative. Following eq. (3) in Kverndokk and Rosendahl (2013), the inverse demand function for fuel $P_f(Q^f)$ can be expressed as $P_f\left(Q^f\right) = \frac{1}{AEEI} P_s\left(\frac{Q^f}{AEEI}\right)$, where P_s denotes the underlying inverse demand function for energy services.[16] From this expression we can derive the expression in (A4).

In order to take account of short- and medium-term effects, the demand functions are specified in the following partial adjustment way (here we include the time notation):

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[16] Note that in Kverndokk and Rosendahl (2013) they use $m = 1/AEEI$ as a measure of fuel efficiency.

(A5) $Q_{s,i,t} = K_{s,i,t} \cdot Q_{s,i,t-1}^{\gamma_{s,i}} = \omega_{s,i,t} \cdot PI_{s,i,t}^{a_{s,i}} \cdot GDP_{s,i,t}^{b_{s,i}} \cdot Pop_{i,t}^{e_{s,i}} \cdot AEEI_{s,i,t} \cdot Q_{s,i,t-1}^{\gamma_{s,i}}$

where $\gamma_{s,i}$ is the lag-parameter (i.e. the effect of demand in the previous period ($0 \leq \gamma_{s,i} < 1$). Then the long-term elasticities are given by: $\alpha_{s,i} = \frac{a_{s,i}}{1-\gamma_{s,i}}$, $\beta_{s,i} = \frac{b_{s,i}}{1-\gamma_{s,i}}$ and $\varepsilon_{s,i} = \frac{e_{s,i}}{1-\gamma_{s,i}}$. In the present model version $\gamma_{s,i} = 0$. Hence, we have no lags on the demand side and the short- and the long-term effects are equal (i.e., $\alpha_{s,i} = a_{s,i}$, $\beta_{s,i} = b_{s,i}$, $\varepsilon_{s,i} = e_{s,i}$). We normalize $Q_{s,i,0} = 1$ and $PI_{s,i,0} = 1$ in the base year. Then, since *GDP*, *Pop* and *AEEI* all are indexes equal to 1 in the base year, it must be that $\omega = 1$ when $\gamma_{s,i} = 0$.

Demand for fuel *f* in sector *s* in region *i* is a function of the demand for the fuel aggregate as well as the changes in the end-user price of the fuel aggregate relative to the end-user price of the fuel:

(A8) $Q^f_{s,i} = \overline{Q}^f_{s,i,0} Q_{s,i} \frac{\theta^f_{s,i}}{\overline{\theta}^f_{s,i}} \left(\frac{PI_{s,i} \big/ \overline{PI}_{s,i}}{PP^f_{s,i} \big/ \overline{PP}^f_{s,i}} \right)^{\sigma_{s,i}}$

where $\overline{Q}^f_{s,i,0}$ is the (exogenous) actual demand in the data year. The elasticities of substitution ($\sigma_{s,i}$) can vary over sectors and regions.

Oil supply side

We have seven or eight oil producing regions *i*, depending on whether or not OPEC is split into OPEC-Core and Non-Core OPEC (this is the case in the current paper). Below we refer to OPEC as the cartel (C) – if OPEC is split into two, only OPEC-Core is assume to act as a cartel, while Non-Core OPEC is assumed to act as a competitive producer. The six Non-OPEC regions (NO) are always modelled as competitive producers.

List of symbols:

Endogenous variables:

P^o	Oil producer price (equal across regions, hence index *i* is not needed)
X^C	OPEC production (includes only OPEC-Core if OPEC is split into two)

X_i^{NO}	Production in Non-OPEC region *i* (includes Non-Core OPEC if OPEC is split into two)
A^C	Accumulated OPEC production
A_i^{NO}	Accumulated Non-OPEC production in region *i*
C^C	Total costs for OPEC
C_i^{NO}	Total costs for Non-OPEC in region *i*
c^C	Unit costs for OPEC
c_i^{NO}	Unit costs for Non-OPEC region *i*
λ^C	Lagrange multiplier for OPEC
λ_i^{NO}	Lagrange multiplier for Non-OPEC region *i*
μ^C	Current shadow price for OPEC
μ_i^{NO}	Current shadow price for Non-OPEC region *i*

Exogenous variables and parameters:

φ_i^{NO}	Lag parameter for Non-OPEC region *i*
η^C	Convexity parameter for OPEC
η_i^{NO}	Convexity parameter for Non-OPEC region *i*
τ^C	Rate of technological progress for OPEC
τ_i^{NO}	Rate of technological progress for Non-OPEC region *i*
r	Discount rate
$K_{s,i}$	Exogenous term representing other variables than price in the demand function in region *i* (i.e., $K_{s,i} = \omega_{s,i} \cdot GDP_{s,i}^{\beta_{s,i}} \cdot Pop_i^{\varepsilon_i} \cdot AIEE_{s,i}$)

Consumption of fuel (aggregate) in Eq. (A5) can be written:

$$\text{(A7)} \quad Q_{s,i} = PI_{s,i}^{\alpha_{s,i}} K_{s,i}$$

where $K_{s,i}$ denotes the exogenous parts of the RHS of (A5).

Global oil consumption is given by (where we use (A1), (A6) and (A7)):

(A8) $$Q^o = \sum_s \sum_i Q^o_{s,i} = \sum_s \sum_i \left\{ \overline{Q}^o_{s,i,0} Q_{s,i} \frac{\theta^f_{s,i}}{\overline{\theta}^f_{s,i}} \left(\frac{PI_{s,i} / \overline{PI}_{s,i}}{PP^o_{s,i} / \overline{PP}^o_{s,i}} \right)^{\sigma_{s,i}} \right\}$$

$$= \sum_s \sum_i \left\{ \overline{Q}^o_{s,i,0} \frac{\theta^f_{s,i}}{\overline{\theta}^f_{s,i}} \left(\frac{\overline{PP}^o_{s,i}}{\overline{PI}_{s,i}} \right)^{\sigma_{s,i}} K_{s,i} \left(PP^o \right)^{-\sigma_{s,i}} PI_{s,i}^{\;\alpha_{s,i}+\sigma_{s,i}} \right\}$$

$$= \sum_s \sum_i \left\{ \Gamma_{1,s,i} \left(PP^o \right)^{-\sigma_{s,i}} PI_{s,i}^{\;\alpha_{s,i}+\sigma_{s,i}} \right\}$$

where $\Gamma_{1,s,i} = \overline{Q}^o_{s,i,0} \frac{\theta^f_{s,i}}{\overline{\theta}^f_{s,i}} \left(\frac{\overline{PP}^o_{s,i,0}}{\overline{PI}_{s,i,0}} \right)^{\sigma_{s,i}} K_{s,i}$ include only exogenous terms.

The optimization problem for the oil producers

OPEC's residual demand (for fixed Non-OPEC production X^{NO}) is:

(A9) $$X^C = Q^o - X^{NO}$$

OPEC maximizes the following discounted profit over time:

(A10) $$\Pi = \sum_t \left\{ \left(1+r\right)^{-t} \left(P^o_t X^C_t - C^C_t \left(X^C_t, A^C_t \right) \right) \right\}$$

s.t. $A^C_t - A^C_{t-1} = X^C_t$

The cost function of OPEC in period t has the following functional form:

(A11) $$C^C_t (X^C_t, A^C_t) = c^C_t (A^C_t) X^C_t$$

where $\mathrm{c}^{\mathrm{C}}_{\mathrm{t}}$ are the unit costs given by the following function:

(A12) $$c^C_t (A^C_t) = c^C_0 \cdot e^{\eta^C A^C_t - \tau^C t}$$

We assume that unit costs are increasing in accumulated extraction A^{C}.Hence, the Lagrangian function becomes:

$$\text{(A13)}\quad L=\sum_t\left\{(1+r)^{-t}\left(P_t^o\left(Q_t^o-X_t^{NO}\right)-c_t^C(A_t^C)\cdot\left(Q_t^o-X_t^{NO}\right)\right)\right\}+\sum_t\left\{\mu_t^C\cdot(1+r)^{-t}\cdot\left(A_t^C-A_{t-1}^C-\left(Q_t^o-X_t^{NO}\right)\right)\right\}$$

$\mu_t^C>0$ is the current value of the shadow price of the resource at period *t*, and where Q^o is a function of P^o (see Eq. (A8) above).

Before differentiating L wrt P^o, it is useful to differentiate Q^o wrt P^o:

$$\begin{aligned}
\text{(A14)}\quad \frac{\partial Q^o}{\partial P^o}&=-\sum_s\sum_i\left\{\Gamma_{1,s,i}\sigma_{s,i}\left(PP_{s,i}^o\right)^{-\sigma_{s,i}-1}PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}}\left(\frac{\partial PP_{s,i}^o}{\partial P^o}\right)\right\}\\
&+\sum_s\sum_i\left\{\Gamma_{1,s,i}\left(PP_{s,i}^o\right)^{-\sigma_{s,i}}\left(\alpha_{s,i}+\sigma_{s,i}\right)PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}-1}\left(\frac{\partial PI_{s,i}}{\partial P^o}\right)\right\}\\
&=-\sum_s\sum_i\left\{\Gamma_{1,s,i}\sigma_{s,i}\left(PP_{s,i}^o\right)^{-\sigma_{s,i}-1}PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}}\right\}\\
&+\sum_s\sum_i\left\{\Gamma_{1,s,i}\theta_{s,i}^0\left(\alpha_{s.i}+\sigma_{s,i}\right)\left(PP_{s,i}^o\right)^{-2\sigma_{s,i}}PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}}\left(\sum_f\theta_{s,i}^f\left(PP_{s,i}^f\right)^{1-\sigma_{s,i}}\right)^{-1}\right\}\\
&=-\sum_s\sum_i\left\{\overline{Q}_{s,i,0}^o\frac{\theta_{s,i}^o}{\overline{\theta}_{s,i}^o}\left(\frac{\overline{PP}_{s,i}^o}{\overline{PI}_{s,i}}\right)^{\sigma_{s,i}}K_{s,i}\sigma_{s,i}\left(PP_{s,i}^o\right)^{-\sigma_{s,i}-1}PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}}\right\}\\
&+\sum_s\sum_i\left\{\overline{Q}_{s,i,0}^o\frac{\left(\theta_{s,i}^o\right)^2}{\overline{\theta}_{s,i}^o}\left(\frac{\overline{PP}_{s,i}^o}{\overline{PI}_{s,i}}\right)^{\sigma_{s,i}}K_{s,i}\left(\alpha_{s,i}+\sigma_{s,i}\right)\left(PP_{s,i}^o\right)^{-2\sigma_{s,i}}PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}}\left(\sum_f\theta_{s,i}^f\left(PP_{s,i}^f\right)^{1-\sigma_{s,i}}\right)^{-1}\right\}\\
&=-\sum_s\sum_i\left\{\overline{Q}_{s,i,0}^o\frac{\theta_{s,i}^o}{\overline{\theta}_{s,i}^o}\left(\overline{PP}_{s,i}^o\right)^{\sigma_{s,i}}K_{s,i}\sigma_{s,i}\left(PP_{s,i}^o\right)^{-\sigma_{s,i}-1}PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}}\right\}\\
&+\sum_s\sum_i\left\{\overline{Q}_{s,i,0}^o\frac{\left(\theta_{s,i}^o\right)^2}{\overline{\theta}_{s,i}^o}\left(\overline{PP}_{s,i}^o\right)^{\sigma_{s,i}}K_{s,i}\left(\alpha_{s,i}+\sigma_{s,i}\right)\left(PP_{s,i}^o\right)^{-2\sigma_{s,i}}PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}}\left(\sum_f\theta_{s,i}^f\left(PP_{s,i}^f\right)^{1-\sigma_{s,i}}\right)^{-1}\right\}
\end{aligned}$$

where we used $\dfrac{\partial PP_{s,i}^o}{\partial P^o}=1$ (cf. equation A1) and

$$\frac{\partial PI_{s,i}}{\partial P^{o}}=\frac{\partial}{\partial P^{o}}\left\{\left[\sum_{f}\theta_{s,i}^{f}\left(PP_{s,i}^{f}\right)^{1-\sigma_{s,i}}\right]^{\frac{1}{(1-\sigma_{s,i})}}\Bigg/\left[\sum_{f}\overline{\theta}_{s,i}^{f}\left(\overline{PP}_{s,i}^{f}\right)^{1-\sigma_{s,i}}\right]^{\frac{1}{(1-\sigma_{s,i})}}\right\}$$

$$=\frac{1}{\Gamma_{2}}\cdot\frac{\partial}{\partial P^{o}}\left[\sum_{f}\theta_{s,i}^{f}\left(PP_{s,i}^{f}\right)^{1-\sigma_{s,i}}\right]^{\frac{1}{(1-\sigma_{s,i})}}$$

$$=\frac{1}{\Gamma_{2}}\frac{1}{(1-\sigma_{s,i})}\left[\sum_{f}\theta_{s,i}^{f}\left(PP_{s,i}^{f}\right)^{(1-\sigma_{s,i})}\right]^{\frac{1}{(1-\sigma_{s,i})}-1}\cdot\theta_{s,i}^{o}\cdot\left(1-\sigma_{s,i}\right)\cdot\left(PP_{s,i}^{o}\right)^{-\sigma_{s,i}}$$

$$=\frac{1}{\Gamma_{2}}\theta_{s,i}^{o}\cdot\left(PP_{s,i}^{o}\right)^{-\sigma_{s,i}}\cdot\left[\sum_{f}\theta_{s,i}^{f}\left(PP_{s,i}^{f}\right)^{(1-\sigma_{s,i})}\right]^{\frac{1}{(1-\sigma_{s,i})}-1}=\theta_{s,i}^{o}\cdot\left(PP_{s,i}^{o}\right)^{-\sigma_{s,i}}\cdot\frac{\left[\sum_{f}\theta_{s,i}^{f}\left(PP_{s,i}^{f}\right)^{(1-\sigma_{s,i})}\right]^{\frac{1}{(1-\sigma_{s,i})}-1}}{\left[\sum_{f}\overline{\theta}_{s,i}^{f}\left(\overline{PP}_{s,i}^{f}\right)^{1-\sigma_{s,i}}\right]^{\frac{1}{(1-\sigma_{s,i})}}}$$

$$=\theta_{s,i}^{o}\cdot\left(PP_{s,i}^{o}\right)^{-\sigma_{s,i}}PI_{s,i}\left(\sum_{f}\theta_{s,i}^{f}\left(PP_{s,i}^{f}\right)^{(1-\sigma_{s,i})}\right)^{-1},\quad\Gamma_{2}=\left[\sum_{f}\overline{\theta}_{s,i}^{f}\left(\overline{PP}_{s,i}^{f}\right)^{1-\sigma_{s,i}}\right]^{\frac{1}{(1-\sigma_{s,i})}}.$$

To ease computation in the following formulation of (A14) is used in GAMS:

$$\text{(A14*)}\quad \frac{\partial Q^{o}}{\partial P^{o}} = -\sum_{s}\sum_{i}\left\{ \sigma_{s,i}\overline{Q}^{o}_{s,i,0}\,\frac{\theta^{o}_{s,i}}{\overline{\theta}^{o}_{s,i}}\left(\overline{PP}^{o}_{s,i}\right)^{\sigma_{s,i}} K_{s,i}PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}}\left(PP^{o}_{s,i}\right)^{-\sigma_{s,i}-1} \right\}$$

$$+\sum_{s}\sum_{i}\left\{ \left(\alpha_{s,i}+\sigma_{s,i}\right)\overline{Q}^{o}_{s,i,0}\,\frac{\left(\theta^{o}_{s,i}\right)^{2}}{\overline{\theta}^{o}_{s,i}}\left(\overline{PP}^{o}_{s,i}\right)^{\sigma_{s,i}} K_{s,i}PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}-1}\left(PP^{o}_{s,i}\right)^{-\sigma_{s,i}}\left(PP^{o}_{s,i}\right)^{-\sigma_{s,i}} PI_{s,i}\,\frac{1}{\sum_{f}\theta^{f}_{s,i}\left(PP^{f}_{s,i}\right)^{1-\sigma_{s,i}}} \right\}$$

$$= -\sum_{s}\sum_{i}\left\{ \sigma_{s,i}\overline{Q}^{o}_{s,i,0}\,\frac{\theta^{o}_{s,i}}{\overline{\theta}^{o}_{s,i}}\left(\overline{PP}^{o}_{s,i}\right)^{\sigma_{s,i}} K_{s,i}PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}}\left(PP^{o}_{s,i}\right)^{-\sigma_{s,i}-1} \right\}$$

$$+\sum_{s}\sum_{i}\left\{ \left(\alpha_{s.i}+\sigma_{s,i}\right)\overline{Q}^{o}_{s,i,0}\,\frac{\left(\theta^{o}_{s,i}\right)^{2}}{\overline{\theta}^{o}_{s,i}}\left(\overline{PP}^{o}_{s,i}\right)^{\sigma_{s,i}} K_{s,i}PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}}\left(PP^{o}_{s,i}\right)^{-2\sigma_{s,i}}\,\frac{1}{\sum_{f}\theta^{f}_{s,i}\left(PP^{f}_{s,i}\right)^{1-\sigma_{s,i}}} \right\}$$

$$= -\sum_{s}\sum_{i}\left\{ \sigma_{s,i}\overline{Q}^{o}_{s,i,0}\,\frac{\theta^{o}_{s,i}}{\overline{\theta}^{o}_{s,i}}\left(\overline{PP}^{o}_{s,i}\right)^{\sigma_{s,i}} K_{s,i}PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}}\left(PP^{o}_{s,i}\right)^{-\sigma_{s,i}-1} \right\}$$

$$+\sum_{s}\sum_{i}\left\{ \left(\alpha_{s.i}+\sigma_{s,i}\right)\overline{Q}^{o}_{s,i,0}\,\frac{\left(\theta^{o}_{s,i}\right)^{2}}{\overline{\theta}^{o}_{s,i}}\left(\overline{PP}^{o}_{s,i}\right)^{\sigma_{s,i}} K_{s,i}PI_{s,i}{}^{\alpha_{s,i}+2\sigma_{s,i}-1}\left(PP^{o}_{s,i}\right)^{-2\sigma_{s,i}}\,\frac{1}{\sum_{f}\theta^{f}_{s,i}\left(\overline{PP}^{f}_{s,i}\right)^{1-\sigma_{s,i}}} \right\}$$

We now differentiate L wrt P^{o}:

$$\text{(A15)}\quad \left(1+r\right)^{t}\frac{\partial L}{\partial P^{o}_{t}} = \left(Q^{o}_{t}-X^{NO}_{t}\right)+\left(P^{o}_{t}-c^{C}_{t}\left(A^{C}_{t}\right)-\mu^{C}_{t}\right)\frac{\partial Q^{o}_{t}}{\partial P^{o}_{t}} = 0$$

where we can insert for $\partial Q^{o}_{t}\big/\partial P^{o}_{t}$ from Eq. (A14) above.

If we rearrange Eq. (A15) we get:

$$\text{(A16)}\quad P^{o}_{t} = c^{C}_{t}\left(A^{C}_{t}\right)+\mu^{C}_{t}-\frac{\partial P^{o}_{t}}{\partial Q^{o}_{t}}\left(Q^{o}_{t}-X^{NO}_{t}\right)$$

Where the last term on the right hand side is the cartel rent.

Next, we differentiate wrt A^{C}:

(A17) $$(1+r)^t \frac{\partial L}{\partial A_t^C} = -\frac{\partial c_t^C\left(A_t^C\right)}{\partial A_t^C}\left(Q_t^C - X_t^{NO}\right) + \mu_t^C - (1+r)^{-1}\mu_{t+1}^C = 0$$

or:

(A18) $$\eta^C c_t^C\left(A_t^C\right)\left(Q_t^C - X_t^{NO}\right) - \mu_t^C + (1+r)^{-1}\mu_{t+1}^C = 0$$

Whereas the discounted shadow price decreases over time, the running shadow price μ can both decrease and increase over time. When the cartel stops producing, the shadow price reaches zero.

Let us turn to the competitive fringe's *optimization problem*. The cost function of Non-OPEC regions in period *t* has the following functional form:

(A19) $$C_{i,t}^{NO}(X_{i,t}^{NO}, A_{i,t}^{NO}) = c_{i,t}^{NO}(A_{i,t}^{NO})e^{\varphi_i^{NO}\left(\frac{X_{i,t}^{NO}}{X_{i,t-1}^{NO}}-1\right)}X_{i,t}^{NO}$$

(A20) $$c_{i,t}^{NO}(A_{i,t}^{NO}) = c_{i,0}^{NO} \cdot e^{\eta_i^{NO}A_{i,t}^{NO} - \tau_i^{NO}t}$$

We here assume that there are no adjustment costs for Non-OPEC production, reflected by the parameter $\varphi_i^{NO} = 0$.

However, we assume the following cost function:

(A19b) $$C_{i,t}^{NO}(X_{i,t}^{NO}, A_{i,t}^{NO}) = \kappa_{A,t}c_{i,t}^{NO}(A_{i,t}^{NO})\left(X_{i,t}^{NO}\right)^{\kappa_{B,t}}$$

where $\kappa_{A,t}$ and $\kappa_{B,t}$ are exogenous parameters. In the initial years, $\kappa_{B,t} > 1$ to reflect increasing marginal costs also within a period. $\kappa_{B,t}$ is then gradually reduced to one over time. $\kappa_{A,t}$ is calibrated so that marginal costs at $X_{i,0}^{NO}$ are the same as with $\kappa_{A,t} = \kappa_{B,t} = 1$, i.e., $\kappa_{A,t} = \left(\kappa_{B,t}\right)^{-1}\left(X_{i,t}^{NO}\right)^{1-\kappa_{B,t}}$

The optimization problem can be written:

(A21) $\text{Max}\sum_t \left\{(1+r)^{-t}\left(X_{i,t}^{NO}P_t - C_{i,t}^{NO}(X_{i,t}^{NO},A_{i,t}^{NO})\right)\right\}$

with $A_{i,t}^{NO} - A_{i,t-1}^{NO} = X_{i,t}^{NO}$.

The Lagrangian function becomes:

(A22) $L = \sum_t \left\{(1+r)^{-t}\left(X_{i,t}^{NO}P_t - C_{i,t}^{NO}(X_{i,t}^{NO},A_{i,t}^{NO})\right)\right\} + \sum_t \left\{\mu_{i,t}^{NO}\cdot(1+r)^{-t}\cdot(A_{i,t}^{NO} - A_{i,t-1}^{NO} - X_{i,t}^{NO})\right\}$

where $\mu_i^{NO} = -(1+r)\lambda_i^{NO} > 0$ is the current value of the shadow price on the resource constraint, and λ_i^{NO} is the present value of the shadow price (the Lagrange multiplier).

The first order condition wrt. $X_{i,t}^{NO}$ is:

(A23) $P_t = \dfrac{C_{i,t}^{NO}(X_{i,t}^{NO},A_{i,t}^{NO})}{X_{i,t}^{NO}} + \dfrac{\varphi_i^{NO}}{X_{i,t-1}^{NO}}C_{i,t}^{NO}(X_{i,t}^{NO},A_{i,t}^{NO}) - (1+r)^{-1}\dfrac{\varphi_i^{NO}X_{i,t+1}^{NO}}{(X_{i,t}^{NO})^2}C_{i,t}^{NO}(X_{i,t+1}^{NO},A_{i,t+1}^{NO}) + \mu_{i,t}^{NO}$

Note that if $\varphi_i^{\text{NO}} = 0$, (A23) simplifies to:

(A24) $P_t = c_{i,t}^{NO}(A_{i,t}^{NO}) + \mu_{i,t}^{NO}$

The first term on the right-hand-side in Eq. (A23) and (A24) is the average unit cost. The second term in (A23) accounts for the rising short-term unit costs. Together, the two first terms are the marginal production costs in the short term (for an exogenous $\text{X}_{\text{t}-1}^{\text{NO}}$). The third term is negative, taking into account the positive effect on future cost reductions of increasing current production. The last term in (A23) and (A24) is the scarcity effect; the alternative cost of producing one unit more today as it increases future costs due to scarcity.

Alternatively, using (A19b) we get the following first order condition:

(A23b) $P_t = \kappa_{B,t}\dfrac{C_{i,t}^{NO}(X_{i,t}^{NO},A_{i,t}^{NO})}{X_{i,t}^{NO}} + \mu_{i,t}^{NO}$

When we differentiate *L* wrt $A_{i,t}^{NO}$ we get the following condition for changes in the Lagrange multiplier (identical to the corresponding condition for OPEC above):

(A25) $$\eta_i^{NO} \cdot C_{i,t}^{NO}(X_{i,t}^{NO}, A_{i,t}^{NO}) - \mu_{i,t}^{NO} + \left(1+r\right)^{-1} \mu_{i,t+1}^{NO} = 0$$

Relationships between price and substitution elasticities

In the model described above, α is the direct price elasticity of the energy aggregate, while σ is the substitution elasticity between energy goods in the energy aggregate. The direct price elasticity of oil follows implicitly from α and σ, as well as the value shares θ and prices of the energy goods. Since we may want to specify the direct price elasticity of oil instead of the elasticity of the energy aggregate, it is useful to derive the exact relationship between these two, and specifically derive a reduced form expression for the latter as a function of the former (and other necessary parameters/variables).

Let $\xi_{s,i}^{o} = \frac{\partial Q_{s,i}{}^{o}}{\partial PP_{s,i}{}^{o}} \frac{PP_{s,i}{}^{o}}{Q_{s,i}{}^{o}}$ denote the direct price elasticity of oil in sector *s* and region *i*. From (A14) and (A8) we have (note that $\frac{\partial Q_{s,i}{}^{o}}{\partial PP_{s,i}{}^{o}} = \frac{\partial Q_{s,i}{}^{o}}{\partial P^{o}}$):[17]

$$\xi_{s,i}^{o} = \frac{\partial Q_{s,i}{}^{o}}{\partial PP_{s,i}{}^{o}} \frac{PP_{s,i}{}^{o}}{Q_{s,i}{}^{o}} = -\sigma_{s,i} + \left(\alpha_{s.i} + \sigma_{s,i}\right) \theta_{s,i}^{o} \frac{\left(PP_{s,i}^{o}\right)^{1-\sigma_{s,i}}}{\sum_{f} \theta_{s,i}^{f} \left(PP_{s,i}^{f}\right)^{1-\sigma_{s,i}}}$$

This can alternatively be expressed as:

(A26) $$\alpha_{s.i} = \left(\xi_{s,i}^{o} + \sigma_{s,i}\right) \frac{\sum_{f} \theta_{s,i}^{f} \left(\overline{PP}_{s,i}^{f}\right)^{1-\sigma_{s,i}}}{\theta_{s,i}^{o} \left(\overline{PP}_{s,i}^{o}\right)^{1-\sigma_{s,i}}} - \sigma_{s,i}$$

In the special case where all end-user prices in a sector/region are equal across energy goods, we get:

(A26*) $$\alpha_{s.i} = \frac{\xi_{s,i}^{o} + \sigma_{s,i}}{\theta_{s,i}^{o}} - \sigma_{s,i}$$

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[17] Here we use the third-to-last expression in (A14).

In the calibration of the model, we use (A26) to derive estimates of α, given estimates of the RHS parameters and base-year levels of the variables.