February 2017

Fuel efficiency improvements –

Feedback mechanisms and distributional effects in the oil market

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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 leakage and the “green paradox”, but also the distributional effects for 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, with the magnitude depending on the oil demand elasticity. In the benchmark simulations, we calculate that almost half of the energy savings may be lost to a direct rebound effect, and an additional 10% to oil price adjustments. In addition, there is substantial intersectoral leakage to 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, international carbon leakage will be significant if policies are not implemented in all regions; we estimate leakage rates of 35 per cent or higher when only major consuming regions implement fuel economy policies. Non-OPEC producers will to a larger degree than OPEC producers cut back on its oil supply as a response to fuel efficiency policies due to high production costs.

Keywords: Fuel efficiency; transport; oil market; market power; distributional effects; feedback mechanisms
JEL classification: D42; Q54; R48

Acknowledgements: Thanks to Cathrine Hagem, Bjart Holtsmark, three anonymous referees, the guest editors and participants at the 11th Tinbergen Institute Conference on “Combating Climate Change” for comments. The project is financed by CREE, the PETROSAM program at the Research Council of Norway and the ENTRACTE Project financed by the European Union. While carrying out this research the authors have been associated with CREE - Oslo Centre for Research on Environmentally Friendly Energy. The CREE Centre acknowledges financial support from The Research Council of Norway.

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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. Among these are worries about its future availability and costs of delivery, especially considering that oil is a non-renewable resource (cf. e.g. the peak-oil debate). Furthermore, security of supply has been a concern as most oil reserves are controlled by a few OPEC countries in the Middle East. Moreover, 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.

A popular policy instrument to reduce oil consumption has been fuel efficiency standards[1] for new vehicles, and there have been significant improvements in energy efficiency globally over the last decades,[2] e.g. in the transport sector, see IPCC (2014). In the United States, the CAFE (Corporate Average Fuel Economy) standards were first introduced in 1975, and have been regularly updated since then. 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 manufacturers.[3] Fuel efficiency standards 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 for households (Kverndokk and Rose, 2008). Many options for improved efficiency 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.[4] Finally, to meet the targets of the Paris Agreement on greenhouse gas emissions signed in December 2015, energy efficiency proves to be essential. Taking the protocol seriously, further large energy efficiency improvements should be expected over the next decades.

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[1] Fuel efficiency is usually measured as miles driven per gallon of fuel, or alternatively how much fuel you need to drive a mile.

[2] 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).

[3] 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).

[4] For instance, EU has a target of at least 27 per cent improvement in energy efficiency by 2030. This will be reviewed in 2020 to see if it can be increased to 30% (http://ec.europa.eu/clima/policies/strategies/2030/index_en.htm, accessed 1 November 2016). Further, in the 13th 5-year plan for China (2016-20), the aim is to reduce energy consumption per unit of gross domestic product (GDP) by 15 per cent and to reduce the carbon intensity in the economy by 18 per cent over the five year period, while the long term aim is a fall in carbon intensity by 60-65% from 2005 to 2030 (http://carbon-pulse.com/16618/, accessed 1 November 2016).

The transport sector is particularly important when studying energy efficiency and its effects in the oil market. The sector currently accounts for around 55 per cent of the world's fuel liquid consumption, and the share is expected to increase to around 60 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.[5] 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.[6]

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. 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 the direct effect of fuel efficiency improvements is reduced oil demand and emissions, they can have some feedback effects, i.e., second order effects in the market, and distributional impacts that are worth considering.

First, 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. Roy, 2000; Small and Van Dender, 2007; Wang et al., 2012; Frondel et al., 2012; Gillingham et al., 2015; Borenstein, 2015; Saunders, 2015). Rebound effects arise because fuel efficiency improvements lower the cost of energy services, encouraging more use of those services and thus energy. 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. (2013), the rebound effect will in most cases be significantly below 100 per cent. To the degree that fuel efficiency improvements reduce global oil demand, the oil price will decline, implying second-order rebound effects that come in addition to the direct effect. As rebound effects increase oil demand, they will thus tend to mitigate the fall in the oil price.

A second feedback mechanism is *carbon leakage* (e.g., Felder and Rutherford, 1993; Böhringer et al., 2014; Habermacher, 2015), which is related to the second-order rebound effect mentioned above.

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[5] 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.

[6] http://www.c2es.org/federal/executive/vehicle-standards/fuel-economy-comparison (accessed 1 November 2016).

Leakage occurs due to the fall in oil prices that results from fuel efficiency improvements decreasing energy demand. It may be intersectoral, meaning that within a region, other sectors may increase oil consumption as the transport sector decreases it. Leakage may also be international (or “spatial” or “geographic”), as when regions with less stringent policies increase their oil consumption in response to lower prices. Policy measures that reduce the demand for oil products may have particularly large leakage effects, as oil is a globally traded good. Thus, oil consumption in other regions and sectors will be stimulated by lower prices. Note, however, that if countries fulfill their pledges in the Paris Agreement, which includes most countries in the world, carbon leakage is less relevant. Thus, leakage is then mostly relevant on the sector level, i.e., that emissions increase in one sector but decreases in other sectors, and if there is some flexibility when to mitigate emissions. On the other hand, it is uncertain to what degree countries will adhere to their pledges.

Thirdly, we study the *“green paradox”* or intertemporal leakage (e.g., Sinn, 2008; van der Ploeg and Withagen, 2012; Fischer and Salant, 2014; Michielsen, 2014; Bauer et al., 2014). Green paradox effects relate to the time profile of oil consumption and oil prices, as when lower oil prices cause increased consumption in early years, before the deeper fuel efficiency improvements reduce demand more in later years. The reason is that fossil fuel suppliers might find it profitable to accelerate extraction if they foresee reduced demand in the future. New studies, however, based on numerical models such as Michielsen (2014) and Bauer et al. (2014) find that intertemporal carbon leakage is a relatively minor concern due to low exhaustability of fossil fuels or that demand side effects may counteract the supply side effects. [7]

The three feedback mechanisms are related to each other, and they all depend highly on the price responsiveness of demand and supply in the energy markets. The rebound effect depends crucially on the price elasticity in the sector or region where the efficiency improvement takes place. The more price elastic the demand is, the higher is the direct rebound effect. To the degree that the efficiency improvement reduces energy demand, the energy price will fall, implying second-order rebound effects as well as leakage in other sectors or regions. These effects depend on price responsiveness of both supply and demand – the more price responsive demand is relative to supply, the bigger are these rebound and leakage effects.[8] As indicated above, the green paradox effect depends heavily on the timing of the efficiency improvements, but also on the price responsiveness. For instance, if the

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[7] There may be incentives on the demand side of future carbon policies as they may want to avoid carbon-lock-in for instance in capacity building in power plants, see Bauer et al. (2014).

[8] Strictly speaking, with imperfect competition on the supply side, it is not really price responsiveness as such, but rather how market changes affect the (optimal) supply of the large producers.

rebound and leakage effects are large due to high demand responsiveness, there will be less shifting of supply between different time periods, limiting eventual green paradox effects.

In addition to the feedback effects, we are interested in the *distributional effects* (e.g., Kverndokk and Rose, 2008). As discussed above, there may be different effects on oil consumption in different regions, sectors and over time due to the rebound, leakage and the green paradox. But there will also be distributional effects among oil producers such as OPEC and Non-OPEC, which may have impact on the political feasibility of fuel efficiency standards as market shares and the oil wealth will be affected.

In this paper we study these feedback mechanisms and distributional effects for different regions, sectors and oil producers of fuel efficiency in the transport sector, using a new 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.

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).[9] We present a model where we assume Cournot behavior, which means that a core of countries

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[9] After the substantial price drop since 2014, a question could be raised whether OPEC's behavior has changed. However, the current situation has certain similarities with the situation in 1985-86, when Saudi Arabia stopped defending the high oil price, mainly due to the loss of market share to various Non-OPEC countries (see e.g. Alkhathlan et al, 2014). Gradually the oil price started to increase, although it took almost two decades before prices were back at the 1985 level, and quotas were

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 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, 2016), however, none of the studies analyze the effects of energy efficiency measures.

The second 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. Dynamics are important for the "green paradox" effect, which depends on the optimal production profile over time. As opposed to Kverndokk and Rosendahl (2013), we introduce a numerical intertemporal model with market power to discuss this effect. 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, while in section 3, the numerical results are presented. Section 4 concludes.

2. Model description

In this paper we introduce a new numerical model, Petro2.[10] The model has seven demand regions: Western-Europe, United States, Rest-OECD, China, Russia, OPEC and Rest-of-World. Each region demands oil, natural gas, electricity, coal, biomass and biofuel. We further distinguish between six end-users within each region with greater detail among transport sectors, and one transformation sector. On the supply side, the two main producers are OPEC and non-OPEC, where OPEC is divided into OPEC-Core (Saudi-Arabia, Kuwait, UAE and Qatar) and non-Core OPEC. The international market for oil is modelled in a dynamic and intertemporal way, including region-specific increasing marginal extraction costs. Thus, the time path of the oil price is endogenous, and we take OPEC-Core´s market power into consideration. The prices of the other energy goods are exogenous.

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used to regulate OPEC members' production volume. A similar situation could take place again, assuming that expensive Non-OPEC production continues to drop out due to the lower oil prices. Thus, OPEC's decision in 2014 to maintain its production quotas could well be in the best interest of the producer group.

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

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.

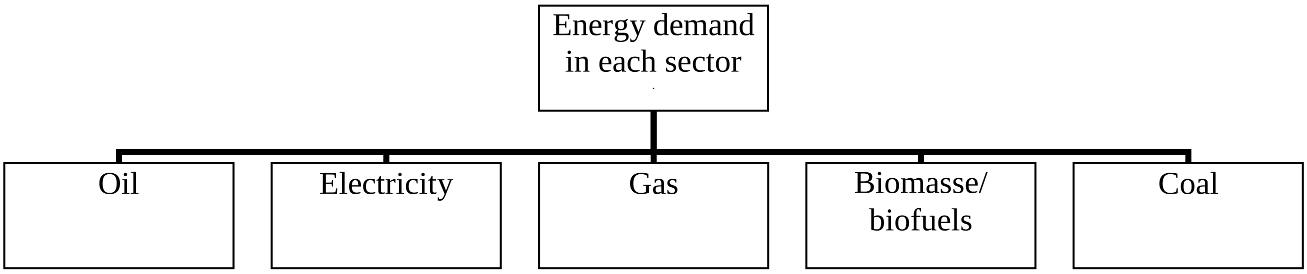
2.1. Demand

Demand is divided into one transformation sector: power generation, and six end-user sectors: Industry, household, road and rail transport, domestic/international aviation and domestic shipping, international shipping, and other sectors. 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 (*Q*) in a sector *s* and region *r* at time *t* is specified as log-linear functions of population (*Pop*), income (GDP) per capita, price of the energy aggregate (*PI*), and a parameter for autonomous energy efficiency improvements (*AEEI*). The exponents α, β and ε are long-term elasticities, whereas the exponent $1+\alpha$ reflects the direct rebound effect (see the Appendix for more details).

$$(1)\ Q_{s,i,t} = \omega_{s,i,t} \cdot PI_{s,i,t}^{\alpha_{s,i}} \cdot GDP_{s,i,t}^{\beta_{s,i}} \cdot Pop_{i,t}^{\varepsilon_{s,i}} \cdot \left(AEEI_{s,i,t} \right)^{1+\alpha_{s,i}}$$

We have six energy goods: Oil (aggregate of different oil products), gas, electricity, coal, biomass and biofuels for transport. The road and rail transport sector, for instance, demands oil, gas, electricity and biofuels (see Figure 1). 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 (2007a, 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). Hence, we are not able to address global CO_2 emissions, but rather focus on international supply and demand for oil. 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.

Figure 1. Illustration of the demand side in the model.



There is a large empirical literature on direct price elasticities for oil. Carol Dahl (2012) has developed a large database and finds that the median long-run price elasticities are -0.55 and -0.33 for gasoline and diesel, respectively. In Dahl (2012) she presents elasticities based on the static studies in her database, reporting median elasticities of -0.34 and -0.16 for gasoline and diesel, respectively. These may be interpreted as intermediate elasticities, i.e., between short- and long-run elasticities.[11] Further, whereas the World Bank (2008) estimates long-run price elasticities for gasoline and diesel at -0.61 and -0.67, respectively, the IEA (2007b) estimates the long-run price elasticity for crude oil demand at -0.15. As is evident, a consensus estimate of the long-run price elasticity of oil demand is difficult to find. Based on the studies mentioned above and the discussion in Fæhn et al (2017), we use the interval [-0.4 -0.5] as our benchmark case. When the oil price elasticity is -0.45 and the budget share of oil in a sector is 0.95, the long-term price elasticity for the energy aggregate is 0.5.[12] Thus, we set the long-term price elasticities for energy to -0.5 for all sectors. However, we use other estimates as well in the sensitivity simulations.

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 U.S. (0.6 per cent p.a.), and that other countries gradually approach the U.S. GDP per capita level by 2200.[13] 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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[11] Dahl refers to them as long-run elasticities, but notes that dynamic models, estimating both short- and long-term elasticities, tend to find long-term elasticities 50-100 per cent above the elasticities found in static studies.

[12] This is in the special case where all end-user prices in a sector/region are equal across energy goods. See the Appendix how the implicit price elasticity for oil is derived.

[13] 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 that 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 transport sector uses different fuels and the share of oil of total fuel use 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 adjustment 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[14].

For technical reasons, the AEEI-parameters are held constant and 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, an efficiency improvement by x per cent does not imply that demand is reduced by x per cent (for a given price). For instance, when cars become more fuel efficient, it becomes cheaper to drive, and car users will tend to travel more miles (assuming price responsive drivers). The more price elastic energy demand is, the higher is the rebound effect, and hence the less is the AEEI-parameter reduced for a given technical improvement in fuel efficiency. As explained in the Appendix, if the (technical) efficiency improvement is x per cent, the AEEI-parameter should be reduced from 1 to $(1-x)(1-x)^{\alpha}$, where the first factor is the direct efficiency effect and the second factor is the indirect price effect due to a change in the price of driving. This indirect effect depends on the direct price elasticity α. For example, given a price elasticity of -0.5, a 30 per cent improvement in fuel efficiency reduces demand from 1 to $0.7^{.5} = 0.84$, or a 16 per cent reduction – a rebound effect of 47 per cent.

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

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 generally can be described as more dependent on oil exports. Many of the OPEC-countries have been dependent on oil for decades and without radical changes in their economic structures, they will continue to stay reliant on oil for the years to come. As they in this way attach more importance to long-term oil income than most countries outside OPEC, it is reasonable to assume that they have a lower discount rate. In addition, 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 OPEC-Core producers include Saudi Arabia, Kuwait, UAE, and Qatar; they belong to the Gulf Cooperation Council, have common cultural background, and having larger oil reserves and lower costs than most other OPEC countries, they have the capacity to adjust production and influence the oil price. Many studies suggest that OPEC-Core is where OPEC cartel power is concentrated. Such literature includes studies by Singer (1983), Dahl and Yucel (1991), Mabro (1991), and Hansen and Lindholt (2008). 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 rate of cost increase due to depletion is calculated from EIA (2012), IEA (2013a) and Lindholt (2015) 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 per year for both the cartel and the fringe.

We assume that it is costly to alter production in the initial years for the fringe producers, which 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, as the extraction level largely is determined by past investments. Because changes in investments can alter future production after a time lag, output is more flexible 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

To design policy scenarios, we assume that the Paris Agreement is taken seriously and that large energy efficiency improvements will take place over the next decades. We do not explicitly study the policies that lead to energy efficiency; we assume that regulatory (non-price) policies are implemented that enhance energy efficiency compared to the business as usual scenario. As three of the four policy scenarios consider efficiency improvements only in the transport sector, energy efficiency will to a large degree be synonymous with fuel efficiency.

We consider four policy scenarios with improved energy efficiency, see Table 1. Three of the scenarios consider improved energy efficiency in the transport sector, building on Sims et al. (2014) who conclude that there are potential energy efficiency and vehicle performance improvements in the global transport sector ranging from 30 to 50 per cent in 2030 compared to 2010. 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. Our fourth scenario assumes improved energy efficiency in other sectors, too. 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 mimics the projections of the New Policy Scenario in IEA (2013a) until 2035, and then assumes 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, electric vehicles and hydrogen fuel cell 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 towards 2050

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 energy efficiency in all transport sectors in all regions (gradually over time)
Global_30_CO_2	30 per cent improvement in energy efficiency in all transport sectors in all regions, combined with a CO_2-tax in the transport sectors that mitigates rebound effects
Global_30_All	30 per cent improvement in energy efficiency in all sectors in all regions (gradually over time)
Regional	50 per cent improvement in energy 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 energy 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.

As explained above, efficiency improvements may lead to rebound effects, both directly due to lower costs of energy services and indirectly through lower oil prices. Thus, in our second policy scenario we investigate the effects of simultaneously implementing a CO_2-tax that is sufficiently high to exactly eliminate this rebound effect in 2050. That is, global oil consumption in the transport sector drops by 30 per cent in 2050. The tax is assumed to rise exponentially over time, similarly to the gradual efficiency improvement in this scenario.

In the third policy scenario, we look into the oil market effects of assuming 30 per cent energy efficiency improvements in all sectors, not only the transport sector. The fourth policy scenario takes into account that different policies may be adopted 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 have some indirect effects on the oil market through non-energy market effects, e.g. that new standards may lead to more expensive vehicles. In addition, we do not model technology spillovers between countries as energy efficiency improvements in one country/region may lead to improvements in fuel efficiency in other countries/regions. We touch upon this in the conclusions.

3.2 Simulation results

Figure 2 shows the development of the oil price towards 2050 in the reference scenario and the four policy scenarios. We emphasize that the reference scenario is not a projection of the future, but a scenario to study the effects of different policies. 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 price falls in 2008-9 and 2014-2015. The price increase continues through 2050 even though the share of oil gradually declines over time in all sectors and regions. The reason is that despite technological improvements in oil extraction, there is a gradual scarcity of oil pushing the oil price upwards. Our reference price scenario is somewhat higher than the New Energy Policy Scenario in IEA (2014), but close to their Current Policy Scenario up to 2040. However, sensitivity analysis suggests that the size of the price growth in the reference scenario is not very important for the effects of the policy measures.[15]

The figure further shows that improved fuel efficiency globally will have noticeable but not dramatic impacts on the oil price.[16] We first focus on the policy scenario Global_30, where fuel efficiency improves by 30 per cent in all transport sectors compared to the reference scenario. The difference between this scenario and the scenarios Global_30_All and Regional is simply the scope of the application of the efficiency improvement, and so they all move together when it comes to price and global supply/demand (but to different degrees). The scenario Global_30_CO_2 is more different, and we return to this later. In the Global_30 scenario, where energy efficiency is improved by 30 per cent in the transport sectors, the price of oil is steadily increasing over time reaching almost $190 per barrel in 2050. As the transport sectors jointly account for almost 60 per cent of all oil consumption worldwide, the first-order effect of this scenario is to reduce global oil demand in 2050 by around 18 per cent (i.e., 30 per cent of 60 per cent).

Figure 2. The oil price towards 2050. $\$_{2007}$ per barrel

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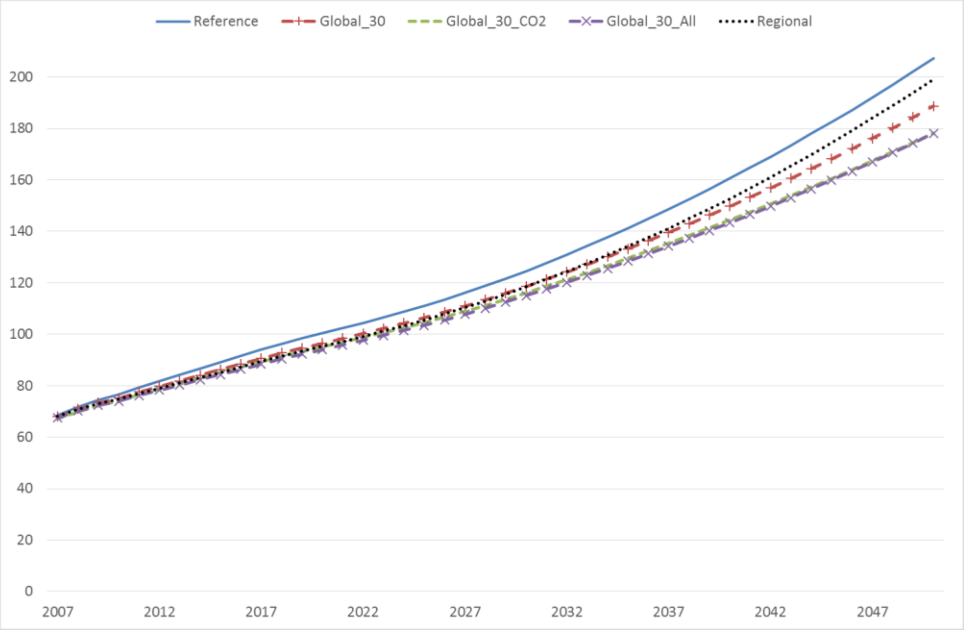
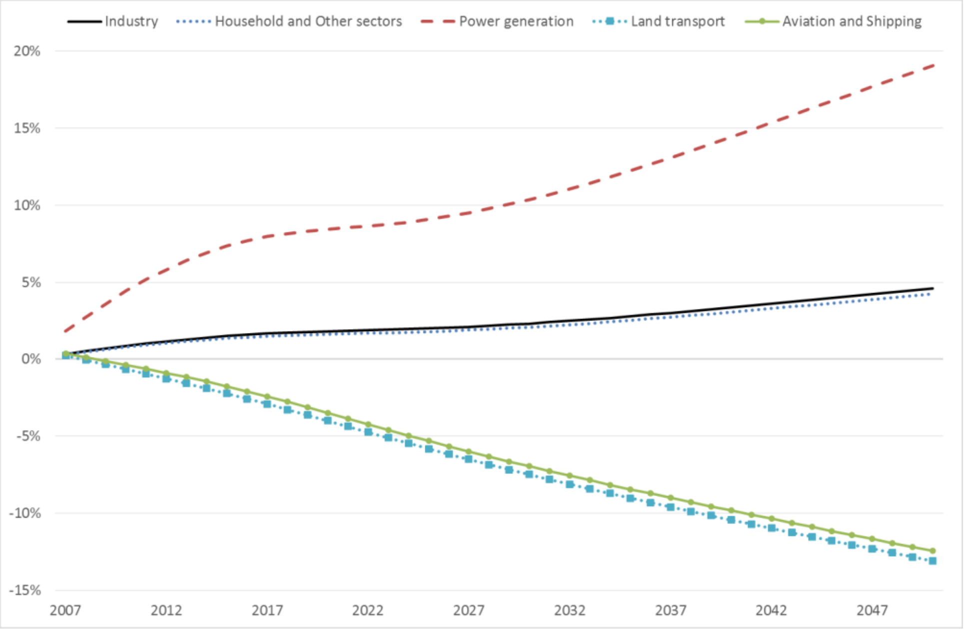
[15] For instance, in an alternative reference scenario with no growth in GDP, the oil price increases to $135 per barrel in 2050. In this case the Global_30 scenario reduces global oil consumption by 5.5 per cent in 2050, compared to 5.6 per cent in the main scenario (see below).

[16] While the oil price is increasing over time in all scenarios, the price at a given time period will be lower. Note that this is different than the conclusion in Kverndokk and Rosendahl (2013), as referred in the introduction above, where the price would increase if the market power of oil producers were sufficiently strong. The reasons for the different results are that Kverndokk and Rosendahl used a static model, where the producers did not take into account the intertemporal aspects, and that the market power is not very strong in our model as only OPEC-Core can utilize it.



The effects on the oil price of improved energy efficiency depends on how demand and supply respond. First, we consider the demand side, starting with 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 effect moderates (but not eliminates) the decline in oil demand. For instance, in the Global_30 scenario the direct rebound effect implies that oil consumption in the transport sectors drops by 16 per cent instead of 30 per cent in 2050. In addition, the oil price reduction itself stimulates oil demand, also moderating the decline in global oil consumption. This leads to another 3-4 percentage points smaller reduction in transport-related oil consumption, so that the net reduction in 2050 is barely 13 per cent, cf. Figure 3. As the transport sector accounts for around 60 per cent of global oil consumption, the 13 per cent reduction in transport-related oil consumption in 2050 translates into 8 per cent when compared to global oil consumption (i.e., 13 per cent of 60 per cent). Note, however, that so far we have not accounted for changes in oil consumption in non-transport sectors, which we return to soon.

Figure 3. Global oil consumption in different sectors towards 2050 in the Global_30 scenario. Percentage change from the reference scenario.



In the transport sectors, we find that around 55 per cent of the initial decline in oil consumption is mitigated due to rebound (i.e., (30-13)/30). This result is close to Gillingham et al (2013), who present a total rebound effect of 60 per cent based on a 30 per cent long-run “microeconomic” rebound effect, a 25 per cent “macroeconomic price” effect, and a 5 per cent “macroeconomic growth” effect. Our simulations suggest a stronger direct (microeconomic) effect and smaller price effect, while our study does not account for the “growth” effect. We return to this issue below when we consider the scenario Global_30_CO_2. Other studies such as Small and Van Dender (2007) report long-term rebound estimates of 20-25 per cent. However, their study is limited to the United States and this may explain why the rebound estimates are lower than ours. Other studies find higher rebound effects for developing countries, such as Roy (2000) who reports a very high rebound effect for transport in India, and Wang et al. (2012) who find that the average rebound effect for passenger transport by urban households in China is around 96 per cent.

Moreover, there are *intersectoral leakage effects* as other sectors benefit from increased fuel efficiency in the transport sector through the lower oil prices (see Figures 3-4), stimulating consumption of oil in these other sectors, which increases jointly by 6 per cent in 2050. This is particularly due to increased use of oil in power production in the Middle East, which is quite price responsive, but also modest increases in the other sectors. The increased oil consumption outside the transport sectors amounts to 30 per cent of the reduced oil consumption in the transport sectors. In total, global oil consumption in 2050 declines by 6 per cent in the Global_30 scenario, cf. Figure 5. The combined effect of reduced oil consumption in the transport sectors and increased consumption in other sectors implies that the transport sector’s share of global oil consumption drops from 62 per cent in the reference scenario to 57 per cent in the Global_30 scenario.

Figure 4. Global oil consumption in different sectors in 2050 in different scenarios. Change from the reference scenario (Mtoe).

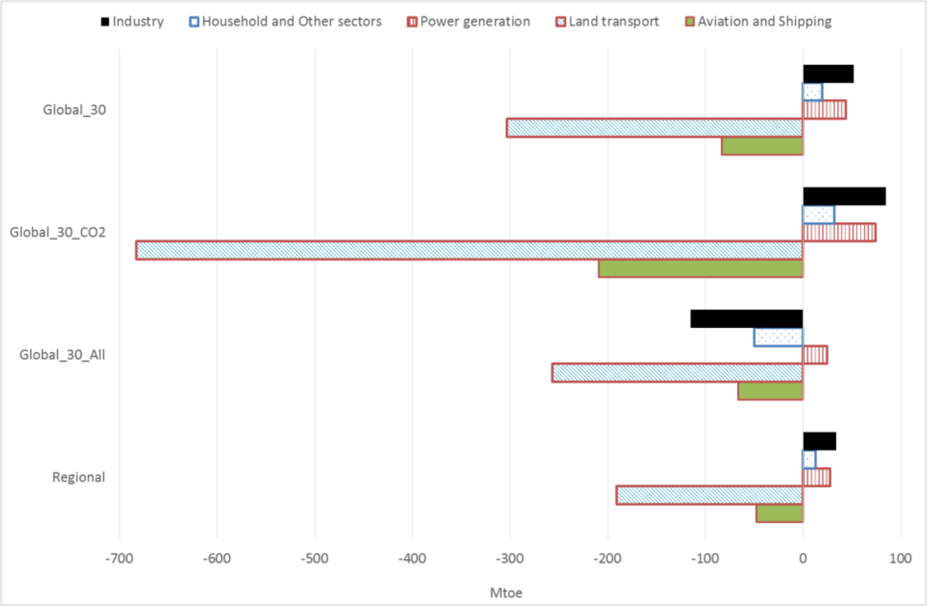
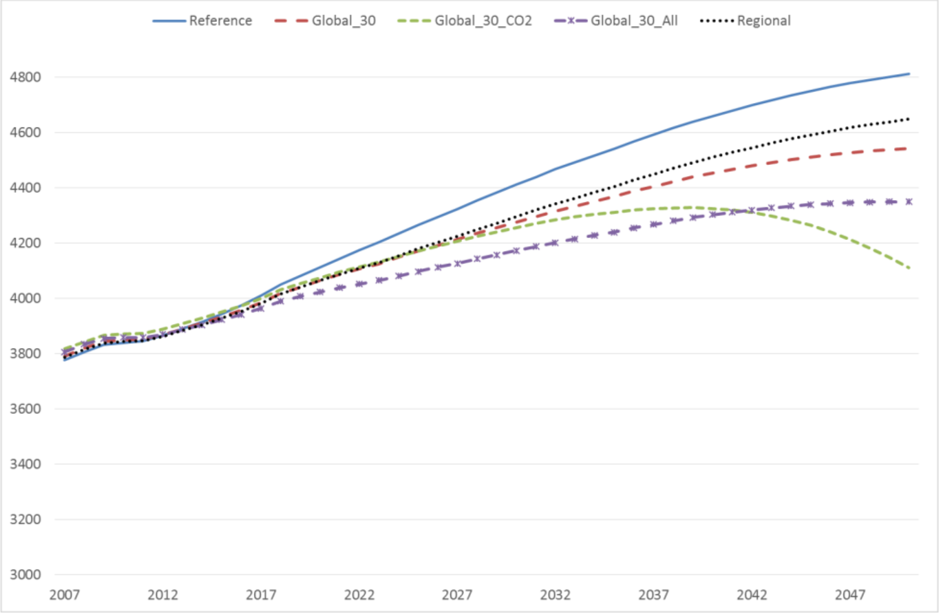


Figure 5. Global oil consumption towards 2050. Mtoe per year[17]



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

To further understand what happens in the oil market, it is useful to consider how OPEC and Non-OPEC producers respond, see Figures 6 and 7 and Table 2. In the reference scenario, both OPEC-Core and non-Core OPEC increase their production somewhat towards 2030. Then production starts to decline in non-Core OPEC, while it continues to increase in OPEC-Core. 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 until 2050, by 14 per cent compared to 2007.[18] Still, OPEC's market share increases from 43 per cent in 2007 to almost 50 per cent in 2050, as OPEC-Core's market share increases from 21 per cent to 29 per cent in this period (see Table 2).

All oil producing regions cut back on their supply in the policy scenarios. However, the policies will have different effects on the *distribution of production* among the different oil producers. The biggest 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_30 scenario, total Non-OPEC production decreases by 6 per cent in 2050. The non-Core OPEC countries also reduce their production by 6 per cent, while production in OPEC-Core countries declines by 4 per cent. Thus, we notice that OPEC-Core finds it profitable to reduce its output slightly less than the competitive producers, cf. the market shares displayed in Table 2. One reason is the lower extraction costs in OPEC-Core – when the oil price declines a larger share of Non-OPEC and non-Core OPEC reserves become unprofitable to extract (and more profitable to postpone marginally profitable resources).[19]

Table 2. Market shares for Non-OPEC, OPEC-Core and non-Core OPEC in different scenarios in 2007 and 2050

	2007			2050		
	Non-OPEC	OPEC-Core	Non-Core OPEC	Non-OPEC	OPEC-Core	Non-Core OPEC
Reference	56.6 %	20.8 %	22.6 %	50.6 %	28.6 %	20.8 %
Global_30	56.4 %	21.1 %	22.5 %	50.3 %	29.0 %	20.7 %

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[18] While Non-OPEC production is around 9 per cent higher in 2040 than in 2020 in our reference scenario, 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.

[19] Our result is different from the one in Böhringer et al. (2014), where the main conclusion is that OPEC cuts back on its supply to such a large degree when the EU imposes unilateral climate policy that the oil price in fact does not decline. Hence, there is no international leakage through the oil market in their simulations. However, that result is mainly due to the particular type of climate policy, where the EU sets a target for global emission reductions design. When they instead consider a fixed CO_2 tax, OPEC is less willing to reduce its production.

Global_30_CO_2	56.0 %	21.6 %	22.4 %	51.8 %	26.8 %	21.4 %
Global_30_All	56.2 %	21.4 %	22.4 %	50.4 %	28.8 %	20.8 %
Regional	56.5 %	20.9 %	22.6 %	50.3 %	28.8 %	21.0 %

We further see from Figure 6 that production in OPEC-Core increases somewhat in the Global_30 scenario in the first 12 years compared to the reference scenario (similar pattern is seen in all policy scenarios). Remember that we assume a gradual increase in fuel efficiency over the period 2007-2050. Thus, although oil demand declines somewhat also initially (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-Core OPEC and 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-Core OPEC and Non-OPEC in the policy scenarios, see e.g. Figure 7 for Non-OPEC.

The intertemporal adjustment by OPEC-Core implies that also global oil consumption is initially increased as a result of the fuel efficiency policy, see Figure 5. Thus, even though fuel efficiency increases slightly, the use of oil actually increases over the first 6 years in the Global_30 scenario. The explanation is of course that the oil price declines (see Figure 2), mainly caused by OPEC-Core's decision to accelerate its extraction. This result shows a *"green paradox"* as discussed in the introduction.

Figure 6. Oil production in OPEC-Core towards 2050. Mtoe per year

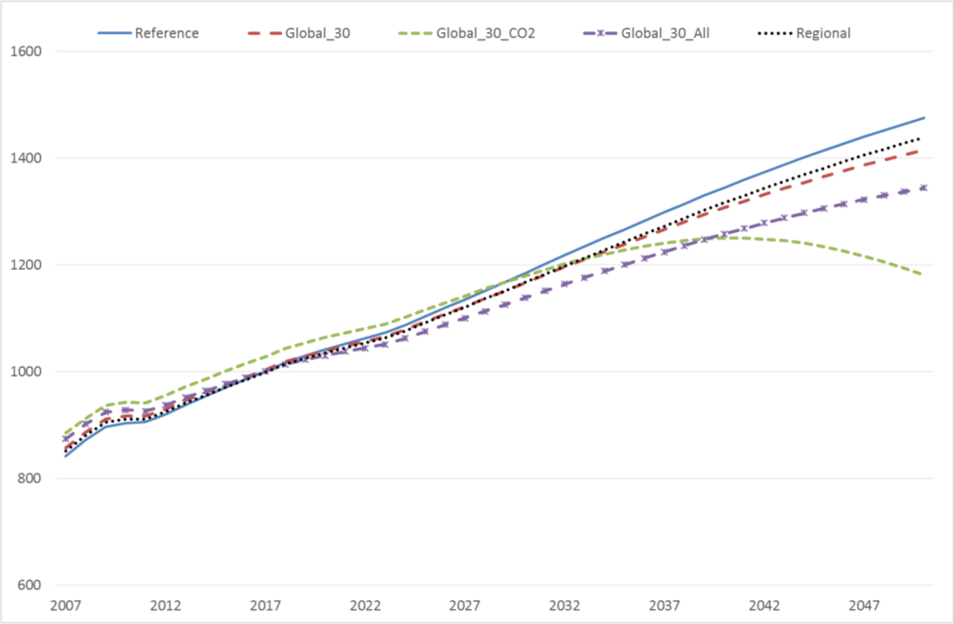
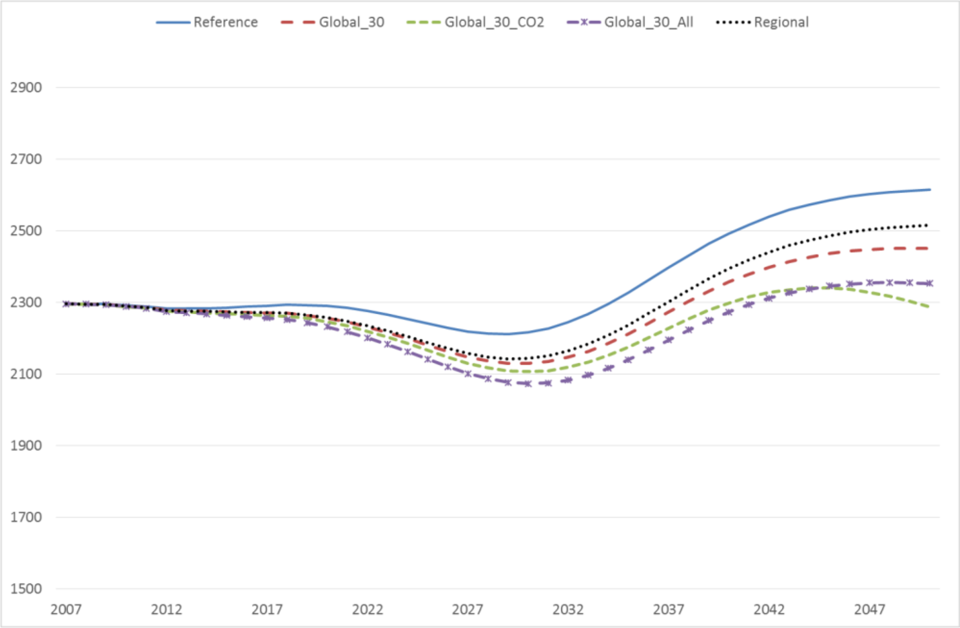


Figure 7. Oil production in Non-OPEC towards 2050. Mtoe per year



As mentioned above, there are significant rebound effects in the transport sectors when fuel efficiency is improved, both directly and indirectly through lower oil prices, and intersectoral leakage to other sectors due to lower oil prices. One way of mitigating these unintended effects 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_30 scenario, sufficiently high to exactly eliminate all rebound effects in the transport sector in 2050. That is, global oil consumption in the transport sector drops by 30 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 5 per cent relative to the Global_30 scenario, or 14 per cent relative to the reference scenario.[20] The price reduction leads to stronger intersectoral leakage effects outside the transport sectors – still global oil consumption falls by 9 per cent compared to the Global_30 scenario in 2050. However, initially there is an even stronger green paradox effect than without the tax, which is caused by the gradual increase in the CO_2-tax until 2050. Over the first nine years, global oil consumption is higher than in the reference scenario, and until 2025 consumption is higher than in the Global_30 scenario. Then we see from Figure 3 that global oil consumption peaks around 2040, and starts to decline earlier than in the other scenarios (global oil consumption peaks between 2050 and 2060 in the other scenarios). The reduced demand affects OPEC-Core production in particular, as this producer group to a larger degree adjusts its supply due to significantly lower demand in 2050 (see Table 2 and Figures 6-7).

Energy efficiency improvements will of course take place not only in the transport sector, but also in other sectors. As explained above, the reference scenario assumes significant improvements in all sectors, and thus the policy scenarios investigate the effects of additional improvements. In the scenario Global_30_All, we assume 30 per cent additional energy efficiency improvements in all sectors, gradually implemented towards 2050. Naturally, the effects on the oil market become stronger than in the Global_30 scenario. For instance, the price reduction in 2050 compared to the reference scenario is 14 per cent, while it was to 9 per cent in the Global_30 scenario. Remember that the transport sectors account for about 60 per cent of global oil consumption. In 2050 global consumption of oil declines by 10 per cent, implying that the rebound effect is still around two thirds. Obviously, there is no longer any intersectoral leakage in this scenario.

In the Regional scenario, fuel efficiency increases only in four of the seven regions, and only in the transport sectors (see Table 1). As indicated before, the effects on global supply and demand, and on the oil price, do not differ qualitatively from the Global_30 scenario. Thus, we focus instead on the impacts on oil consumption in different regions, see Figure 8, as this scenario emphasizes the

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[20] The rebound effect in 2050 can be decomposed as follows: The direct rebound effect is (as before) 14 percentage points. The rebound effect of a lower global oil price is 5-6 percentage points. Thus, as the rebound effect is neutralized by the CO_2 tax (by construction), the direct effect of the CO_2 tax is to reduce oil consumption in the transport sector by around 20 per cent.

distributional effects on regions' oil consumption if the fuel efficiency standards vary across regions. 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 8. Regional oil consumption towards 2050 in the Regional scenario. Percentage changes relative to the reference scenario

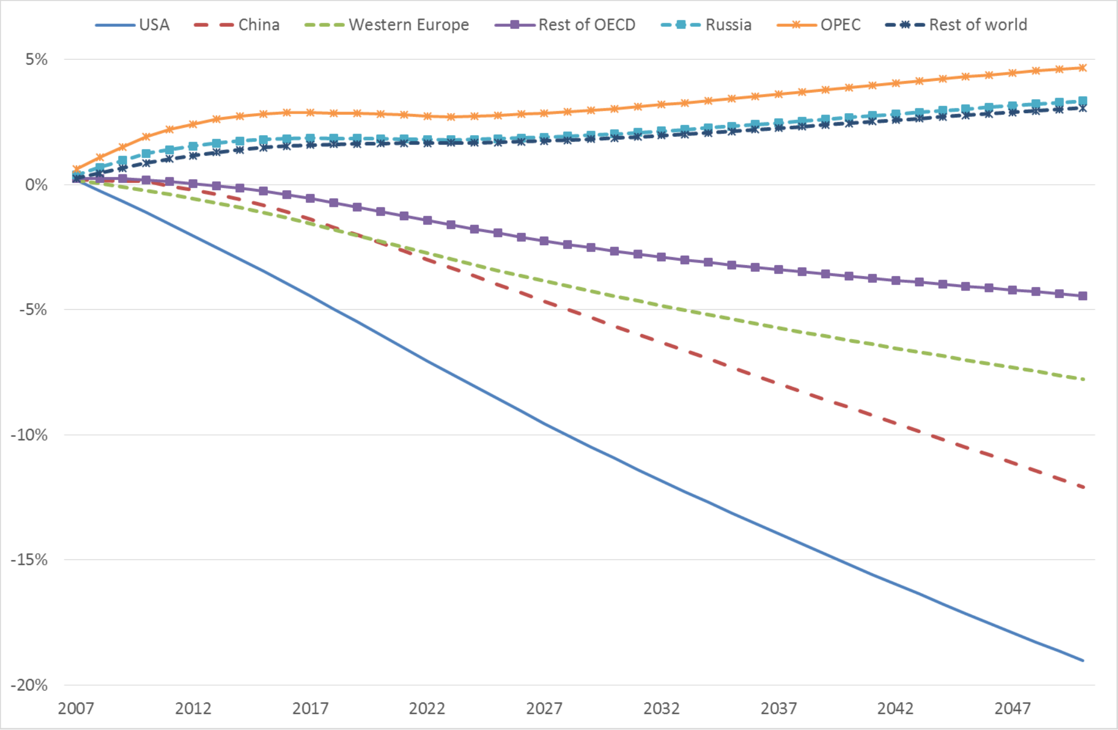

Figure 8 further shows that oil consumption increases in the three regions that do not implement additional fuel efficiency policies, i.e., *international leakage*. Again, this result is due to the lower oil price seen in Figure 2, which benefits oil consumers in these regions. The biggest increase is seen for OPEC, where oil power production in 2050 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

25-40 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 that may justify such policies.

Finally, our quantitative results are contingent on a number of uncertain parameters, especially related to the future development of supply and demand conditions. Thus, we have performed several sensitivity analysis, focusing on three parameters that are both crucial and to some degree uncertain: i) price elasticity of energy demand, ii) substitution elasticity between different energy goods, and iii) the long-term supply elasticity of oil represented by the convexity parameter in the cost function. The two former elasticities are decreased by 50 per cent, whereas the convexity parameter is increased by 50 per cent implying less elastic supply. In addition, we consider the case where OPEC-Core acts as a competitive producer. In all these cases, both the reference scenario and the policy scenarios are changed,[21] but we are mainly interested in the relative effects of the policy scenarios, focusing here on the Global_30 scenario and the rebound effect and intersectoral leakage. The main findings are summarized in Table 3.

With lower demand elasticity of energy, the direct rebound effect becomes smaller as oil consumers react less to lower driving costs coming from improved fuel efficiency (see Section 2.1). Thus, oil demand is reduced more than in our main simulations, which leads to a stronger reduction in the price of oil, cf. Table 3. A bigger price reduction normally means a bigger increase in demand, but since the price elasticity has been reduced, the price effect on demand is quite similar as in our main simulations. Hence, it is mainly the direct rebound effect that is changed when the price elasticity is changed. In total, global use of oil in the transport sectors declines by 20 per cent in 2050 (relative to the reference scenario), whereas global oil consumption drops by 9 per cent, that is, somewhat stronger reductions than in the benchmark simulations. Thus, with lower price elasticity the rebound effect becomes smaller (one third instead of 55 per cent), and the reduction in rebound effect more than outweighs the slightly higher intersectoral leakage pressures.

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[21] For instance, the transport sectors' share of the oil market in 2050 is increased in the case with low demand or supply elasticity, while it is decreased in the case with low substitution elasticity or competitive supply (compared to the benchmark case). This explains the seemingly inconsistent percentage results in Table 3.

Table 3. Sensitivity analysis. Relative changes in important variables in 2050 under different model assumptions (Global_30 scenario compared to reference scenario).

	Change in oil price	Change in global oil consumption	Change in transport-related oil consumption	Change in non-transport-related oil consumption
Benchmark case	*- 9%*	*- 6%*	*- 13%*	*+ 6%*
Low demand elasticity of energy	- 18%	- 9%	- 20%	+ 7%
Low substitution elasticity	- 9%	- 6%	- 13%	+ 2%
Low supply elasticity of oil	- 10%	- 6%	- 12%	+ 4%
Competitive oil market	- 8%	- 6%	- 13%	+ 4%

With lower substitution elasticity between energy goods, the rebound effect does not change much compared to the benchmark case as oil has a very dominant share in the transport sector. Thus, substitution between energy goods in this sector is not very important anyway. On the other hand, intersectoral leakage then decreases because the lower oil price to a lesser degree leads to increased use of oil in other sectors when the substation elasticity is lower.

If long-term oil supply is less price elastic, meaning that extraction costs increase faster than in the benchmark case, the oil price reacts slightly more in the policy scenario as oil producers to a lesser degree respond by cutting back on supply. The result is a marginally higher (indirect) rebound effect. We see from the table that oil consumption outside the transport sector responds less than in the benchmark case despite a slightly bigger drop in the oil price – this result is because the oil price becomes very high when long-term extraction costs increase, and hence the use of oil in the power sector is much smaller than in the benchmark case (where oil use in the power sector is responsible for a large part of the increase in non-transport-related oil use).

If the oil market was competitive, i.e., OPEC-Core also acted as a competitive producer (with initially inflexible supply like other producers), the oil price would rise less rapidly over time in the reference scenario due to substantially more supply from OPEC-Core. We see from Table 3, however, that the relative impacts of enhanced fuel efficiency in the transport sector would not change much compared to the benchmark case where OPEC-Core utilizes its market power.

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 leakage and the “green paradox”, as well as distributional effects across regions, sectors and oil producers. To study these effects, 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, and that lower oil prices due to reduced oil demand in the transport sector may stimulate oil consumption in other sectors. In the scenario Global_30, with 30 per cent fuel efficiency improvements in the global transport sectors, the cumulative effects of rebound and oil price adjustments amount to around 55 per cent. The majority of this rebound is a direct rebound effect (for a given oil price) while the rest is due to lower oil prices. The intersectoral leakage amounts to 30 per cent of the reduced oil consumption in the transport sectors. 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 spatial carbon leakage if the policy is not implemented in all regions, with leakage rates of 35 per cent 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 leakage 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 spatial leakage effects. Leakage through international energy markets is generally hard to avoid without having more countries implementing carbon policies (see Böhringer et al., 2014, for one exception though, cf. footnote 19). Thus, reducing rebound and carbon leakage seems to be hard as introducing a global carbon market is most likely some time into the future. The Paris Agreement, however, gives some hope. As this agreement includes most countries in the world, international leakage is less likely if countries fulfill their pledges. The countries also have incentives to mitigate rebound and intersectoral leakage with national policy measures, such as carbon pricing, too meet their climate targets. The intertemporal effect in the oil market leading to the green paradox is not strong in our simulations, and has a lower importance compared to the other feedback effects. One way of mitigating the green paradox is to introduce higher carbon prices initially. Also in this case, the Paris agreement may mitigate the increase in oil consumption if successful.

Introduction of fuel efficiency standards also give distributional effects for sectors, regions and oil producers, especially if standards are not introduced in all regions and sectors at the same time. Oil intensive sectors will benefit the most from tighter fuel efficiency standards due to the negative effect on the oil price. This is also the case for oil intensive economies if other regions or countries reduce their demand due to new standards. Thus, fuel efficiency standards may get political accept as means to reduce oil consumption and greenhouse gas emissions in these countries.

Finally, we find that Non-OPEC producers to a larger degree than OPEC producers will cut back on its oil supply as a response to 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 economies, as well as a shorter time horizon for their oil production.

In our analysis, we have modelled fuel efficiency improvements as exogenous, and not as a consequence of particular policies or deliberate activities of firms. It may be argued that stricter fuel efficiency would increase production costs, and thus prices, for vehicles, ships, airplanes etc., reducing the demand for these. On the other hand, as the operating costs would decline due to increased efficiency, demand for such equipments could also expand. Hence, it is difficult to know how this would affect the demand for oil. Our model does not allow for more specific types of fuel efficiency standards either, such as standards that differ across vehicles. Furthermore, fuel efficiency improvements in a subset of regions or sectors could lead to efficiency improvements in other regions/sectors, too, through technology spillovers, which would tend to reduce oil demand in these regions/sectors and thus mitigate some or all of the leakage effects we find in our analysis.

We should also emphasize that our analysis is a partial one in several respects. First, we do not address emissions from other fossil fuels than oil, as the prices of these fuels are exogenous in the model and held constant across scenarios. Given constant prices of coal and natural gas, the consumption of these fuels decline along with lower oil prices in the scenarios with improved fuel efficiency (but not in the scenario with also a CO_2 tax). This leads to lower emissions from coal and natural gas. However, the size of this environmental benefit is unclear, and a complete modelling of coal and natural gas markets would be needed when considering the climate benefits of fuel efficiency improvements. Second, we do not model welfare effects, which would be necessary if a cost-benefit analysis of the policies were to be undertaken.

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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 end-user 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. Further, the model has one transformation sector: Power generation. 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	Power generation	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:

Endogenous variables:

$Q_{s,i}^{f}$	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*

<u>Exogenous variables and parameters:</u>

$GDP_{s,i}$	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*
$\theta^f_{s,i}$	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*
$v^f_{s,i}$	Existing taxes/subsidies on fuel *f* in sector *s* in region *i*
$z^f_{s,i}$	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:

$$\text{(A1)}\quad PP^f_{s,i} = P^f_i + z^f_{s,i} + v^f_{s,i}$$

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*:

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

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:

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

where prices and quantities in (A3) are measured at $t = 0$. We allow for exogenous changes in $\theta_{s,i}^{f}$ 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:

$$\text{(A4)}\; Q_{s,i,t} = K_{s,i,t} \cdot \left(AEEI_{s,i,t} PI_{s,i,t}\right)^{\alpha_{s,i}}$$

where $K_{s,i}$ is an exogenous factor representing other variables than the price:

$$K_{s,i,t} = \omega_{s,i,t} \cdot GDP_{s,i,t}^{\beta_{s,i}} \cdot Pop_{i,t}^{\varepsilon_{s,i}} \cdot AEEI_{s,i,t}\,.$$

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.[22] 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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[22] Note that in Kverndokk and Rosendahl (2013) they use $m = 1/AEEI$ as a measure of fuel efficiency.

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

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., $\alpha_{s,i} = a_{s,i}$, $\beta_{s,i} = b_{s,i}$, $\varepsilon_{s,i} = e_{s,i}$). Then (A5) is identical to (A4). 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 indices 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) $Q_{s,i}^{f} = \overline{Q}_{s,i,0}^{f} Q_{s,i} \frac{\theta_{s,i}^{f}}{\overline{\theta}_{s,i}^{f}} \left(\frac{PI_{s,i} \big/ \overline{PI}_{s,i}}{PP_{s,i}^{f} \big/ \overline{PP}_{s,i}^{f}} \right)^{\sigma_{s,i}}$

where $\overline{Q}_{s,i,0}^{f}$ 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:

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

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)):

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

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

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

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:

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

OPEC maximizes the following discounted profit over time:

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

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:

$$\text{(A11)}\quad C^C_t (X^C_t , A^C_t) = c^C_t (A^C_t) X^C_t$$

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

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

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:

$$\text{(A14)}\quad \frac{\partial Q^o}{\partial P^o}=-\sum_s\sum_i\left\{\Gamma_{1,s,i}\sigma_{s,i}\left(PP_{s,i}^o\right)^{-\sigma_{s,i}-1}PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}}\left(\frac{\partial PP_{s,i}^o}{\partial P^o}\right)\right\}$$

$$+\sum_s\sum_i\left\{\Gamma_{1,s,i}\left(PP_{s,i}^o\right)^{-\sigma_{s,i}}\left(\alpha_{s,i}+\sigma_{s,i}\right)PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}-1}\left(\frac{\partial PI_{s,i}}{\partial P^o}\right)\right\}$$

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

$$+\sum_s\sum_i\left\{\Gamma_{1,s,i}\theta_{s,i}^0\left(\alpha_{s.i}+\sigma_{s,i}\right)\left(PP_{s,i}^o\right)^{-2\sigma_{s,i}}PI_{s,i}{}^{\alpha_{s,i}+\sigma_{s,i}}\left(\sum_f\theta_{s,i}^f\left(PP_{s,i}^f\right)^{1-\sigma_{s,i}}\right)^{-1}\right\}$$

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

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

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

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

where we used $\frac{\partial PP_{s,i}^o}{\partial P^o}=1$ (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 the following formulation of (A14) is used in GAMS:

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

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

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

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

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

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

We now differentiate L wrt P^o:

(A15) $$\left(1+r\right)^t \frac{\partial L}{\partial P_t^o} = \left(Q_t^o - X_t^{NO}\right) + \left(P_t^o - c_t^C\left(A_t^C\right) - \mu_t^C\right)\frac{\partial Q_t^o}{\partial P_t^o} = 0$$

where we can insert for $\partial Q_t^o / \partial P_t^o$ from Eq. (A14) above.

If we rearrange Eq. (A15) we get:

(A16) $$P_t^o = c_t^C\left(A_t^C\right) + \mu_t^C - \frac{\partial P_t^o}{\partial Q_t^o}\left(Q_t^o - X_t^{NO}\right)$$

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

Next, we differentiate wrt A^C:

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

or:

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

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

Note that if $\varphi_1^{NO} = 0$, (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 X_{t-1}^{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) $$P_t = \kappa_{B,t} \frac{C_{i,t}^{NO}(X_{i,t}^{NO}, A_{i,t}^{NO})}{X_{i,t}^{NO}} + \mu_{i,t}^{NO}$$

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

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 $\xi^o_{s,i} = \frac{\partial Q_{s,i}{}^o}{\partial PP_{s,i}{}^o}\frac{PP_{s,i}{}^o}{Q_{s,i}{}^o}$ denote the direct price elasticity of oil in sector *s* and region *i*. From (A14) and (A8) we have (note that $\frac{\partial Q_{s,i}{}^o}{\partial PP_{s,i}{}^o} = \frac{\partial Q_{s,i}{}^o}{\partial P^o}$):[23]

$$\xi^o_{s,i} = \frac{\partial Q_{s,i}{}^o}{\partial PP_{s,i}{}^o}\frac{PP_{s,i}{}^o}{Q_{s,i}{}^o} = -\sigma_{s,i} + \left(\alpha_{s.i} + \sigma_{s,i}\right)\theta^o_{s,i}\frac{\left(PP^o_{s,i}\right)^{1-\sigma_{s,i}}}{\sum_f \theta^f_{s,i}\left(PP^f_{s,i}\right)^{1-\sigma_{s,i}}}$$

This can alternatively be expressed as:

$$\text{(A26)} \qquad \alpha_{s.i} = \left(\xi^o_{s,i} + \sigma_{s,i}\right)\frac{\sum_f \theta^f_{s,i}\left(\overline{PP}^f_{s,i}\right)^{1-\sigma_{s,i}}}{\theta^o_{s,i}\left(\overline{PP}^o_{s,i}\right)^{1-\sigma_{s,i}}} - \sigma_{s,i}$$

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

$$\text{(A26*)} \qquad \alpha_{s.i} = \frac{\xi^o_{s,i} + \sigma_{s,i}}{\theta^o_{s,i}} - \sigma_{s,i}$$

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.

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

Oil Demand share by sector and region

Table A2. Oil demand share by sector and region in 2007. Per cent.

	Western Europe	OPEC	Rest-OECD	Rest of the world	Russia	U.S.	Average sector share of total oil demand
Industry	21	23	27	25	30	19	23
Households	7	7	5	8	6	3	6
Other Sectors	5	3	9	7	6	3	6
Power Generation	4	20	10	11	12	2	8
Road and Rail Transport	46	38	40	37	36	60	45
Aviation and Domestic Shipping	9	4	7	7	8	9	8
International Shipping	8	6	3	5	2	3	5
Total Regional Oil Demand	100	100	100	100	100	100	