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Oil market impacts and welfare effects

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Abstract:
This paper studies the oil market effects of phasing out oil consumption subsidies in the transport sector. Welfare effects in different countries are also examined. We investigate potential feedback mechanisms of oil subsidy removal via lower oil prices in the global oil market, which may stimulate oil consumption in other regions. An intertemporal numerical model of the international oil market is applied, where OPEC-Core producers have market power. The major subsidizers of oil are OPEC countries, and we find that the effects of subsidy removal here are quite pronounced. Consumption of oil in the transport sector of OPEC countries declines significantly. As a result, the global oil price falls slightly, and other regions increase their oil consumption to some degree. Although OPEC consumers are worse off by the subsidy removal, total welfare in OPEC increases due to higher profits from oil production.

Keywords: Fossil fuel subsidies; transport; oil market; market power; distribution: feedback mechanisms

JEL classification: D42; Q54; R48

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Sammendrag

Konsum av fossil energi er subsidiert i OPEC og mange andre land utenfor OECD. I dette arbeidet ser vi på effektene i det globale oljemarkedet ved utfasing av forbrukersubsidiene til olje i transportsektoren. Det skjer i dag en gradvis utfasing av disse subsidiene, noe som kan begrunnes både utfra fiskale hensyn og klimapolitikk. Vi benytter en intertemporal numerisk modell for det internasjonale oljemarkedet, der en kjerne av OPEC-produsenter har markedsmakt. Oljeforbruket regnes som subsidiert dersom prisen på hjemmemarkedet er lavere enn den internasjonale prisen. Vi finner at fjerning av subsidier vil redusere etterspørselen etter olje i transportsektoren i OPEC og dette gir til en viss grad lavere global oljepris. Dette fører til at forbruket øker en del i andre regioner. Resultatene gir en svak støtte til «det grønne paradoks», det vil si at oljeproduksjonen øker initialt ettersom oljeprodusentenes framtidsutsikter blir dårligere når oljesubsidiene fjernes over tid. Konsumentene i OPEC vil ha et velferdstap som følge av at subsidiene blir fjernet, men velferdsøkningen for OPEC samlet fra å selge oljen til verdensmarkedspris mer enn oppveier denne negative effekten. Sett fra Norge vil subsidieutfasing føre til noe lavere oljeprisbane framover..

1. Introduction

Many countries subsidize the production and consumption of fossil fuels. Most subsidies are given downstream, that is, to reduce the cost of consuming fossil fuels (Coady et al, 2016). While fossil fuel subsidies benefit fuel consumers, at least in the short run, such subsidies have a number of negative effects (IEA, 2014). First, they contribute to fiscal imbalances and thus crowd out other government spending. Second, subsidies stimulate excessive fossil fuel consumption contributing to increased emissions of harmful pollution such as CO_2. Finally, in the long run low oil prices encourage the development of energy-intensive industries and discourage development of renewable technologies. Despite the negative effects it has proven difficult to remove fossil fuel subsidies. In many countries fossil fuel subsidies were originally introduced to improve consumer welfare and proposals to remove such subsidies could result in citizen protests. We find, however, that the biggest subsidizers may increase their welfare by removing its oil subsidies. The reason is that subsidy removal allows these countries to shift oil from the domestic market to the international market where prices are higher.

The biggest fossil fuel subsidizers are also major producers and exporters of oil and gas. In fact, the heaviest fossil fuel subsidizers are the OPEC-countries, mostly located in the Middle-East and North-Africa (MENA) region. Public spending on subsidies – estimated as the gap between international and domestic prices – is, on average, much higher in the oil exporting MENA region than in other countries. In particular, there are extensive subsidies in the transport sector. According to IMF (2014), subsidies of gasoline and diesel in the MENA countries, representing around half of all energy subsidies in the region, amounted to almost 4 per cent of the regional GDP in 2012. Oil products used in the transport sector are also subsidized to a certain degree in other Non-OECD countries (GIZ, 2014). In this study we examine the effects of eliminating subsidies in the transport sector, focusing especially on the OPEC countries but also some other Non-OECD countries.

Price control is often a key element in fossil fuel consumption subsidies. However, subsidies can also include cash transfers directly to consumers, as well as tax exemptions and rebates. Assessing the magnitude of fossil fuels subsidies in all its forms is a task challenged by poor data quality, limited data availability and lack of data comparability (Ellis, 2010). Like many other studies we use the price-gap method, which calculates the combined effect of reducing the wedge between domestic and international (reference) prices (Koplow, 2009). The reference price on goods that are traded on the international market, like oil, is usually the international or border price adjusted for market exchange rates, transport and distributional costs, and country specific taxes and tariffs. As we focus on price-gap subsidies in the transport sector, we can apply a consistent and uniform dataset as in GIZ (2014) (former GTZ), which lists the retail prices of diesel and gasoline in 174 countries, and assess the effects of subsidy reforms.[1]

Oil prices were halved from October 2014 to January 2015, and are, according to current futures prices, expected to remain around 50-60 USD per barrel for several years. The oil price fall presents countries with a unique opportunity to phase out fossil fuel consumption subsidies, since the wedge between the global oil prices and the domestic prices in subsidizing countries have been reduced. As a result, consumers would be less hurt by subsidy removal, at least in the short run. In addition, the recent drop in the oil price has reduced government incomes in OPEC countries, and removal of fossil fuel subsidies would help improve fiscal balances. Several OPEC countries have recently reduced (implicit) subsidies on gasoline and diesel, including Angola, UAE, Saudi-Arabia, Iran, Kuwait and Qatar (IEA, 2016a). In 2016, fuel prices in Venezuela increased dramatically due to reduced subsidies (Bloomberg, 2016). Other countries outside OPEC, such as India, have also started similar price reforms on gasoline and diesel (IEA, 2016a).

This paper analyzes how removal of oil consumption subsidies in the transport sectors might affect oil consumption and production in major geographic regions in the world. The transport sector is important for the oil market as it currently accounts for 54 per cent of the world's fuel liquid consumption, and the share is expected to increase to almost 60 per cent in 2040 (IEA, 2014). We focus on subsidy removal primarily in OPEC countries, but also to a certain extent in other countries. We also consider a situation where all subsidizing countries introduce moderate fuel taxes. We compare the welfare effects of these policies for different regions, distinguishing between effects on consumers, producers and the government. To analyse these effects, we use a numerical model of the international oil market called Petro2 (Aune et al, 2016). The model incorporates dynamic behavior by oil producers, and distinguishes between competitive producers and producers with market power. The model is described in more detail below.

Our analysis suggests that OPEC may achieve significant welfare gains by removing the oil subsidies in their transport sector. On the one hand, OPEC consumers experience a loss due to the higher consumer prices following subsidy removal. In addition, there is a producer surplus loss following a

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[1] Note that fossil fuel consumption is also subsidized through other means, such as research programs and favorable investment financing, which we do not consider here. Our analysis also omits subsidies that are given in the form of uncompensated negative environmental externalities from energy consumption and production.

lower world market oil price. On the other hand, removing oil subsidies involves a huge transfer from oil consumers to the government (or to oil producers, depending on who is in fact paying the subsidies), such that the losses from reduced subsidies are dominated by government gains. The reason is that subsidy removal reduces OPEC oil consumption, and this oil can be sold in the global oil market at significantly higher prices. In other words, the willingness to pay for oil is higher in the global oil market than within OPEC (before subsidies are removed). Further, we find that when all countries remove oil subsidies in the transport sector, the global welfare gains increase. However, our analysis suggests that this leads to lower welfare gains for OPEC as the value of their oil resources deteriorates due to lower oil prices. This is described in more detail in Section 4.3.

Although subsidy removal may be profitable for OPEC, it may have some feedback effects in the oil market that is worth studying. One feedback mechanism is leakage, i.e. reduced demand for oil in the transport sector in OPEC may lead to lower oil prices and correspondingly higher consumption in other countries (see, e.g., Felder and Rutherford, 1993; Böhringer et al, 2014). Another feedback mechanism is related to the “green paradox” (see e.g. Sinn, 2008; van der Ploeg and Withagen, 2012), 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 phasing out of subsidies, more stringent climate policies etc. The two feedback mechanisms are related to each other, and both are highly dependent on the price responsiveness of demand and supply in the energy markets. The more price responsive demand is relative to supply, the bigger the leakage effects. As indicated above, the green paradox effect depends heavily on the timing of the subsidy removal, but also on the price responsiveness.

Two characteristics of the oil market may be of particular importance when we study the feedback mechanisms of subsidy removal, namely market power and intertemporal behavior. 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; Huntington et al., 2013).[2] 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 been made in earlier simulation models of the oil market (e.g., Salant, 1982;

[2] After the substantial decline in the oil price since 2014, a question could be raised whether OPEC’s behavior has changed. However, the current situation is to a certain extent similar 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 (Alkhathlan et al, 2014).

Berg et al., 1997, 2002; Aune et al., 2010; Okullo et al., 2015). However, none of these studies analyze the effects of phasing out subsidies.[3]

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 (Hotelling, 1931). This is taken into account in our model, as oil producers are forward-looking and maximize their net present value of oil extraction. This dynamic feature is important for the "green paradox" effect.

Many studies have analyzed different effects of reducing fossil fuel subsidies. Ellis (2010) surveys five studies that examine the effect of reducing price-gap subsidies on fossil fuels. All studies find an increase in welfare in the countries where policy measures are taken. Burniaux and Chateau (2014) presents an analysis of a phase out of fossil fuel price-gap consumption subsidies based on a general equilibrium model. Their analysis suggests that such a subsidy reform will reduce GHG-emissions and be welfare improving for the world as a whole, although some regions will experience reduced welfare. The above mentioned studies do not focus on fuel subsidies in particular and their impact on the global oil market. Some studies focus on the effects of fuel subsidy removal on the subsidizing country's welfare, using oil supply and demand elasticities, such as Larsen and Shah (1992), Salehi-Isfahini (1996) and Gurer and Ban (2000). Despite the huge subsidies in the transport sector, we have only found one study that focuses on the effects of fuel subsidy removal on the global oil market, i.e. Balke et al (2015). They find that subsidy removal in 24 oil-producing countries generally is welfare enhancing for both oil-importing and oil-exporting countries. However, their model is static and the producers have competitive behavior. Thus, our contribution is to study the implications for the oil market, taking into account both market power and the intertemporal aspect of exhaustible resources.

The paper is organized as follows. Section 2 describes the Petro2 model, Section 3 presents the policy scenarios analyzed, the approach used in the analysis of welfare effects, and results from the numerical model. Section 4 concludes.

2. Model description

Petro2 is a dynamic simulation model that permits for analysing oil market effects of policy changes or other external shocks to the market (e.g., shifts in cost or oil reserve levels). The main outputs from

[3] Somewhat related, Berg et al (1997) study the effects of a global carbon tax for the fossil fuel markets, finding that when OPEC acts as a cartel, the crude oil price is almost unchanged as OPEC reduces production in order to maintain a high oil price level, whereas the price effect is much stronger under a hypothetical competitive market setting.

the model are oil prices and production/consumption in different regions and sectors, both in the short and long run. Petro2 has seven regions: Western-Europe, United States, Rest-OECD, China, Russia, OPEC and Rest-of-World. In each region there are six energy consuming sectors: Industry, household, electricity, road and rail transport, domestic/international aviation and domestic shipping, and other sectors. There is also one global sector: international shipping. Each sector in each region demands oil, natural gas, electricity, coal, biomass and biofuel. The oil price is endogenous, whereas the prices of the other energy goods are exogenous (based on projections from the IEA, 2013). In this study we focus on oil and the transport sectors. On the supply side OPEC is divided into OPEC-Core (Saudi-Arabia, Kuwait, UAE and Qatar) and non-Core OPEC, assuming that only OPEC-Core exerts market power. The supply of oil in all regions is modeled intertemporally, meaning that oil producers maximize the net present value of current and future extraction.

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. Appendix A provides a formal description.

2.1. Demand

Every region and sector demands an energy aggregate, modeled as a Constant Elasticity of Substitution (CES)-aggregate of the various energy goods. The price of this energy aggregate (in a sector in a region) is assumed to be the weighted CES-aggregate of the prices of these energy goods, where the initial budget shares are weights. The model specifies the long-term demand for the energy aggregate as log-linear functions of population, income (GDP) per capita, and price of the energy aggregate. 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 specific energy good.

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 and regional product prices are linked as follows: The end-user price of a given fuel in a given sector and region 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.

End-user prices, regional product prices and taxes/subsidies are generally taken from OECD (2009), IEA (2016b), GTZ (2009) and GIZ (2014). 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 (2013). Costs of transportation, distribution and refining as well as taxes/subsidies are held constant (in USD_{2007}) over the time horizon. Thus, future end-user prices move in tandem with future product prices.

The demand functions are calibrated to agree with consumption of the respective energy goods in 2007 given prices and taxes/subsidies this year. Growth rates of GDP and population are exogenous in the model. 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 (2013), 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 capita in 2035 (this is adjusted for each sector).

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 (2016)[4]. The substitution possibilities determine how fast the demand for a particular energy good responds 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 (see, e.g., Serletis et al, 2011).[5] 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 (2013) up until 2035, and then as depicted in IPCC (2014) from 2035 to 2100.[6]

2.2. Oil Supply

Production allocation over time is important for the suppliers since oil is an exhaustible resource. Extracting one more unit today will affect a supplier's costs or access to oil resources in the future. Hence, a rational producer will not only consider the current price or market condition before choosing the current optimal oil supply. 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. Oil

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

[5] Except for the power sector where it is set to 2.

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

production in OPEC is more government-controlled than in most other regions. Their oil extraction is also to a larger extent than Non-OPEC countries undertaken by state-owned companies. Thus, OPEC may attach more weight to long-term income than most other producers.

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 with one Cournot producer and a competitive fringe. Production figures are from IEA (2016b).

The initial cost level of the different producer groups differs, reflecting among other things that extraction costs in OPEC-countries generally are 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 of the oil resources. The scarcity rent of a producer then reflects that extracting one more unit today increases costs tomorrow. Hence, we focus on economic exhaustion rather than physical exhaustion. The depletion rates in the cost functions are calibrated based on data and supply projections from EIA (2012), IEA (2013, 2014) and Lindholt (2013), and varies substantially across regions (lowest for OPEC and highest for Western Europe).

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 all producers.

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 is 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 for the fringe producers must be equal to marginal costs plus the scarcity rent. The latter is the negative of the shadow costs associated with cumulative production, i.e., 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 oil subsidy removal in transport sectors

As subsidies are removed, consumer prices rise in previously subsidizing countries. Consumers in these countries will buy less oil, and this will put a downward pressure on the global oil price. So while removal of oil subsidies reduces oil consumption in some regions, oil consumption will likely increase elsewhere. Below we explore the oil market effects of three scenarios for oil subsidy removal. We also estimate the welfare changes following subsidy removal for consumers, producers and the government for the OPEC core countries. A brief sensitivity analysis with respect to the calibration of important Petro2 parameters is given in Appendix B.

3.1 Policy scenarios

We consider three policy scenarios for fossil fuel subsidies removal in the transport sector, see Table 1, and compare the effects for the oil market and for the welfare in different countries. In the first scenario, subsidies are removed only in OPEC countries, while in the second scenario subsidies are removed in other countries, too. Removal of fossil fuel subsidies could be driven by fiscal necessity but also by international pressure related to climate policy. The third scenario considers the case where, in addition to subsidy removal, fuel taxes in the transport sector are increased to the current US level (regions with tax levels at least as high as in the US do not change their taxes). While removal of fossil fuel subsidies would improve the fiscal situation of subsidizing countries, these countries may also experience social instability when consumers' welfare is reduced. If the overall welfare effect in society is positive, fossil fuel consumers may be compensated for their welfare loss. For each scenario we explore the welfare effects to see if such compensation is feasible.

Subsidy removal is implemented in the model by removing negative wedges between the global oil market price (plus fixed transport and distributional costs) and the domestic price for oil in the transport sector (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 (2013) until 2035, and then assumes a gradual decline in the use of oil in all sectors of the economy (following, e.g., IPCC, 2014).

Table 1. Policy scenarios for subsidy removal

Scenario name	**Scenario description**
Reference scenario	Follows the New Policy Scenario in IEA (2013) until 2035. A gradual decline in the growth of oil demand thereafter.
TranspOPEC	Gradually phase out fossil fuel consumption subsidies to all transport sectors in OPEC within 2020
TranspAll	Gradually phase out fossil fuel consumption subsidies to all transport sectors globally within 2020
TranspTax	Gradually phase out all fossil consumption subsidies to transport sectors globally, and move to a minimum of US tax levels in all regions within 2020

4. Numerical analysis

In this section we present numerical results for the oil market from the different simulations, including region specific effects on welfare following the subsidy removal policies. Before examining the policy scenarios, we briefly present the reference scenario.

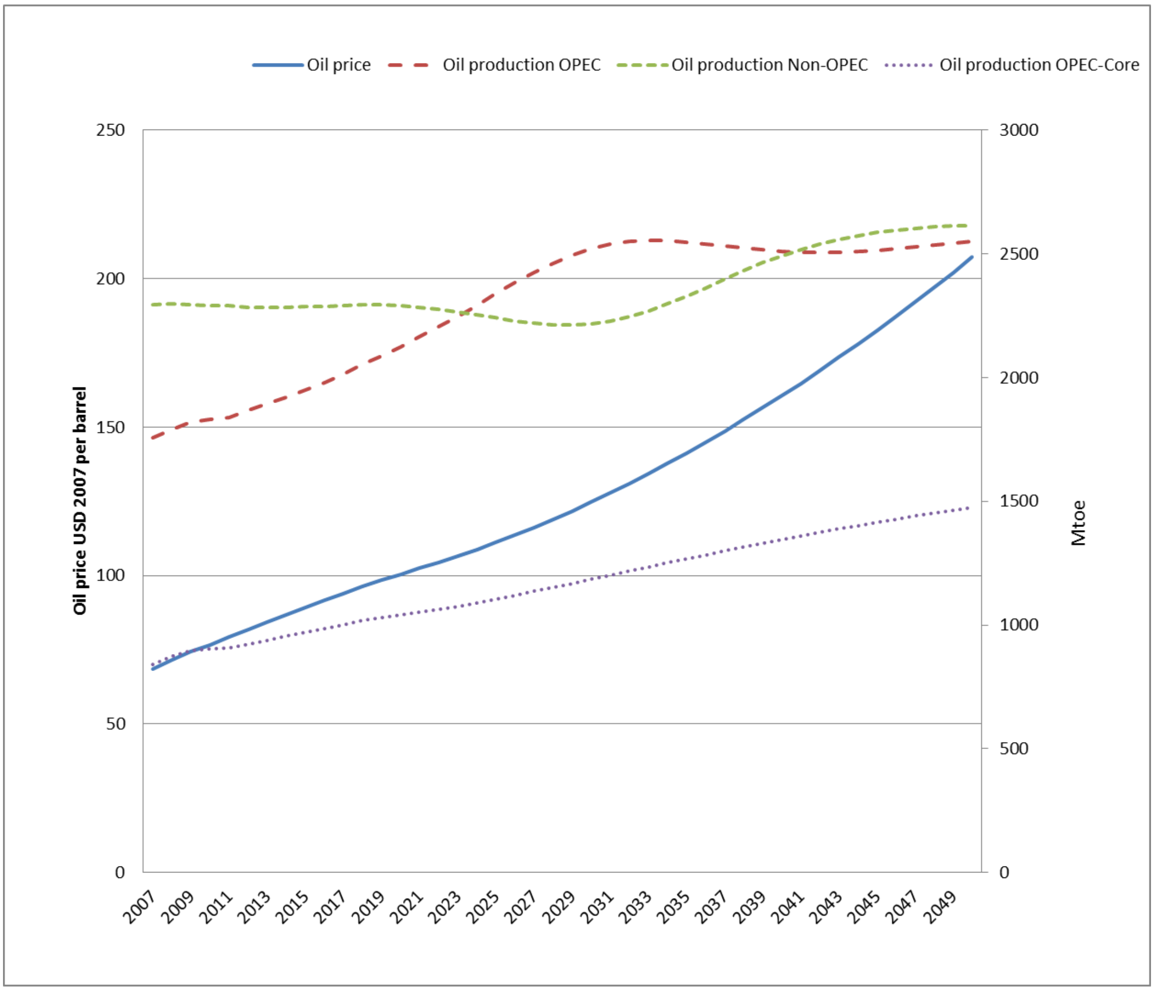
4.1 Simulation results: Reference scenario

Figure 1 shows the development of the oil price towards 2050 in the reference scenario. We emphasize that the reference scenario is not a projection of the future, but a starting point 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 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. 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 (2015), but in the range of their Current Policy Scenario up to 2040. Note that the price growth in the reference scenario is not important for the effects of the various policy scenarios.

Figure 1 also shows the development in OPEC and Non-OPEC production towards 2050. We notice that global production is increasing over time, especially until 2040, and that OPEC's market share is growing. The latter is due to bigger reserves and lower extraction costs than in Non-OPEC countries.

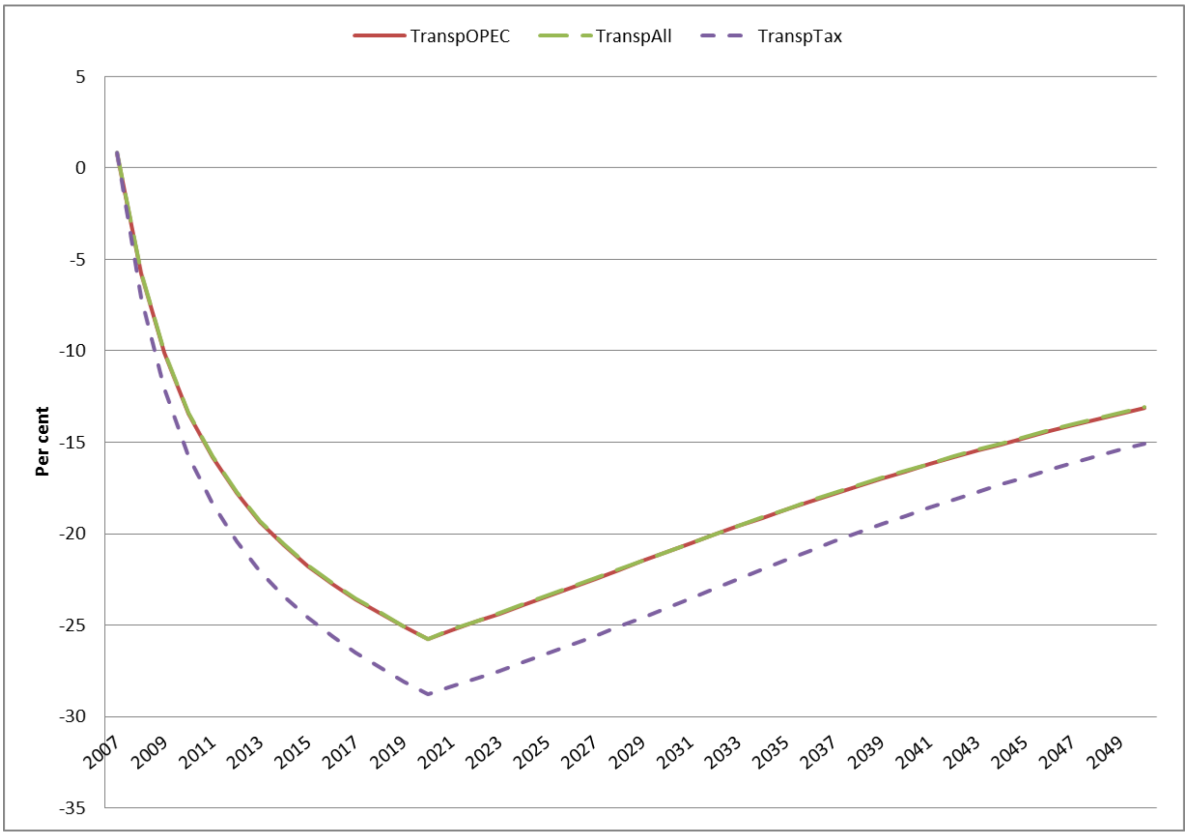
Figure 1. Reference scenario. Oil price (USD_{2007} per barrel), OPEC oil production (Mtoe) and Non-OPEC oil production (Mtoe).



4.2 Simulation results: Policy scenarios

Figure 2 shows the effects on oil consumption in the transport sector in OPEC in the three policy scenarios. If fuel subsidies are gradually removed over the period 2007-2020, fuel demand contracts substantially, with 26 per cent reduction in 2020. After 2020, the relative reduction is moderated somewhat as the relative importance of the existing subsidies declines along with higher oil prices in the reference scenario. Removing subsidies in other Non-OECD countries could have some indirect effects on OPEC consumption through oil price changes, but these effects are negligible (see the figure). However, if fuel taxes are also implemented in OPEC countries (at US levels), oil demand is further reduced by an additional 3 percentage points. Thus, removing fuel subsidies has far bigger impacts on OPEC's oil demand than implementing fuel taxation at US levels.

Figure 2. Percentage changes in oil consumption in the OPEC transport sector compared to the reference scenario.



Effects on global consumption of oil in the transport sector are shown in Figure 3. In the scenario where only OPEC countries remove their subsidies, global consumption is reduced by up to 3 per cent.

This reflects that OPEC countries account for almost 10 per cent of global oil consumption in the transport sector in 2020. However, due to somewhat lower oil prices (see Figure 4) there is a slight increase in oil demand in Non-OPEC countries' transport sector. The oil consumption leakage is 22 per cent in 2020 in the scenario when only OPEC countries remove their subsidies. When all countries remove their subsidies, the decline in oil consumption is only slightly bigger, as fuel subsidies are much more widespread in OPEC countries than in most other countries. Implementing fuel taxes at a minimum of US levels has bigger impacts on oil consumption, cf. Figure 3.

We also notice from the figure that there is in fact a slight increase in initial oil consumption in the three policy scenarios. The explanation is that oil producers (mainly OPEC-Core), foreseeing that fuel subsidies are gradually removed over time, realize that future oil prices will be reduced. As a result, it is optimal to accelerate extraction to some degree, implying slightly lower oil prices also initially. We return to this issue below (in relation to Figure 5).

Figure 3. Percentage changes in oil consumption in the global transport sector compared to the reference scenario.

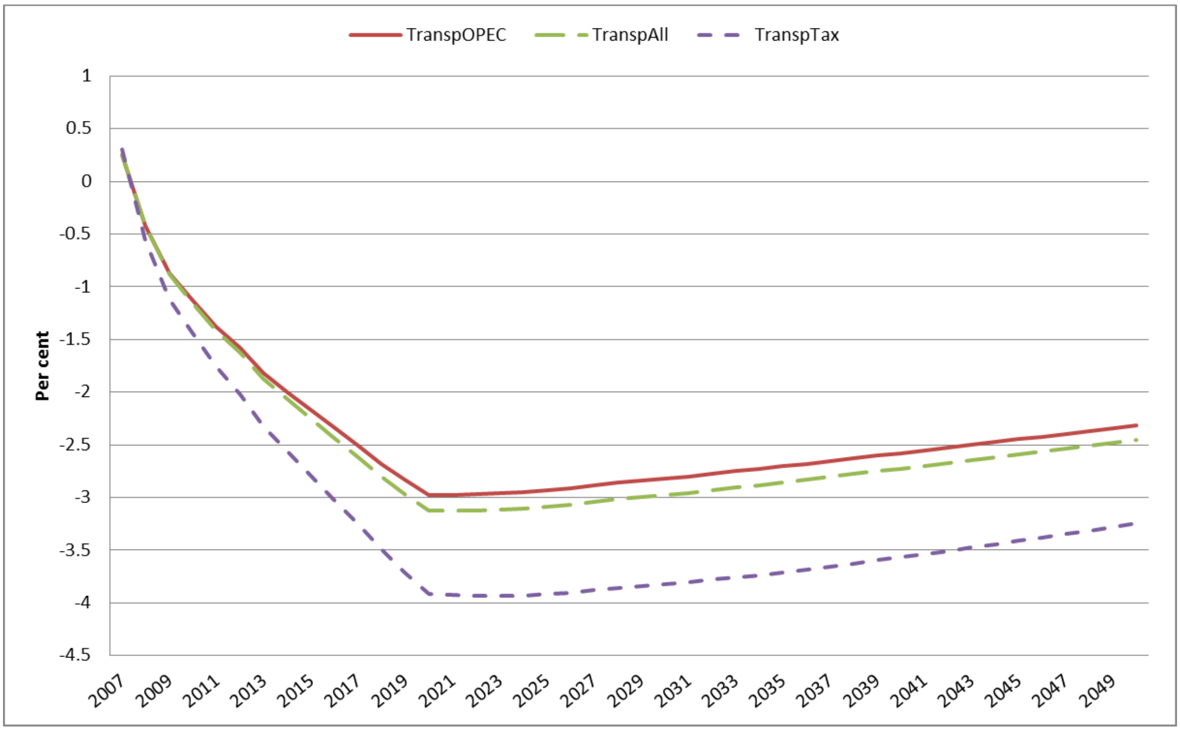
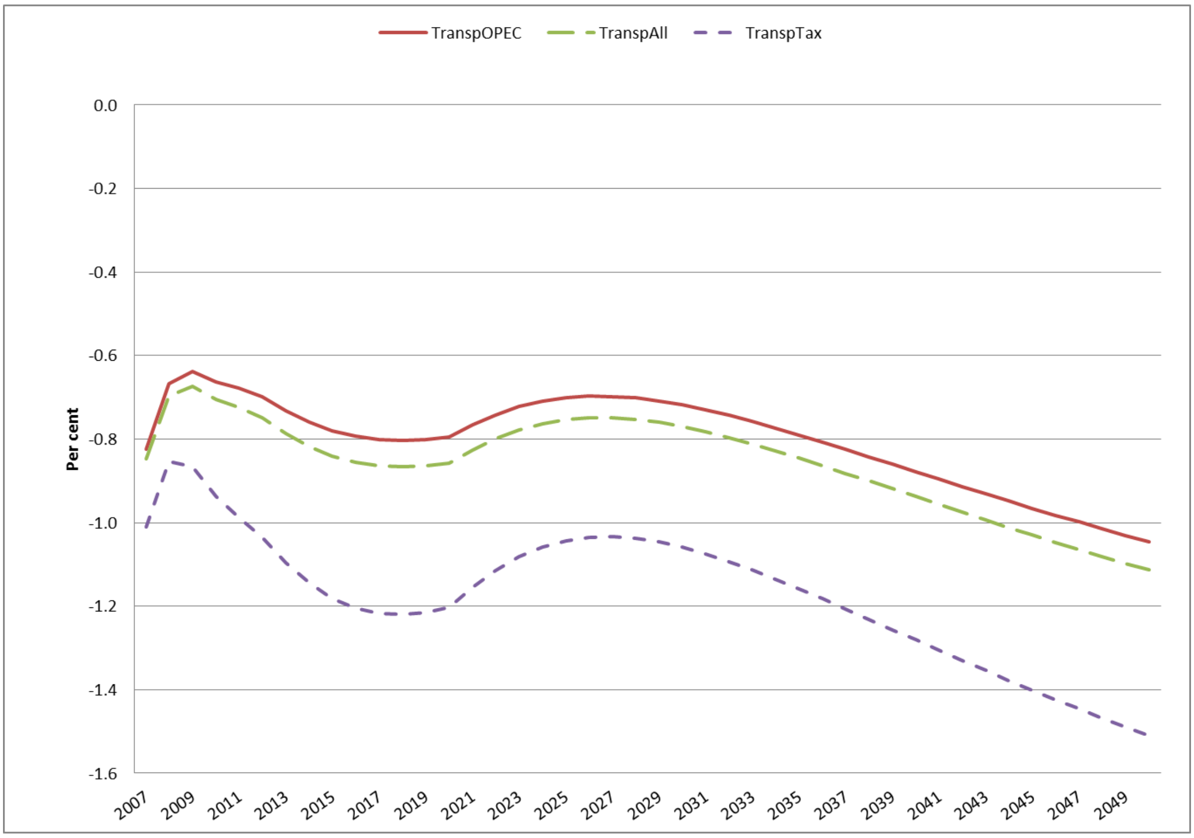


Figure 4 shows the percentage change in the oil price towards 2050 compared to the reference scenario. A removal of subsidies to oil in OPEC, with associated reduced consumption, persistently lowers the oil market price by 0.7 to 1 per cent (until 2050). Removing subsidies in other countries as well have limited impacts as subsidies are much more prevalent in OPEC than in most other countries. One reason for the moderate price effect is that lower oil prices lead to increased demand in other countries, dampening the initial price effect of reduced demand due to subsidy removal. We have only found one study that looks at subsidy removal when the oil price is endogenous (Balke, 2015). However, the oil price decline in our study is lower than in their study, where the removal of fuel subsidies in oil producing countries would reduce the world market price of oil by six per cent. Part of the reason could be that we model OPEC-Core as a cartel, which finds it profitable to reduce production to prevent the oil price from declining too much (see Figures 5-6 below).

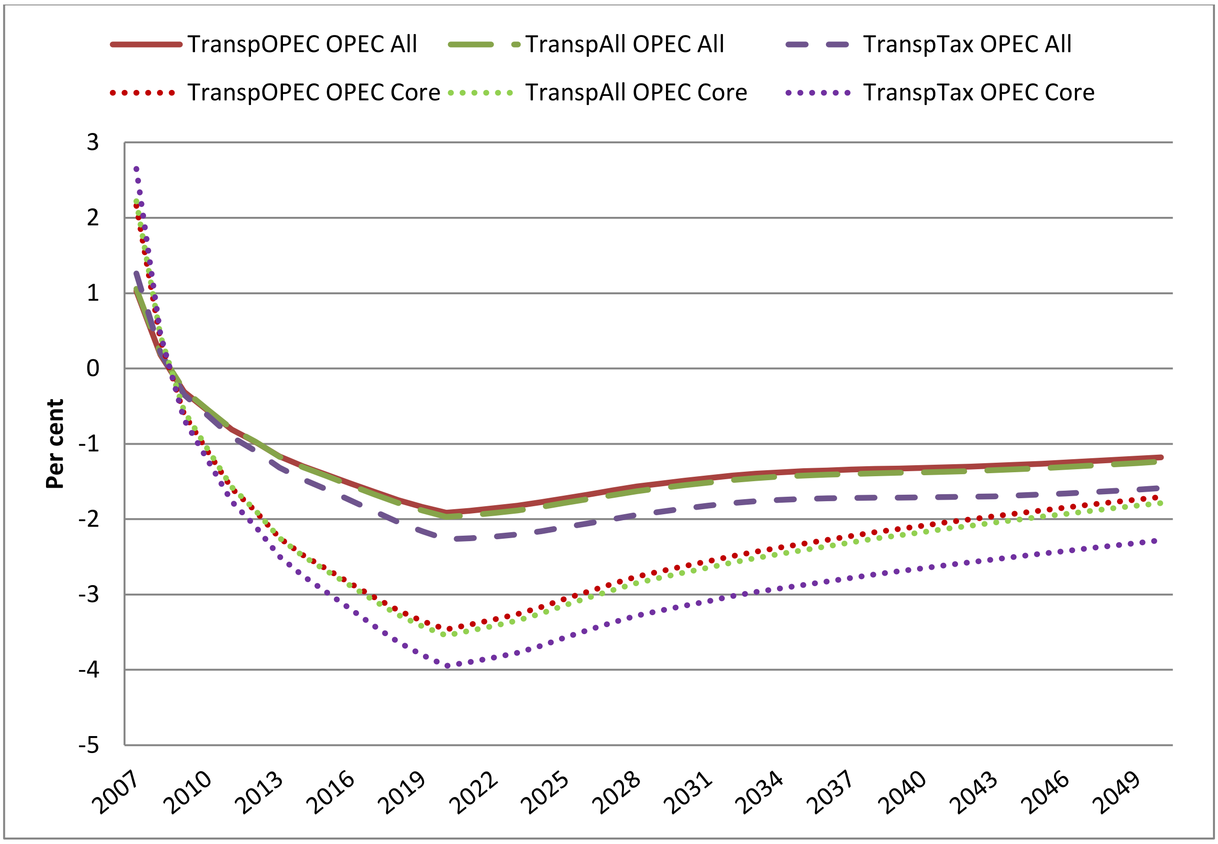
Figure 4. Percentage changes in the global oil price compared to the reference scenario



Furthermore, we see from the figure that if fuel taxes in the transport sector are increased in all regions up to a minimum of the current US level (i.e., regions with initially higher fuel taxes do not change their tax levels), the oil price declines somewhat more, i.e., by 1 to 1.5 per cent. Still, it is fair to conclude that the oil price is not much affected by subsidy removal or moderate fuel taxation.

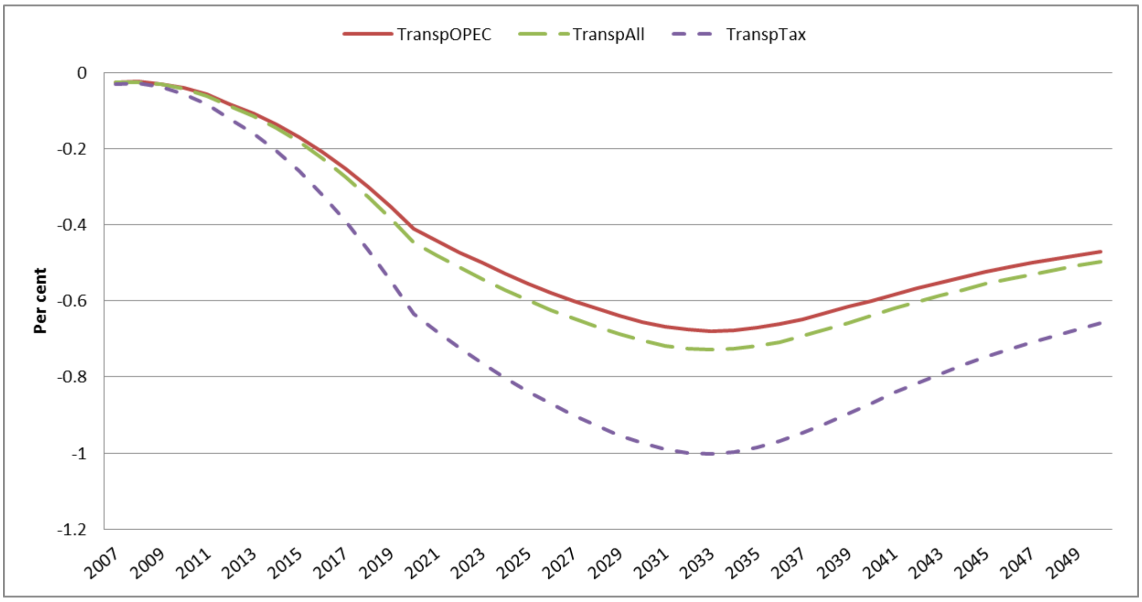
Figures 5 and 6 show the production of OPEC and Non-OPEC countries, respectively.[7] Both groups of producers reduce their oil production in the policy scenarios. Except for the first few years, we see that the biggest reduction comes from OPEC-Core. This reflects that OPEC-Core takes into account its market power, knowing that it can influence the oil price by cutting back on its production when demand contracts. On the other hand, we also notice that OPEC-Core produces more initially (Figure 5) to compensate for the bleaker demand prospects in future years. This is similar to the “green paradox” effect mentioned in the introduction, which is a result of our modelling of oil as an exhaustible resource. That is, extraction of oil has intertemporal effects as it reduces available resources in the future. Due to spare capacity, OPEC-Core is more able to adjust its initial production than other oil producers, who hardly change their initial extraction as a result of the subsidy removal.

Figure 5 Percentage changes in OPEC and OPEC Core oil production compared to the reference scenario.



[7] OPEC production includes the production of OPEC-Core countries as well as the production of non-Core OPEC countries.

Figure 6. Percentage changes in Non-OPEC oil production compared to the reference scenario.



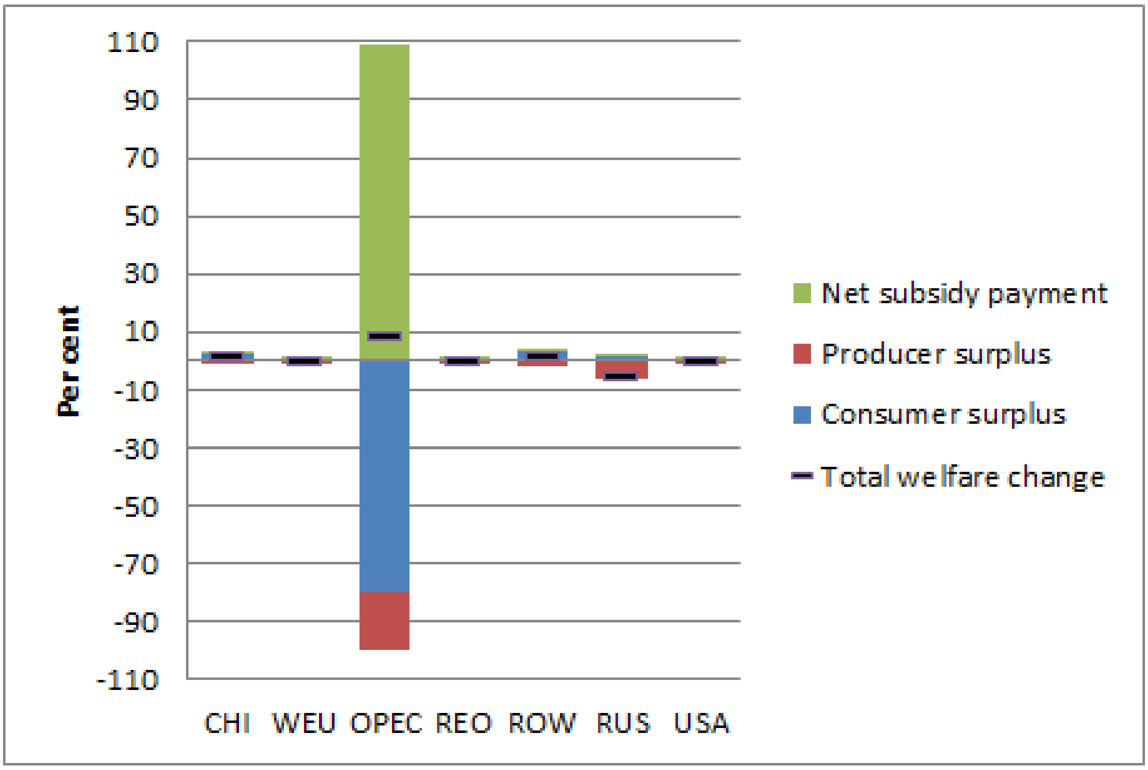
4.3 Welfare effects following subsidy removal policies

This section examines how removing oil subsidies in the transport sector affects welfare. We approximate changes in welfare, as compared with the reference scenario, using yearly changes in consumer surplus, producer surplus and net subsidy payments. We then calculate the present values of these changes for all regions and sectors over time, using a yearly social discount rate of 5 per cent and linear approximations to the demand and supply functions around the market outcome.

The welfare effects following subsidy removal policies in a given region depend on whether it is a net exporter or net importer of oil. As shown in the previous section, subsidy removal reduces the global oil price. This affects the terms of trade between regions. Whereas lower oil prices benefit net oil importers through a lower net oil import bill, net exporters loose income from oil sales. Further, removing oil subsidies involves a transfer from oil consumers to the government. We do not consider the distributional effects this may have in the present paper, and consumer losses from reduced subsidies are to a large extent dominated by government gains.

Figure 7 shows the changes in regional welfare, relative to the reference scenario, for the simulation where we phase out fossil fuel consumption subsidies to all transport sectors in OPEC within 2020 (TranspOPEC). In order to get a sense of the magnitudes, we present the figures as percentages of regional GDP in 2007.[8] As expected, the effects are much larger in OPEC than in the other parts of the world.

Figure 7. Approximated changes in regional welfare in the TranspOPEC scenario compared to the reference scenario. Net present value as per cent of regional GDP in 2007.



* CHI: China, WEU: Western Europe, OPEC: OPEC countries, REO: Rest of OECD, ROW: Rest of the world, RUS: Russia, USA: United States of America.

The net present value of the welfare gain amounts to 9 per cent of the base year GDP in OPEC. Except for Russia and Rest of OECD, all other regions are net importers of oil over the whole time horizon and thus also experience welfare gains due to lower oil prices, but the magnitudes are modest and less than 2 per cent of regional base year GDP. Russia is a net exporter of oil and loose due the lower oil prices. The Russian welfare loss is approximated to 5 per cent of its GDP. Rest of OECD switches from being a net importer to a net exporter in 2034 (in all scenarios), and gains very little from lower oil prices.

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[8] That is, 100 multiplied with the present value of the sum of changes in current and future welfare for a given region divided by regional GDP in 2007, using a yearly discount rate of 5 per cent. An alternative is to weigh the present value welfare changes against the present value stream of future regional GDP figures used in the model. This yields a welfare gain equal to 0.3 per cent for OPEC (see also Figure 8).

As expected, OPEC consumers experience a loss due to the higher consumer prices following subsidy removal. Regarding changes in OPEC oil revenue, the change in producer surplus depicted in Figure 7 refers to the initial producer surplus loss following a lower world market oil price. On the other hand, we know that subsidy removal allows OPEC to sell all its oil at the world market oil price, which is substantially higher than the low subsidized prices in the reference scenario. The associated increase in oil revenue is equal to the "net subsidy payment" in Figure 7. OPEC also increases its yearly oil exports by between 1 and 2 per cent (it varies over time) when OPEC consumer subsidies are removed. The change in the value of OPEC oil resources following subsidy removal may be interpreted as equal to the sum of "net subsidy payment" and "producer surplus" in Figure 7.[9]

The significant welfare gain in OPEC may explain why Saudi Arabia, UAE and other OPEC countries reduced their oil subsidies on gasoline and diesel in 2015 (IEA, 2016b). As we see in Figure 7, however, there is a substantial OPEC consumer loss associated with subsidy removal, which can make these policies unpopular and difficult to implement. This may help explaining the timing of the OPEC members' cut in oil subsidies. That is, they may use the current low oil price to dampen the experienced loss in consumer surplus following oil market subsidy reductions.

Figure 8 illustrates how phasing out OPEC fossil fuel transportation subsidies affects the producer surplus, consumer surplus and net subsidy payments in OPEC over time. The first two years feature a drop in OPEC consumer oil prices, and hence a positive change in consumer surplus. The explanation is that subsidy removal is only gradually implemented, and initially this effect is dominated by the fall in the world oil prices (cf. discussion of this above). Thereafter, the changes in the welfare components all have the expected sign. The total change in welfare, measured in percentages of OPEC yearly GDP, grows initially as the subsidy is phased out and peaks at 0.61 per cent. The increase in projected GDP thereafter causes a gradual decline in the percentage welfare change over time. These results are in the range of the findings of the studies surveyed by Ellis (2010), which showed that GDP increased from 0.10 to 0.70 per cent per year from 2010 to 2040 in the countries that introduced subsidy reforms.

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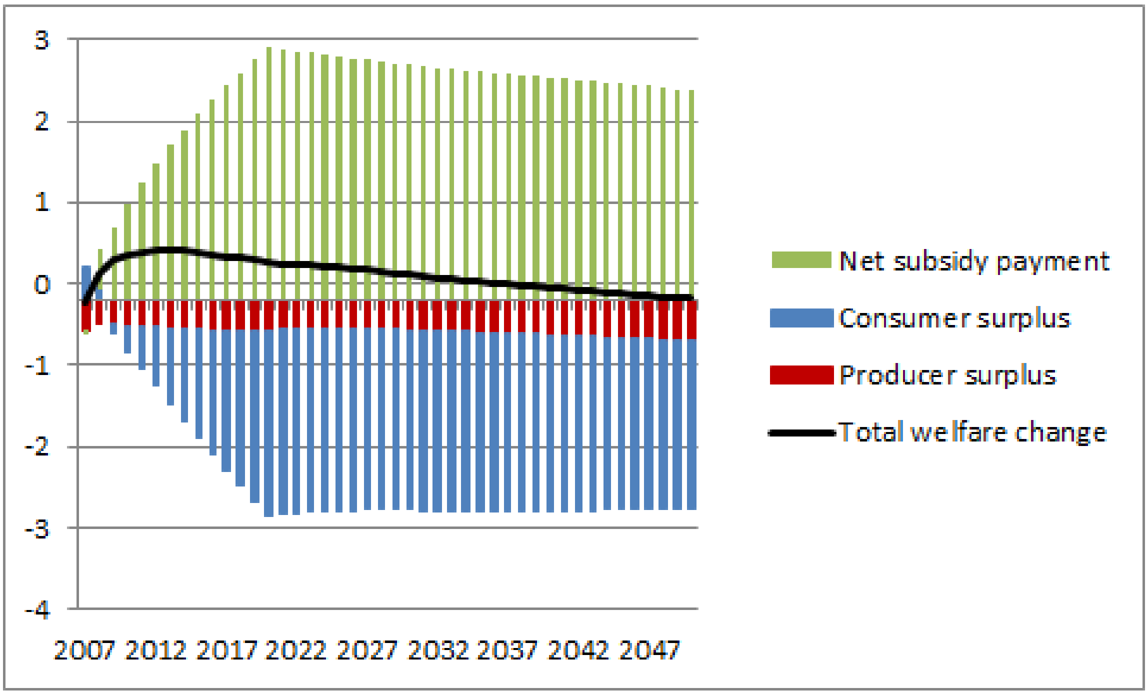
[9] This interpretation of "net subsidy payment" is mainly valid for OPEC, which is a net exporter of oil in all scenarios. It requires the assumption that OPEC first sells oil to its own consumers at low (subsidized) prices, and then sells the rest of yearly oil production in the global oil market.

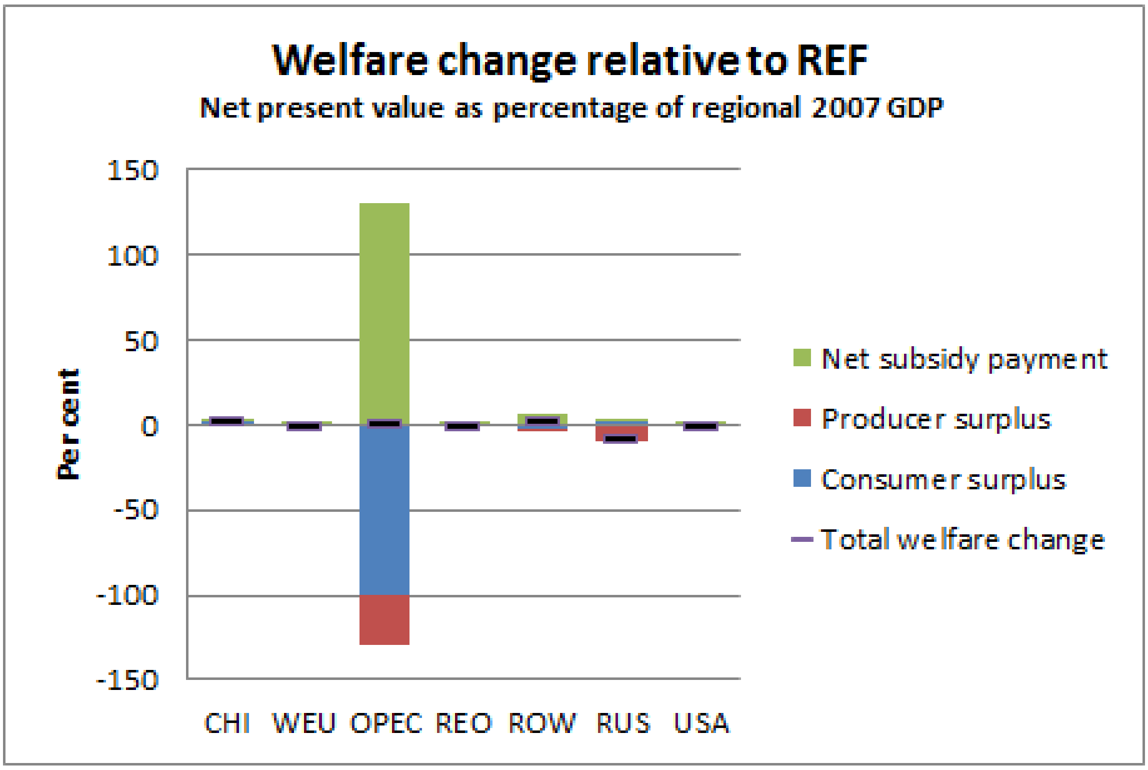
Figure 8. Approximated undiscounted yearly welfare changes in OPEC in the TranspOPEC scenario compared to the reference scenario. Per cent of yearly GDP.



The second scenario we consider in this section is the TranspTax scenario, where we phase out all oil consumption subsidies to transport sectors and implement US transport tax levels in all regions within 2020 (given that the region initially has taxes below US tax levels).[10] As expected the effects are somewhat larger in all regions, but still small compared with OPEC, see Figure 9. The lower global oil price reduces the value of oil further and the decline in producer surpluses are larger than those associated with the TranspOPEC scenario. OPEC welfare gain is therefore only 2 per cent, and Russia now experiences a welfare loss equal to 7 per cent. Except for OPEC, the largest net welfare gain is in China (2 per cent), where consumers benefit from lower oil prices. The robustness of our results with respect to important parameters is presented in Appendix B.

[10] The results in the TranspAll scenario are very similar to those of TranspOpec, and therefore omitted from this section.

Figure 9. Approximated changes in regional welfare in the TranspTax scenario compared to the reference scenario. Net present value as per cent of regional GDP in 2007.



* CHI: China, WEU: Western Europe, OPEC: OPEC countries, REO: Rest of OECD, ROW: Rest of the world, RUS: Russia, USA: United States of America.

5. Conclusions

Many OPEC countries and some other Non-OECD countries subsidize fossil fuel consumption, which is problematic for a number of reasons. It leads to inefficiently high consumption, depletes government finances and has negative environmental effects. Countries subsidize fossil fuel consumption in a multitude of ways and it can be challenging to measure the magnitude of the actual subsidies.

We focus on price-gap subsidies where the price-gap is the difference between the international and the domestic oil prices that is not a result of taxes or transportation or distributional costs. Price-gap subsidies are generally largest in the transport sector in OPEC countries. In this study we therefore examine the effects of eliminating subsidies in the transport sector, focusing especially on the OPEC.

We apply a new intertemporal numerical model of the international oil market, where OPEC-Core producers have market power. That is 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.
We investigate potential feedback mechanisms of oil subsidy removal. Our results show that consumption in the transport sector in OPEC countries declines significantly and as a result the global oil price falls, which stimulates oil consumption in other regions. However, the oil price decline in our study is lower compared to other studies. One explanation may be that we model OPEC-Core as a cartel making it profitable for them to reduce production to prevent the oil price from declining too much. Our results also suggest a small green paradox effect as OPEC-Core finds it profitable to accelerate its extraction somewhat.

We also investigate regional welfare effects of phasing out subsidies. Although OPEC consumers are worse off by the subsidy removal, total welfare in OPEC increases due to higher profits from oil production. Our central results are robust with respect to important parameters.

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Appendix A: 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
United States of America	Other sectors	Electricity
Rest of 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>

$Q^f_{s,i}$ 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*:

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

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:

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

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:

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

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

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):

$$\text{(A5) } Q_{s,i,t} = K_{s,i,t} \cdot Q_{s,i,t-1}{}^{\gamma_{s,i}} = \omega_{s,i,t} \cdot PI^{a_{s,i}}_{s,i,t} \cdot GDP^{b_{s,i}}_{s,i,t} \cdot Pop^{e_{s,i}}_{i,t} \cdot AEEI_{s,i,t} \cdot Q_{s,i,t-1}{}^{\gamma_{s,i}}$$

where $\gamma_{s,i}$ is the lag-parameter (i.e. the effect of demand in the previous period ($0 \le \gamma_{s,i} < 1$). 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 $\gamma_{s,i} = 0$.[11]

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:

$$\text{(A8)}\quad Q_{s,i}^{f} = \overline{Q}_{s,i,0}^{f} Q_{s,i} \frac{\theta_{s,i}^{f}}{\overline{\theta}_{s,i}^{f}} \left(\frac{PI_{s,i} / \overline{PI}_{s,i}}{PP_{s,i}^{f} / \overline{PP}_{s,i}^{f}} \right)^{\sigma_{s,i}}$$

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:

<u>Endogenous variables:</u>

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

[11] In this paper, *AEEI* is held fixed at 1 in all scenarios. Aune et al. (2016) considers the effects of increased fuel efficiency by adjusting the *AEEI* parameter.

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)):

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

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

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

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:

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

subject to $A^C_t - A^C_{t-1} = X^C_t$ .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 c^C_t are the unit costs given by the following function:

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

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

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

$+\sum_t\left\{\mu_t^C\cdot(1+r)^{-t}\cdot\left(A_t^C-A_{t-1}^C-\left(Q_t^o-X_t^{NO}\right)\right)\right\}$

where $\mu_t^C>0$ 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

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

$$= \frac{1}{\Gamma_2}\cdot\frac{\partial}{\partial P^o}\left[\sum_f \theta^f_{s,i}\left(PP^f_{s,i}\right)^{1-\sigma_{s,i}}\right]^{\frac{1}{(1-\sigma_{s,i})}}$$

$$= \frac{1}{\Gamma_2}\frac{1}{(1-\sigma_{s,i})}\left[\sum_f \theta^f_{s,i}\left(PP^f_{s,i}\right)^{(1-\sigma_{s,i})}\right]^{\frac{1}{(1-\sigma_{s,i})}-1}\cdot\theta^o_{s,i}\cdot\left(1-\sigma_{s,i}\right)\cdot\left(PP^o_{s,i}\right)^{-\sigma_{s,i}}$$

$$= \frac{1}{\Gamma_2}\theta^o_{s,i}\cdot\left(PP^o_{s,i}\right)^{-\sigma_{s,i}}\cdot\left[\sum_f \theta^f_{s,i}\left(PP^f_{s,i}\right)^{(1-\sigma_{s,i})}\right]^{\frac{1}{(1-\sigma_{s,i})}-1} = \theta^o_{s,i}\cdot\left(PP^o_{s,i}\right)^{-\sigma_{s,i}}\cdot\frac{\left[\sum_f \theta^f_{s,i}\left(PP^f_{s,i}\right)^{(1-\sigma_{s,i})}\right]^{\frac{1}{(1-\sigma_{s,i})}-1}}{\left[\sum_f \overline{\theta}^f_{s,i}\left(\overline{PP}^f_{s,i}\right)^{1-\sigma_{s,i}}\right]^{\frac{1}{(1-\sigma_{s,i})}}}$$

$$= \theta^o_{s,i}\cdot\left(PP^o_{s,i}\right)^{-\sigma_{s,i}} PI_{s,i}\left(\sum_f \theta^f_{s,i}\left(PP^f_{s,i}\right)^{(1-\sigma_{s,i})}\right)^{-1}, \quad \Gamma_2 = \left[\sum_f \overline{\theta}^f_{s,i}\left(\overline{PP}^f_{s,i}\right)^{1-\sigma_{s,i}}\right]^{\frac{1}{(1-\sigma_{s,i})}}.$$

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:

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

where we can insert for $\partial Q^o_t / \partial P^o_t$ 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:

$$\text{(A17)}\quad (1+r)^t \frac{\partial L}{\partial A^C_t} = -\frac{\partial c^C_t \left(A^C_t \right)}{\partial A^C_t} \left(Q^o - X^{NO}_t \right) + \mu^C_t - (1+r)^{-1} \mu^C_{t+1} = 0 \text{ or:}$$

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

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 with respect to $X_{i,t}^{NO}$ is:

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

Note that if $\varphi_1^{\mathrm{NO}} = 0$, (A23) simplifies to:

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

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 $\mathrm{X}_{t-1}^{\mathrm{NO}}$). 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:

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

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):

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

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 $\xi^o_{s,i} = \frac{\partial Q_{s,i}{}^o}{\partial PP_{s,i}{}^o} \frac{PP_{s,i}{}^o}{Q_{s,i}{}^o}$ denote the direct price elasticity of oil in sector *s* and region *i*. From (A14) and (A8) we have (note that $\frac{\partial Q_{s,i}{}^o}{\partial PP_{s,i}{}^o} = \frac{\partial Q_{s,i}{}^o}{\partial P^o}$):[12]

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

This can alternatively be expressed as:

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

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

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

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.

Appendix B: Sensitivity results

Table B1 below shows the results from model simulations with different values on selected key parameters in Petro2. This indicates that the results are robust with respect to the calibration of these parameters. In particular, the signs on the effects remain the same through the sensitivity analysis. Moreover, the results confirm the importance of market power, as OPEC-Core countries reduce production to a larger extent than Non-OPEC in all scenarios.

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

Table B1. Sensitivity results

Comparison of Reference scenario and TranspOPEC scenario	Per cent change oil price		Per cent change OPEC oil production		Per cent change OPEC-Core oil production		Per cent change Non-OPEC oil production		Per cent change NPV welfare OPEC
	2020	2040	2020	2040	2020	2040	2020	2040	
Base case parameter values	-0.8	-0.9	-1.9	-1.3	-3.5	-2.1	-0.4	-0.6	9.3
Price elasticity of demand reduced 50 per cent	-0.4	-0.4	-1.2	-1.1	-2.6	-2.1	-0.2	-0.2	9.4
Price elasticity of demand increased 50 per cent	-1	-1.1	-2.4	-1.3	-4.1	-1.9	-0.5	-0.9	12.5
Elasticity of substitution reduced 50 per cent	-0.5	-0.6	-2.1	-1.5	-4.4	-2.8	-0.3	-0.4	11.6
Elasticity of substitution increased 50 per cent	-1	-1.1	-1.6	-1.1	-1	-1.1	-0.5	-0.8	7.4

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