CESifo Working Papers

www.cesifo.org/wp

Climate Policies in a Fossil Fuel Producing Country – Demand Versus Supply Side Policies

Taran Fæhn
Cathrine Hagem
Lars Lindholt
Ståle Mæland
Knut Einar Rosendahl

CESifo Working Paper No. 5105
Category 10: Energy and Climate Economics
December 2014

CESifo *Working Paper No. 5105*

Climate Policies in a Fossil Fuel Producing Country – Demand Versus Supply Side Policies

Abstract

In absence of joint global climate action, several jurisdictions unilaterally restrict their domestic demand for fossil fuels. Another policy option for fossil fuel producing countries, not much explored, is to reduce own supply of fossil fuels. We explore analytically and numerically how domestic demand and supply side policies affect global emissions, contingent on market behaviour. Next, in the case of Norway, we find the cost-effective combination of the two types of policies. Our results indicate that given a care for global emissions, and a desire for domestic action, a majority of emission reductions should come through supply side measures.

JEL-Code: H230, Q410, Q540.

Keywords: climate policies, carbon leakages, oil extraction, supply side climate policies, demand side climate policies.

Taran Fæhn
Statistics Norway
Research Department
Oslo / Norway
tfn@ssb.no

Cathrine Hagem
Statistics Norway
Research Department
Oslo / Norway
cah@ssb.no

Lars Lindholt
Statistics Norway
Research Department
Oslo / Norway
lli@ssb.no

Ståle Mæland
Statistics Norway
Research Department
Oslo / Norway
stm@ssb.no

Knut Einar Rosendahl
Norwegian University of Life Sciences
School of Economics and Business
1432 Ås / Norway
knut.einar.rosendahl@nmbu.no

We are grateful to Torbjørn Hægeland and Ådne Cappelen for comments on an earlier draft. We would also like to thank the research centre CREE (Centre for Research on Environmentally friendly Energy) for funding. The authors Fæhn, Hagem, Lindholt and Rosendahl are associated with the CREE-centre.

1 Introduction

In the context of a global climate agreement, a cap on fossil fuel consumption would have the same effects on global emissions as a cap on fossil fuel extraction, as consumption must equal extraction at the global level. If fossil fuel markets were efficient, the global costs of reducing emissions would also be the same. In this first-best situation, demand and supply side policies coincide with respect to efficiency. However, with limited participation in a climate agreement, or with unilateral action by a single country or coalition of countries, demand side versus supply side policies matters. Many jurisdictions show willingness to reduce CO_2-emissions by restricting domestic demand for fossil fuels. Domestic supply side policies are less frequently discussed, let alone pursued.

The purpose of this paper is to deduce the cost-effective combination of the two types of policies, given a target for a country's (or coalition's) contribution to global CO_2 abatement. The result hinges critically on how domestic demand side and supply side policies affect global emissions through international markets. We explore analytically and numerically how the optimal domestic climate policies depend on market behaviour in the fossil fuel markets, the emissions from extraction, and the costs of downscaling domestic fossil fuel demand and supply.

Domestic policy measures that reduce fossil fuel demand lead to lower international energy prices, and may also reduce the competitiveness of domestic firms in the world markets for energy-intensive goods. Both effects cause so-called carbon leakages, i.e. increased consumption of and emissions from fossil fuels among free-riders; see, among others, Markusen et al. (1993; 1995), Rauscher (1997), and Böhringer et al. (2010). Leakages occur also through supply side policies, i.e. policies that reduce fossil fuel extraction. Such supply side leakages result from increased supply by countries outside a climate coalition as international fuel prices rise. Harstad (2012) shows that supply side leakages can be completely avoided if the coalition buys marginal foreign fossil fuel deposits and conserves them. This renders the non-coalition's supply curve locally inelastic. Although this is a promising result, buying deposits may face several practical problems such as asymmetric information, contract incompleteness, and bargaining failures. In our paper, we focus on the trade-off between domestic demand and supply side measures. We, thus, reserve a given unilateral contribution to global abatement to *domestic* action; the options of purchasing foreign fossil fuel deposits or international emission quotas are excluded.

Our case in the numerical analysis is Norway, which has an ambitious target for domestic demand side measures for 2020, but has so far not considered using supply side measures. The Norwegian lack of focus on supply side policies has been questioned by NGO's and media at home and internationally, see, e.g., The Economist (2009). While the country accounts for around 2 per cent of global oil production, it contributes to less than 0.3 per cent of global oil consumption (BP, 2013). The global combustion of fossil fuels extracted in Norway leads to CO_2 emissions that are about ten times higher than total emissions of CO_2 within Norway. Even though leakages are likely to be larger with supply side measures than demand side measures, we conclude that it is cost-effective for Norway to let most of the contribution to global emission reductions be achieved through supply side measures. In our benchmark scenario, only one third of a given global reduction should be realised through demand side measures; the remaining two thirds should come through supply side measures, that is, by reducing oil extraction.[1]

Previous literature on optimal (second-best) climate policy in the presence of carbon leakages through the international fuel markets has derived the optimal combination of producer and consumer taxes in a climate coalition, given a target for global emission reductions. Hoel (1994) models an aggregate fossil fuel market, and derives analytical expressions for optimal tax levels. Golombek et al. (1995) extend Hoel's analysis by modelling three fossil fuel markets (oil, coal and gas) and provide a numerical illustration of optimal producer and consumer taxation for a coalition of OECD countries, given competitive fossil fuel markets. They find that the optimal producer tax of oil should be negative, due to terms-of-trade effects dominating the leakage effects (OECD is a net importer of oil).

[1] In practical policy the domestic action to meet a given global target will have to concur with other existing climate ambitions and commitments. For instance, Norway has demand side commitments in the EU Emissions Trading System and in the Kyoto agreements. Chapter 3 explains how these are accounted for in the computations. Note that to the extent that these commitments are not met by the domestic actions studied here, their fulfillment may imply extra costs. However, Norway has already shown willingness to do more than simply complying with international commitments, e.g., through over-fulfilling the Kyoto obligations in 2008-12, financing technology transfer and engaging in rainforest preservation in REDD+.

Hagem (1994) compares numerically the costs of pure demand side policy with pure supply side policy in the case of Norway, given a target for its contribution to global emission reductions in 2000. The calculations assume competitive fuel markets and conclude that it would be less costly to reduce oil production than to introduce uniform taxes on fossil fuel consumption.

Our paper contributes to the theoretical literature by analysing how differences in emissions from fossil fuel extraction across countries affect the relative performance of demand side policies versus supply side policies. Furthermore, it supplements previous numerical analyses of demand versus supply sides policies in several ways: First, we analyse the impact of various non-competitive oil market assumptions. Second, we take into account emissions due to extraction of fossil fuels and, particularly, the differences in emission intensity across countries. Third, we incorporate the fact that both production costs and emission intensities are relatively high in the decline phase of an oil field – here we use detailed cost information from Norwegian oil fields. Fourth, previous estimates on cost and emission effects are outdated. In our updating of the information base we have included a review of the empirical literature on relevant price elasticities in order to assess likely carbon leakage rates on the demand as well as the supply side. The robustness of our calculations is checked with thorough sensitivity analyses.

Assumptions regarding supply and demand elasticities, as well as the competitive environment on the fuel markets, are decisive for our results on the optimal distribution of demand versus supply side policies. There is a large literature on OPEC behaviour (see e.g. Griffin, 1985; Alhajji and Huettner, 2000; Smith, 2005; Hansen and Lindholt, 2008). Although the conclusions from this literature are rather mixed, one conclusion is that OPEC does not behave as a competitive producer. In our main case we model OPEC as a strategic player that seeks to maximize its income from annual oil production, while other producers are price-takers. To check the robustness of our results, we also consider the competitive case, along with situations where OPEC has price or production targets.

As fossil fuels are non-renewable resources, there are important dynamic properties of the market that our static analysis does not capture. A fossil fuel producer's optimization behaviour implies finding an extraction path that maximizes the present value of the resource, which depend on the expected, future price path (Hotelling, 1931). If producers expect a gradual tightening of climate policies, they may accelerate their extraction; see Sinn (2008) for a discussion of this "green paradox". Thus, leaving out dynamic considerations may have implications for the results. On the other hand, Venables (2011) shows that although decreasing prices may speed up production on *existing* fields, it is offset by their postponing effect on field openings; see also Österle (2012) for a similar study. Furthermore, the government can control the available cumulative production through their production licencing. Hoel (2013) considers supply-side policies and argues that conserving the marginal, most costly resources reduces both total and immediate resource extraction. These studies show the relevance of analysing fossil fuel policies in a static framework as ours even if some intertemporal reallocation is ignored. We restrict our carbon leakage considerations to those stemming from the fossil fuel markets, disregarding carbon leakages through the market for energy-intensive goods. These leakages can be mitigated or completely abolished by compensation schemes for exposed industries (e.g. free allocation of permits) or by border tax adjustments (Böhringer et al., 2012a, and Hoel, 1996). We therefore ignore this channel of carbon leakages.

2 Theoretical analysis

2.1 Unilateral climate policy

We consider a fossil fuel producing and consuming home country that aims to contribute to a certain reduction in global greenhouse gas (GHG) emissions ($\bar{A}$), through a combination of domestic demand side and supply side policies. The country's aggregate benefits from domestic consumption of fossil fuels are given by $B(y_o, y_c, y_g)$, where y_o, y_c and y_g denote domestic consumption of oil, coal, and gas, respectively. Without loss of generality, all fuels $i=o,c,g$ are measured in units of their carbon content. We assume that the benefit function is increasing in each of the fuels.

Furthermore, let $c_i(x_i)$ denote the home country's aggregate cost of producing fossil fuel *i*, where x_i denotes home production of this fuel. We assume that the cost functions are increasing and strictly convex. Fossil fuels are traded in international markets at prices P_o, P_c and P_g.

The objective for the regulator is to maximize welfare (*W*), subject to the global contribution target, $\bar{A}$, where *W* is utility of consuming fossil fuels net of production and net import costs:

$$\begin{aligned} &\underset{y_i, x_i}{\text{Max}}\ W = B\left(y_o, y_c, y_g\right) - \sum_{i=o,c,g} c_i\left(x_i\right) - \sum_{i=o,c,g} P_i\left(\cdot\right)\left(y_i - x_i\right) \\ &\text{s.t.} \\ &E \leq E^0 - \bar{A}, \end{aligned} \tag{1}$$

where *E* is global emissions and E^0 is the global emissions in absence of the unilateral, domestic policies. From the first-order conditions for this maximization problem, we find that:

$$B'_{y_i} = P_i + P'_{y_i}\left(y_i - x_i\right) + \lambda E'_{y_i} \tag{2}$$

$$c'_i\left(x_i\right) = P_i - P'_{x_i}\left(y_i - x_i\right) + \lambda E'_{x_i} \tag{3}$$

λ is the shadow cost of the emission constraint, while E'_{y_i} and E'_{x_i} are the marginal effects on global emissions of increased consumption and production of fuel *i* in the home country, respectively. They depend on the impacts of domestic demand and supply changes in the fossil fuel markets, which we will explore further in the next subsection.

$P'_{y_i}(y_i - x_i)$ and $P'_{x_i}(y_i - x_i)$ are the terms-of-trade effects. If the country is a net exporter of a fuel, a higher price improves terms of trade. Hence, the terms-of-trade effects for a fuel exporter will tend to favour supply side policies, i.e. to reduce production rather than consumption. Note that this effect occurs also in the absence of climate policy. In the following we will disregard terms of trade effects, as the price changes and consequently the welfare impacts of this can be considered minor for the small home country, relative to the other terms in eqs. (2)-(3). Small price changes do not imply, however, that global emission effects of these price changes can be ignored – consumption effects abroad may well be of the same order of magnitude as consumption effects in the home country; see next subsections. From (2) and (3), we then find:

$$\frac{B'_{y_i} - P_i}{E'_{y_i}} = \frac{P_i - c'_i(x_i)}{E'_{x_i}} = \lambda. \tag{4}$$

Hence, optimal climate policy implies that the marginal cost of global emission reductions through domestic demand side policy ($\frac{B'_{y_i} \text{-} P_i}{E'_{y_i}}$) should equal the marginal cost of global emission reductions through domestic supply side policy ($\frac{P_i \text{-} c'_i(x_i)}{E'_{x_i}}$), across all fuels. Given that domestic consumers and producers are price takers and maximize their net benefit and profit, it is shown in Golombek et al. (1995) that the optimal outcome can be achieved by introducing fuel-specific consumer taxes, $t_i^c = \lambda E'_{y_i}$, and producer taxes, $t_i^p = \lambda E'_{x_i}$.

We will proceed by deriving expressions for E'_{y_i} and E'_{x_i} in a partial fossil fuel market model. In the following subsection we disregard emissions in the fossil fuel extraction processes, but return to this in subsection 2.3.

2.2 Global emissions from demand and supply side measures

Let capital letters denote foreign production and consumption of the three fossil fuels (X_i and Y_i, $i = o,c,g$). As all fuels are measured in units of their carbon content, total global emissions from combustion of fossil fuels, $\tilde{E}$, must equal global fossil fuel production, which again must equal global consumption:

$$\sum_{i=o,c,g} x_i + \sum_{i=o,c,g} X_i = \tilde{E} = \sum_{i=o,c,g} y_i + \sum_{i=o,c,g} Y_i. \tag{5}$$

To simplify the analytical derivations, we treat domestic consumption (y_i) and production (x_i) as exogenous variables, set by the domestic regulator.[2] In the numerical analysis we derive the optimal consumer and producer taxes, given profit maximizing domestic producers and welfare maximizing domestic consumers.

We assume that foreign consumers are price takers, where demand for each fuel is a function of all energy prices ($Y_i = D_i\left(P_o, P_c, P_g\right)$, where $\frac{\partial D_i'}{\partial P_j} < 0$ for $i = j$ and $\frac{\partial D_i'}{\partial P_j} > 0$ for $i \neq j$). For each fuel market, foreign production must equal foreign consumption plus net import from the home country:

$$X_i = D_i\left(P_o, P_c, P_g\right) + y_i - x_i, \quad i = o, c, g. \tag{6}$$

We further assume competitive behaviour by foreign coal and gas producers. Their aggregate supply functions are given by:

$$X_i = S_i\left(P_i\right), \quad \frac{\partial S_i}{\partial P_i} > 0, \quad i = c, g. \tag{7}$$

The oil market is characterised by a dominant producer (OPEC) with a competitive fringe (Non-OPEC):

$$X_o = Z + S_o\left(P_o\right), \tag{8}$$

where Z is output from the dominant oil producer, and $S_o\left(P_o\right)$ is aggregate supply from the competitive fringe. From (6) - (8), we write the equilibrium fuel prices as functions of net import from the home country and supply of oil from the dominant oil producer:

$$P_i = P_i\left(y_o - x_o - Z, y_c - x_c, y_g - x_g\right), \quad i = o, c, g. \tag{9}$$

---

[2] For a small country such as Norway, this is a reasonable simplification.

Our default assumption is that the dominant oil producer maximises net income. However, we also consider other objective functions in the numerical analysis[3].

If the dominant oil producer seeks to maximize net income, Z is found from:

$$\underset{z}{\text{Max}}\left[P_o \cdot Z - C\left(Z\right)\right], \tag{10}$$

where $C\left(Z\right)$ is the production cost. The first order condition is given by:

$$P_o + P'_{oZ} \cdot Z - C'\left(Z\right) = 0. \tag{11}$$

From (9) and (11), we can write all prices as functions of net import from the home country:

$$P_i = f_i\left(y_o - x_o, y_c - x_c, y_g - x_g\right), \quad i = o,c,g. \tag{12}$$

As international fossil fuel prices are functions of net import from the home country, domestic climate policies will affect emissions abroad. We define the marginal demand side carbon leakage of fuel *i*, denoted L_i^D, as the *increase* in consumption *abroad* (measured in carbon units) following from a unit *decrease* in domestic consumption of fuel *i*:

$$L_i^D = \frac{\partial \sum_{j=o,c,g} Y_i}{-\partial y_i} = -\sum_{j=o,c,g} \sum_{k=o,c,g} D'_{jk} \frac{\partial f_k}{\partial\left(y_i - x_i\right)}. \tag{13}$$

To simplify the discussion, we make the following reasonable assumption:[4]

$$0 < L_i^D < 1. \tag{14}$$

[3] In Fæhn et al. (2013b), Appendix A, we derive the equilibrium price functions given that the dominant oil producer a) operates as a competitive price taker, b) keeps the oil price constant, and c) keeps its production constant.

[4] Equation (14) is satisfied when the following three conditions hold for each of the fuels (see Golombek et al, 1995): 1) Increased net demand of one of the fuels leads to higher prices of all fossil fuels, 2) An increase in the price reduces the sum of demand of all fuels, measured in carbon content, and 3) Higher net demand increases total production of fossil fuels from abroad, measured in carbon content. (14) is satisfied in our numerical model.

We define marginal supply side leakage of fuel *i* (L_i^S) as the *increase* in total fossil fuel production *abroad* (measured in carbon units) following from a unit *decrease* in domestic production of fuel *i*. As total consumption must equal total production, and y_i is exogenous, we see from (6) that:

$$L_i^S = -\frac{\partial \sum_{j=o,c,g} X_j}{\partial x_i} = -\frac{\partial \left[\sum_{i=o,c,g} D(\cdot) - x_i \right]}{\partial x_i} = 1 + \sum_{j=o,c,g} \sum_{k=o,c,g} D'_{jk} \frac{\partial f_k}{\partial (y_i - x_i)} = 1 - L_i^D. \qquad (15)$$

Hence, we can express the marginal impact on total emissions of domestic climate policies as functions of the demand side carbon leakage:

$$\begin{aligned} \tilde{E}'_{y_i} &= 1 - L_i^D, \\ \tilde{E}'_{x_i} &= L_i^D. \end{aligned} \qquad (16)$$

We see from (16) that demand side policies are more (less) effective in terms of global emission reduction than supply side policies when the demand side leakage rate is less (bigger) than 0.5 ($\tilde{E}'_{y_i} - \tilde{E}'_{x_i} > 0$ for $L_i^D < 0.5$). We also notice that $\tilde{E}'_{y_i} + \tilde{E}'_{x_i} = 1$. If both domestic consumption and domestic production decrease by one unit, there is no impact on fossil fuel prices, and the final global impact is one unit less emitted.

So far we have disregarded emissions due to extraction of fossil fuels. Fossil fuels are used as input factors in the extraction process, and emission intensities vary quite a lot across sources. Hence, the global impact of domestic policies should be adjusted accordingly.

2.3 Including emissions from fossil fuel extraction

Let *E* denote total emissions (fossil fuel consumption including emissions from extraction):

$$E = \tilde{E} + \sum_{i=o,c,g} \alpha_i(x_i) + \sum_{i=o,c,g} \beta_i(X_i), \qquad (17)$$

where $\alpha_i\left(x_i\right)$ and $\beta_i\left(X_i\right)$ are emissions as functions of extraction of fossil fuel *i* in the home country and abroad, respectively. We find (see Appendix A):

$$
\begin{aligned}
E'_{y_i} &= \tilde{E}'_{y_i} + \frac{\partial \sum_{j=o,c,g} \beta_j\left(X_j\right))}{\partial y_i} = 1 - L^D + \beta'_{X_i} - \sum_{j=o,c,g} \beta'_{X_j} \cdot l^D_{ji}, \\
E'_{x_i} &= \tilde{E}'_{x_i} + \alpha'_{x_i} + \frac{\partial \sum_{j=o,c,g} \beta_j\left(X_j\right)}{\partial x_i} = L^D_i + \alpha'_{x_i} - \beta'_{X_i} + \sum_{j=o,c,g} \beta'_{X_j} \cdot l^D_{ji},
\end{aligned} \tag{18}
$$

where l^D_{ji} is the demand side leakage from fuel *j* (increased consumption of fuel *j* abroad due to reduced consumption of fuel *i* at home):

$$
l^D_{ji} = -\sum_{k=o,c,g} D'_{jk} \frac{\partial f_k}{\partial\left(y_i - x_i\right)}. \tag{19}
$$

We see that $E'_{y_i} + E'_{x_i} = 1 + \alpha'_{x_i}$. If both domestic consumption and production decrease by one unit, there is still no leakage, but as domestic fuel production causes emissions from extraction, global emissions decrease by more than one unit.

Comparing the impact on global emissions with and without including the emissions from fossil fuel extraction, we find that:

$$
E'_{y_i} - \tilde{E}'_{y_i} = \beta'_{X_i} - \sum_{j=o,c,g} \beta'_{X_j} \cdot l^D_{ji}, \tag{20}
$$

$$
E'_{x_i} - \tilde{E}'_{x_i} = \alpha'_{x_i} - \beta'_{X_i} + \sum_{j=o,c,g} \beta'_{X_j} \cdot l^D_{ji}. \tag{21}
$$

We cannot in general say whether including emissions from extraction makes demand side policies more or less effective than supply side policies, in terms of global emission reductions. This depends on the leakages (l_{ji}^D), the differences in emission intensities in extraction across fossil fuels abroad (β'_{X_j}) and across countries (home (α'_{x_i}) versus abroad (β'_{X_i})).

Given that emissions from extraction of fossil fuels abroad are identical, ($\beta'_{X_g} = \beta'_{X_c} = \beta'_{X_o} = \beta'_X$), we find:

$$E'_{y_i} - E'_{x_i} = 1 - 2L_i^D + 2\beta'_X \left(1 - L_i^D\right) - \alpha'_{x_i}. \tag{22}$$

We see that for any given leakage rate L_i^D, including emissions from extraction makes demand side policy more effective relative to supply side policy the larger is the foreign emission intensity (β'_X), and the smaller is the domestic emission intensity (α'_{x_i}). Furthermore, the emissions from foreign extraction have larger impact on the difference between E'_{y_i} and E'_{x_i}, the larger the supply side leakage $(1\text{-}L_i^D)$. Moreover, if foreign and domestic intensities are the same ($\beta'_X = \alpha'_{x_i}$), we notice that $E'_{y_i} - E'_{x_i} = \left(1 + \alpha'_X\right)\left(1 - 2L_i^D\right)$, which is equal to zero if $L_i^D = 0.5$.

3 Numerical analysis

We now turn to the comparison of demand and supply side policies in the case of Norway. In Section 3.1 we estimate marginal costs of Norwegian unilateral reductions in fossil fuel demand and supply. This means quantifying $B'_{y_i} - P_i$ and $P_i - c'_i\left(x_i\right)$, respectively; see Eq. (4). Demand side abatement is assessed by means of a computable general equilibrium (CGE) model for Norway. Supply side measures are quantified by identifying representative, marginal cuts in Norwegian oil production. Norway is also a significant producer of gas, accounting for around 3 per cent of global gas production (BP, 2013). Gas is, however, a fossil fuel with relatively low emissions and with larger substitutability against the high-emitting coal. Hence, it is not clear whether reduced Norwegian gas extraction would decrease or increase global emissions and we do not consider this supply side option in our analysis.[5]

In Section 3.2 we analyse the effects on global emissions by exploiting a partial model of the global fossil fuel market effects, where we also take into account emissions from extraction of fossil fuels. These computations will provide the values of the denominators in Eq. (4), E'_{y_i} and E'_{x_i} . In Section 3.3 we combine the findings in the two preceding sections to derive the optimal combination of demand and supply side policies for Norway as expressed in Eq. (4).

3.1 Unilateral climate policy

3.1.1 Demand side policies

The Norwegian parliament has announced high ambitions for its contribution to global (demand side) emissions reductions, corresponding to a 30 per cent reduction from Norwegian 1990 emissions by 2020. Moreover, it has emphasised that the lion's share of the reductions is to result from domestic action. To obtain a marginal cost function for demand side measures in Norway, we use Statistics Norway's technology-rich CGE model for the Norwegian economy, MSG-TECH (see Fæhn et al., 2013a). We simulate costs of uniform emissions pricing, given different demand side abatement levels. The effects are measured from a reference scenario that incorporates climate policies already implemented, approved, or promised for the years up to 2020. From 2008, this includes the participation in the EU ETS.[6]

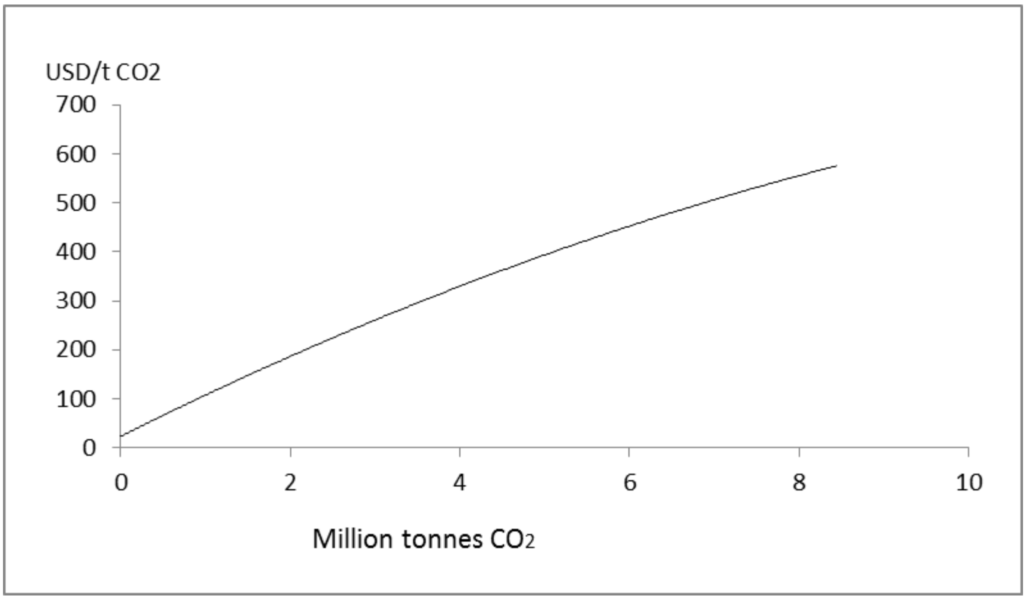
Since we assume that the demand side abatement aims to contribute to global emissions reductions, we only consider emissions pricing in sectors outside the EU ETS. With the cap on total

[5] We abstract from the technical challenges of separating oil and gas extraction, but return to this issue in Section 3.3.1.

[6] The same simulated scenario is used in Climate Cure 2020 (2010), the report of an officially appointed commission tasked with preparing the ground for evaluating Norway's climate policy.

emissions in the EU ETS, additional cuts in Norwegian ETS sectors will merely displace emissions to ETS-regulated installations in other European countries.

Figure 1: Marginal costs of foregone fossil fuel consumption in Norway.



Based on a number of simulations, we find a marginal cost curve for Norwegian demand side measures as expressed by Eq. (23) and depicted in figure 1. For all the simulated emission targets, virtually all abatement takes place as reduced oil consumption, mostly within the transport sector.

$$B'_{y_i} - P_i = -2.5A_D{}^2 + 86.6A_D + 23.4. \qquad (23)$$

A_D denotes the level of domestic emission reductions (measured in million tonnes of CO_2).

3.1.2 Supply side policies

The costs of supply side measures in our static framework are the forgone profits by not extracting the oil, corresponding to $P_o - c'_o\left(x_o\right)$; see the numerator of the second fraction of Eq. (4). We single out oil fields which can be characterized as marginal, in the sense that terminating extraction involves small profit losses per unit extracted. Oil fields in the decline phase generally have higher costs than fields in the plateau phase. Explanations are that marginal operating costs, including energy input, are increasing as remaining oil in the reservoir declines. In addition, IOR (Improved Oil Recovery) activities to prolong the lifetime of maturing fields can involve new costly investments, implying that the profit losses of not undertaking an IOR project may be modest (not always though).

Typically, these fields also have higher emission intensity. Unfortunately, we have limited information about IOR costs (see below).

For the years 2009-2011 we have singled out nine Norwegian fields where oil constituted a major part of total petroleum production (several were pure oil fields). In addition, these fields were in, or close to, the decline phase. We have field data from Statistics Norway on production volumes and variable costs, costs that would not accrue if oil production were terminated.[7] Based on these data we have constructed the marginal production cost curve.

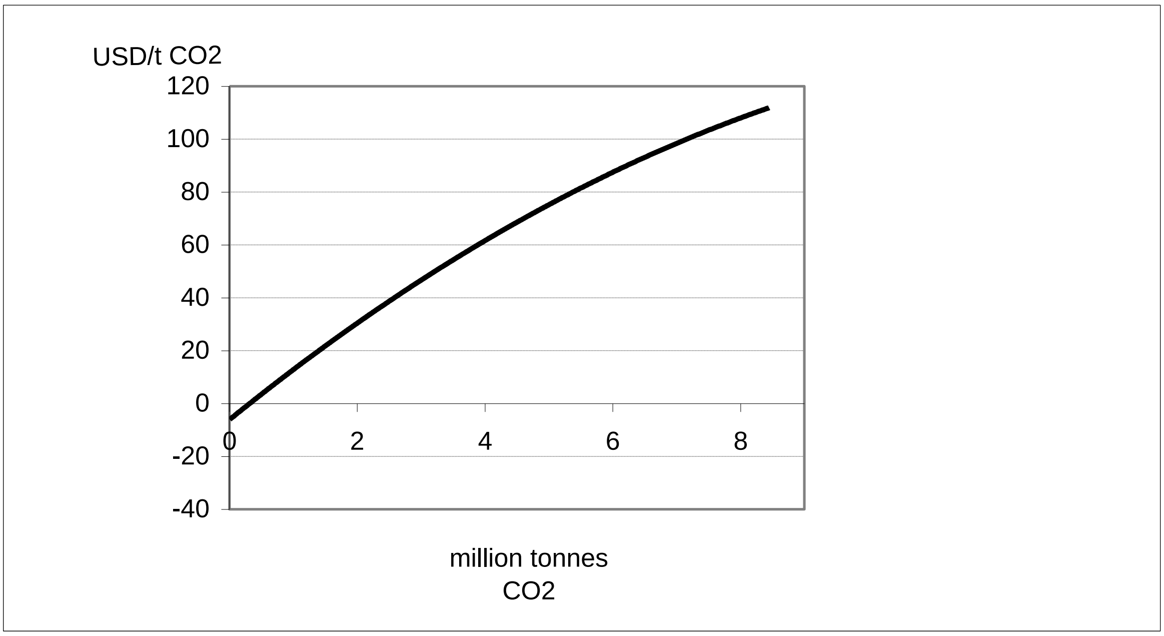
To calculate marginal forgone profits by reduced oil production, we apply the average oil price over the period (USD 84.5 per barrel of Brent Blend), and subtract the marginal production costs. The results can be considered as the marginal costs of forgone oil extraction in Norway, and are shown in Figure 2. The supply side cost curve, where A_S is reduced extraction measured in million tonne s of CO_2, is:

$$P_o - c_o'\left(x_o\right) = -0.7 A_S{}^2 + 19.6 A_S - 6.1. \tag{24}$$

We see that it is actually profitable to reduce 0.7 Mt of CO_2, irrespective of climate benefits, due to high production costs of some of the smaller fields.

[7] See Fæhn et al. (2013b), Appendix B

Figure 2: Marginal costs of foregone oil extraction in Norway.



In our study we are interested in abatement options in the near future such as 2020. Thus, the relevant question is to what extent the cost function depicted in Figure 2 is representative for coming years. Several of the fields we have studied for the years 2009-2011 will stop producing before 2020. On the other hand, some fields that are now in their plateau phase will be in their decline phase around 2020, suggesting that their costs per unit production will increase. It is difficult to know whether the net effect of these considerations will push the cost curve in Figure 2 up or down.

However, there are several reasons why we may have underestimated the total costs of production, i.e., overestimated the costs of reducing production. First, we do not have specific information about the costs of IOR projects, which are often projects with limited profits per unit of extraction.[8] Second, we have only considered advanced termination of maturing fields, in which case development costs are sunk. A cost-effective downscaling of oil production may also imply that some fields with limited profitability are not developed at all. Then development costs, that incur during the first initial years and can be considerable, are not sunk.

To help assessing the relevance of Figure 2 for coming years, we have also gathered information on an oil field named Ivar Aasen that is decided to be developed. Here we have access to information about both expected annual development and operating costs, as well as production (The Norwegian Oil Company, 2012)[9]. Investments for this field started in 2013, with production expected to set off in 2016. Based on the reported data we calculate a break-even oil price of USD 60 per barrel for this field, using a discount rate of 6 per cent which the oil company uses.[10] With an average production of 1.4 million Sm^3 over the period 2016-2028 and a break-even oil price of USD 60 per barrel, this is comparable to the data behind Figure 2 for the years 2009-2011 (i.e., the lower third part of the curve).[11] In addition, Rystad (2013) points to several Norwegian (undeveloped) oil fields with break-even prices above USD 72 per barrel. These observations support our belief that the costs of reducing oil production are lower than what we assume in our analysis.

The oil price around 2020 may be higher than it was in 2009-2011, which for given costs suggests that forgone profits of reduced oil extraction may be higher. However, extraction costs have tended to be positively correlated with the oil price, meaning that the effect of a high oil price on forgone profits could be moderated. In addition, a higher oil price would entail higher oil production in the reference case, i.e., a situation without new policies. We are interested in the marginal costs of reducing oil production compared to this reference case. Hence, it is not certain that a higher oil price will lead to higher costs of reducing oil production from a level endogenously determined by the oil price.

To sum up, although the uncertainties are rather large, it seems more likely that the marginal costs of supply side measures around 2020 lie below than above the curve shown in Figure 2.

---

[8] The variable costs for the nine fields reported above also include some investment costs for drilling purposes, which may be characterized as IOR-activities. We do not have complete information about the IOR projects, however.

[9] This was the only oil field with sufficiently detailed official data to calculate approximate break-even prices.

[10] The break-even oil prices with 4 and 10 per cent discount rates are USD 58 and USD 65, respectively. Note that these estimates must be seen as approximate as the information is gathered by looking at graphs. The future oil price used in the impact assessment of the Ivar Aasen project seems to be around USD 90 per barrel.

[11] An oil price of USD 84.5 per barrel, and a break-even price of USD 60 per barrel, implies a cost of USD 24.5 per barrel forgone oil production, corresponding to USD 58 per tonne CO_2. 1.4 million Sm^3 of oil leads to 3.7 million tonnes of CO_2 when it is combusted.

3.2 Numerical analysis of global fossil fuel markets

3.2.1 The partial fossil fuel market model

Based on the exposition in Section 2, we construct a simple numerical model that makes it easy to identify and adjust the basic assumptions driving the results. The main drivers are i) price responsiveness on the demand side (including substitution effects between oil and other fossil fuels), ii) price responsiveness of Non-OPEC supply, iii) OPEC's response, and iv) differences in emission intensity in oil extraction. We consider iso-elastic demand functions (i.e., with constant direct and cross price elasticities), iso-elastic supply functions for competitive fossil fuel producers, and constant unit production costs for OPEC (when behaving as a dominant producer). As we are focusing on a permanent cut in oil supply as a potential supply-side measure, we are mostly interested in the long-run effects in the market, i.e., we consider long-run elasticities. Finally, we model fixed emission intensities in oil extraction, but these should be interpreted as emission intensities of marginal production. Appendix B contains a detailed discussion of the main drivers, in particular a review of existing demand and supply elasticity estimates from the literature. Here we only present the assumptions of our benchmark case, which are motivated in the appendix.

Oil price increases may reduce oil consumption in various ways. Oil consumers may reduce their total energy use, or they may switch to other energy goods such as coal, gas or renewables. Switching to other energy goods requires that there are viable alternatives, which will vary across sectors. Reducing total energy use may either involve reduced use of energy services (e.g., driving fewer miles, producing/consuming less energy-intensive products), or using more energy-efficient vehicles (or transport modes), capital, or equipment. In the long run, higher prices may also stimulate the development of more oil-efficient technologies. In principle, long-run price elasticities should capture all these effects. Based on the literature review, we apply a direct price elasticity of -0.5 in the long run, and cross-price elasticities for coal and gas of 0.08. However, we report the effects of other estimates as well.

Higher prices of oil increase the profitability of oil exploration, new fields developments, and IOR projects. Oil resources that are relatively cheap to extract will not be influenced by moderate oil price changes – it is merely a matter of time when these resources will be extracted.[12] Thus, an increase in the price of oil will mostly affect extraction of so-called marginal resources, such as exploration and field development in ultra-deep waters, developments of smaller fields and unconventional oil, and IOR projects. Higher oil prices may also lead to improved technologies in the long run, similarly to oil-efficiency improvements on the demand side. Based on the literature review, we use a supply elasticity of 0.5 for Non-OPEC. This implies that oil demand and Non-OPEC supply are equally price elastic. However, due to substitution between oil and other fossil fuels, the fossil fuel demand elasticity (with respect to the oil price, and measured in carbon units) becomes around -0.4.

As discussed in Section 2, our default assumption in our benchmark case is that OPEC behaves as a dominant producer. The unit production cost of OPEC then has to be calibrated so that our reference simulation is consistent with base year data (2011). In our benchmark case, the unit marginal production cost of OPEC turns out to be 45 per cent of the oil price, which is within the range of production costs reported by IHS CERA for OPEC countries (see e.g. Figure 3.9 in Ministry of Petroleum and Energy, 2011).[13] When we model OPEC as a competitive producer, we assume the same supply elasticity as for Non-OPEC.

Although the lion's share of CO_2-emissions from oil use takes place as the oil is combusted, emissions from oil extraction have to be counted, as well. According to OGP (2012), the average GHG emissions per unit production worldwide in 2011 were 159 tonnes CO_2e (CO_2 equivalents) per 1,000 toe hydrocarbon produced. The figure for the Middle East is only 51 tonnes CO_2e, but the coverage is less comprehensive for this region – hence the real average could potentially be higher.

The European figure is 84 tonnes CO_2e. OGP (2012) does not report figures for Norway, but based on data from Statistics Norway we calculate the average Norwegian emission intensity in 2011

[12] The timing of extraction may of course be affected by price changes, cf. the discussion in Section 1.

[13] Note that the calibrated unit cost for OPEC is increasing in the absolute value of the residual demand elasticity. When the residual demand is more elastic, OPEC is less interested in cutting supply to increase the oil price, and hence unit costs must be higher to obtain a reference case consistent with base year data.

to be 60 tonnes CO_2e per 1,000 toe . For the rest of Non-OPEC we make a rough calculation based on the OGP (2012) figures for the Middle East, Europe and the world, arriving at around 200 tonnes CO_2e.[14]

The average figures reported above will typically deviate from the marginal change in emissions of increased or reduced oil production. Reduced oil production in Norway could e.g. involve reduced IOR activity or advanced termination of a field. In both these cases, energy use per unit extraction will tend to be higher than average, see Fæhn et al. (2013b), Appendix C. The same could be true for reduced oil exploration or field developments, at least in aggregate, as the marginal areas or fields will tend to be less profitable, which often means that more costly energy is needed per unit production.

Similarly, increased supply from other Non-OPEC producers could imply higher-than-average emission intensities. For instance, Canadian oil sands are considered relatively costly and thus marginal resources, with average emission intensities around three times the world average. When it comes to OPEC supply, however, increased production may come from increased extraction of developed fields in countries like Saudi Arabia, and thus to a lesser extent involve higher emission intensities.

Our benchmark case assumption is that marginal emission intensities are 50 per cent above the reported average figures above. For Norway and (other) Non-OPEC this is related to the marginal supply most likely being more emission-intensive than average supply. For OPEC the increase is partly related to less comprehensive reporting and reliance on Middle East figures (see above) and partly to marginal supply possibly being more emission-intensive than average supply. Thus, we set the emission intensities in Norway, OPEC and Non-OPEC equal to respectively 90, 76 and 300 tonnes CO_2e per 1,000 toe.[15] For comparison, emissions from consuming (i.e., combusting) 1,000 toe of oil is

[14] OGP (2012) reports both emissions and production data for seven regions of the world. We deduct emissions and production from the Middle East and half of those from Europe (i.e., Norway), and calculate the emission intensity for the remaining regions, which we then assume is representative for Non-OPEC.

[15] It could be argued that the emission intensity of Norwegian oil extraction should be set to zero, as these emissions are regulated by the EU ETS, which has a cap on overall emissions (cf. the discussion of ETS sectors in Section 3.1.1). As seen in the following subsection, however, these emissions are of less importance.

about 3,070 tonnes of CO_2. Although of minor importance here, we also account for emissions from extracting other fossil fuels, and set emission intensities for coal and gas equal to the Non-OPEC emission intensity reported above.

3.2.2 Effects on global emissions of demand and supply side policies

We first report the simulation results of exogenously reducing Norwegian oil extraction or consumption by one unit of carbon. We are interested in the net effects on global emissions, i.e., the denominators E'_{x_i} and E'_{y_i} in Eq. (4). As shown in Section 2, the sum of E'_{x_i} and E'_{y_i} should equal one plus α'_{x_i}, i.e., the emissions from domestic extraction (relative to emissions from consumption).

Table 1 displays the net global emission reductions when OPEC acts as either a dominant or a competitive producer. The table also shows the various components of the emission reductions. Note that the leakage rate L^D defined in Section 2 is equal to minus the sum of "Oil market leakage" and "Coal/gas market leakage" under "Demand side" policy (and also equal to the sum of the three first components under "Supply side" policy).

We first notice that leakage through the oil market is around 50 per cent for both demand side and supply side leakage. This is certainly the case if OPEC acts competitively, and follows straightforwardly from the assumption of equal (absolute values of) supply and demand elasticities. If OPEC acts as a dominant producer, it is optimal for the producer group to adjust its supply slightly more to changes in Norwegian supply or demand compared to in the competitive case, but the difference is not big: Supply side leakage through the oil market is 55 per cent, compared to 45 per cent for demand side leakage.

Next, we see from Table 1 that overall market leakage is substantially lower under demand side policy than under supply side policy, whether OPEC behaves competitively or as a dominant producer. This is due to substitution between oil and other fossil fuels, which obviously goes in different direction depending on whether the oil price drops (demand side) or increases (supply side). When oil demand abroad increases (decreases) due to reduced Norwegian oil consumption (extraction), coal and gas consumption is somewhat reduced (increased). This effect alone accounts for almost 10 per cent of the gross emission reduction.

Finally, the importance of emissions from fossil fuel extraction is modest, accounting for less than 10 per cent of total emissions from extracting and consuming oil. The effects are highest for demand side policy, as under supply side policy increased emissions from oil extraction outside Norway are modified by reduced emissions from oil extraction in Norway.

Table 1. Net global emission reduction from reduced Norwegian oil extraction or consumption by one unit of CO_2. Benchmark case.

	OPEC: Dominant producer		OPEC: Competitive producer	
	Supply side	Demand side	Supply side	Demand side
Gross emission reduction	1	1	1	1
Oil market leakage	-0.546	-0.454	-0.507	-0.493
Coal/gas market leakage	-0.088	0.088	-0.096	0.096
Domestic extraction	0.028	0	0.028	0
Foreign extraction	-0.041	0.041	-0.043	0.043
Net emission reduction	0.353	0.676	0.383	0.646

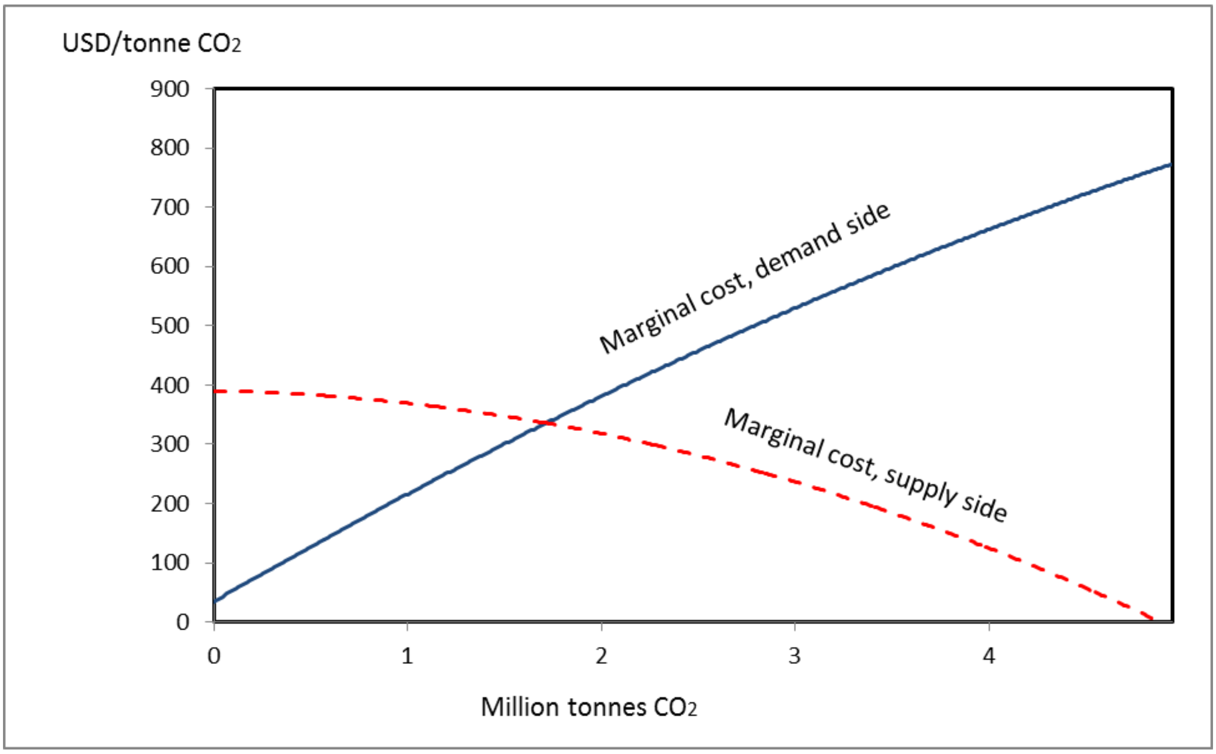
Obviously, net emission reductions are sensitive to a number of assumptions such as price elasticities and OPEC behaviour. Hence, in subsection 3.3.2 below we present a detailed sensitivity analysis. We now use the findings in Table 1 to analyse the optimal balancing of demand and supply side policies, focusing on the case with OPEC as a dominant producer.

3.3 Optimal balancing of demand and supply side policies

3.3.1 The cost-effective solution

By combining the demand side and supply side cost curves and their net effects on global emissions derived above, we can find the optimal composition of domestic action for any global contribution target, $\bar{A}$, as expressed in Eq. (1). We pick a target of 5 Mt of CO_2 by 2020.[16] In Figure 3 we show a bath tub diagram with length equal to $\bar{A} = 5$, and where the marginal costs of demand (supply) side measures are shown from left to right (right to left). The intersection point between the two curves shows the optimal combination of demand and supply side measures. We notice that about 2/3 of the global contribution target should be met through reduced oil extraction. The corresponding marginal costs of reducing global CO_2 emissions are 336 USD per ton. If the global reductions were to be met through demand side measures alone, costs would more than double.

Figure 3: Combining leakage-adjusted demand and supply side marginal cost curves



Implementing this combination of demand and supply side measures would mean that domestic CO_2 emissions should be reduced by 2.5 Mt of CO_2, e.g., through a domestic CO_2 tax on non-EU ETS sectors of 228 USD per tonne CO_2 (cf. Figure 1).[17] Almost 90 per cent of the measures

[16] 5Mt of global CO_2 emission reductions by 2020 is in line with the global emissions reductions (including leakages) that can be achieved by fulfilling the Norwegian target for domestic emissions reductions by increased abatement in Norwegian non EU-ETS sectors, see Fæhn et al. (2013b).

[17] The domestic CO_2 tax is found by multiplying the marginal cost of reducing global CO_2 emissions (336 USD per ton) with the net effect on global emissions of reduced Norwegian consumption (0.676 – see Table 1).

that are profitable to carry out relate to transportation, of which reduced private transport accounts for 20 per cent and transition to more climate friendly vehicles accounts for the rest.

Moreover, Norwegian oil extraction should be reduced by 3.5 million Sm^3, which is 3.1 per cent of total Norwegian oil production in 2012. This reduction can be achieved in different ways, e.g., through a production tax on Norwegian oil extraction. The optimal marginal cost of reduced CO_2 emission estimated above corresponds to a production tax of USD 50 per barrel,[18] i.e., around half of the current crude oil price. As mentioned in Section 3.1.2, the break-even price of the Ivar Aasen oil field, which can be characterized as relatively profitable, is around USD 60 per barrel.

Below we discuss the pros and cons of implementing a production tax. Here we want to emphasize that a production tax of around USD 50 per barrel could potentially lead to a much bigger reduction in oil extraction than the 3.1 per cent calculated above. The reason is that, as underlined in Section 3.1.2, we most likely overestimate the costs of reducing oil extraction.

3.3.2 Sensitivity analysis

There are other uncertainties in our calculations, too, especially the effects in the fossil fuels markets of reduced oil extraction or consumption in Norway. In Table 2 we present a number of sensitivity analyses where we adjust assumptions from our benchmark case.[19] The global contribution target is held fixed at 5 Mt CO_2.

We notice from Table 2 that assuming competitive behaviour by OPEC gives more or less the same results as above – this is not surprising given the results in Table 1. Besides that, we see that the share between supply- and demand side measures depends quite a lot on what we assume about the oil market. If we think that OPEC keeps its supply fixed, *or* if demand is twice as elastic as supply, cuts in oil extraction are even more effective in reducing global emissions, and the share of supply side measures increases to around 90 per cent. Nevertheless, the optimal production tax does not change

[18] The production tax is found by multiplying the marginal cost of reducing global CO_2 emissions (336 USD per ton) with the net effect on global emissions of reduced Norwegian extraction (0.353 – see Table 1), and then multiplying this with the CO_2 content of a barrel of oil (0.42).

[19] The sensitivity analysis is discussed in more detail in Fæhn et al. (2013b), Appendix C.

much. The global emission effects of reduced oil extraction (E'_{x_i}) are increased, shifting the supply side curve in Figure 3 downwards. Likewise, the demand side curve in Figure 3 shifts upwards. Still, the intersection point drops down, meaning that the shadow cost of the emission constraint λ (cf. eqs. (2)-(3)) declines. However, the optimal tax on oil extraction is proportional to E'_{x_i} (cf. Section 2), which has increased. The domestic CO_2 price drops quite substantially, though, due to a combination of lower λ and lower E'_{y_i} .

If we think that supply is twice as elastic as demand, cuts in oil extraction is less effective and the share of supply side measures drop to 25 per cent. Again, we see that the optimal production tax is less affected, while the domestic CO_2 price has increased quite a lot. If OPEC for some reason chooses to keep the oil price fixed, reduced oil extraction gives no climate benefits at all, and we are back to the conventional choice of only doing demand side policies.

If we have overestimated the costs of reduced oil extraction, we should undertake even more supply side measures than suggested by Figure 3. Moreover, the optimal domestic CO_2 price and the optimal production tax for Norwegian oil extraction should then be reduced. For instance, if we scale down the supply side cost curve by 50 per cent, supply side measures should account for 83 per cent of total abatement, with the optimal domestic CO_2 price and production tax being 126 USD per tonne CO_2 and 28 USD per barrel; see Table 2.

On the other hand, we have ignored the challenges of separating oil and gas extraction, which may suggest that we have underestimated the forgone profits of reduced oil extraction. However, the share of gas in total oil and gas production for the nine fields studied above was merely 5 per cent. Moreover, for 8 of the 13 fields currently under development on the Norwegian shelf, more than 90 per cent of recoverable reserves are oil (Ministry of Petroleum and Energy, 2013). Hence, this may be of limited importance.

The higher the oil price, the less profitable it is to restrict extraction from a given oil field. As explained in subsection 3.1.2, however, a higher oil price does necessarily mean that supply side measures become more costly, as more expensive resources will then be extracted in the reference case. Anyway, it is very unlikely that it is cost effective to rely only on demand side measures. Given the benchmark case estimates of E'_{x_i} and E'_{y_i}, it is optimal to implement some supply side measures as long as the net revenue of the least profitable oil extraction is less than 116 USD per barrel.

Table 2. Sensitivity analysis. Effects of reducing Norwegian extraction or consumption of oil by one unit of carbon.

	Net emission reduction*		Supply- vs. demand side		Optimal taxes	
	E'_{x_i}	E'_{y_i}	Supply	Demand	Prod. tax \$/barrel	CO_2 tax \$/ton
Benchmark case	0.353	0.676	66%	34%	50	227
Competitive OPEC	0.383	0.646	72%	28%	50	200
Fixed OPEC supply	0.49	0.539	87%	13%	48	127
Fixed oil price	0.005	1.025	0%	100%	-	386
Supply two times more elastic than demand	0.204	0.825	25%	75%	38	364
Demand two times more elastic than supply	0.528	0.5	90%	10%	47	107
50% lower supply side costs	0.353	0.676	83%	17%	28	126

* Net global emission reduction from reduced Norwegian oil extraction (supply side) or consumption (demand side) by one unit of carbon.

3.3.3 Policy alternatives and discussion

So far we have taken for granted that the Norwegian government will impose sufficiently strong measures to reach its global contribution target, $\bar{A}$. A reasonable first step towards this goal could be to implement supply side policies comparable to the demand side policies already in place in

Norway. The current CO_2 tax imposed on Norwegian non-ETS sectors is 66 USD per tonne CO_2.[20] Using the benchmark case value of E'_{y_i} (see Table 2), this translates into a shadow price of global emission reductions (λ) of 98 USD, which further translates into a corresponding production tax of 14 USD per barrel (when using the benchmark case value of E'_{x_i}), cf. Eq. (4). That is, supplementing a domestic CO_2 price of 66 USD per tonne CO_2 in non-ETS sectors with an oil production tax of 14 USD per barrel would imply a cost-effective combination of demand and supply side climate policies. Naturally, the global target, $\bar{A}$, would not be reached with these moderate measures – global emissions would decline by a little more than one million tonnes.

In our benchmark case, the derived marginal costs of emission reductions translate into a shadow price on oil production equal to 50 USD per barrel. This shadow price can in principle be implemented through a corresponding production tax on all oil production in Norway. However, implementing such a large tax overnight is not without drawbacks. First, we have already noted above that we may have overestimated the costs of reducing oil extraction. As a thought experiment, assume that half of Norwegian oil production becomes unprofitable with the indicated tax level, and that the forgone profits amount to on average 25 USD per barrel, i.e., half of the tax. Using the production level of 2012, total costs would then be 17 billion USD, compared to 1.1 billion USD in the benchmark solution. Although this thought experiment may be somewhat extreme, it illustrates that there is a substantial downside risk by implementing such a large production tax for such a big sector.

Second, Norwegian authorities have, for good reasons, been cautious about changing the taxation rules, at least for already developed fields. Implementing additional taxes could be seen as changing the rules of the game, increasing the risk of doing business on the Norwegian continental shelf. Hence, it is easier to make a case for imposing a large production tax on extraction from undeveloped fields, unexplored areas and even developed fields requiring upgrading through IOR projects, than on sanctioned extraction from developed fields.

[20] The Norwegian CO2 tax is differentiated across fuels and sectors. The highest tax level in non-ETS sectors is on petrol, at 393 NOK (66 USD) per tonne CO_2 (in 2013), cf. Ministry of Finance (2012).

An alternative supply side policy, e.g., combined with a more limited production tax, could be to have a more restrictive practise when it comes to opening new areas for oil exploration. At least it seems reasonable to take a global perspective similar to the one in this paper when undertaking impact assessments of opening new areas for exploration

4 Conclusions

The conventional way of implementing policies to reduce CO_2 emissions is through the demand side, that is, introducing measures or instruments to reduce the consumption of fossil fuels. In a closed market such as the global economy, demand and supply side measures may be equivalent. This is not the case, however, when only one or a group of countries implement climate policies. Demand and supply side measures will then have different effects, depending, in particular, on the price responsiveness on the demand and supply side of the market.

In this paper we have derived analytical expressions for the optimal combination of demand and supply side policies for a fossil fuel producing and consuming country that has a fixed target for its contribution to reducing global emissions. We have also accounted for emissions from the extraction of fossil fuels, which comes in addition to emissions from the use (i.e., combustion) of the fuels.

Based on this analytical framework, we have analysed the optimal combination of demand and supply side climate policies for a small oil producing country, Norway, using data for domestic abatement costs and forgone profits for Norwegian oil production, as well as a transparent model of international fossil fuel markets. We find that a majority of measures should be implemented on the supply side, that is, by reducing Norwegian extraction of oil. In our benchmark case the optimal combination of demand and supply side measures involves annual cuts in Norwegian oil extraction of around 3.5 million Sm^3 (around 3 per cent of current Norwegian oil production), and annual domestic reductions in CO_2 emissions of 2.5 million tonnes of CO_2 (almost 5 per cent of current Norwegian CO_2 emissions). In contrast, the Norwegian Government suggests using demand side measures, only. We find that such a strategy more than doubles the costs. It should be noted that as our numerical approaches are designed for long run assessments, transaction costs of reallocating resources to the new equilibrium are not included. These can be significant, given our focus on the year 2020. However, it should be noted that transaction costs are relevant for both demand and supply side strategies. Despite a number of uncertainties in our calculations, the conclusion that a majority of the global emission reductions should be taken through supply side measures, seems quite robust.

The optimal policy combination is, at least in principle, a tax per tonne domestic CO_2 emissions and a tax per barrel of domestic oil extraction. The tax levels we derive in our benchmark case are high, driven e.g. by the high costs of reducing Norwegian emissions from sectors that are not regulated by the EU ETS. Implementing such high taxes overnight is not without drawbacks, especially on the supply side, and we have discussed alternative ways of implementing cuts in Norwegian oil extraction.

Although our numerical case has been Norway, the question of demand side versus supply side climate policies is relevant for all fossil fuel producing countries. For instance, the EU has introduced a number of demand side measures such as the EU ETS, but no supply side measures yet. Reduced coal extraction is a potential climate policy measure, given that it leads to higher international coal prices and lower coal consumption outside the EU. Thus, an interesting follow-up study could be to examine the optimal combination of demand and supply side measures in the EU or other countries with unilateral climate policies.

References

Alhajji, A. and D. Huettner (2000): OPEC and World Crude Oil Markets From 1973 to 1994: Cartel, Oligopoly, or Competitive?, *The Energy Journal* 21(3), 31-60.

Askari, H. and N. Krichene (2010): An oil demand and supply model incorporating monetary policy, *Energy 35*, 2013–2021.

Böhringer, C., C. Fischer, and K.E. Rosendahl (2010): The Global Effects of Subglobal Climate Policies, *The B.E. Journal of Economic Analysis&Policy* 10(2), (Symposium) Article 13.

Böhringer, C., B. Bye, T. Fæhn and K. E. Rosendahl (2012a): Alternative designs for tariffs on embodied carbon – a global cost-effectiveness analysis, *Energy Economics* 34 (suppl. 2), 143-153.

Böhringer, C., J.C. Carbone, and T.F. Rutherford (2012b): Unilateral climate policy design: Efficiency and equity implications of alternative instruments to reduce carbon leakage. *Energy Economics* 34, Supplement 2 (The Role of Border Carbon Adjustment in Unilateral Climate Policy: Results from EMF 29), 208–217.

BP (2013): BP Statistical Review of World Energy 2013, London: BP.

Brons, M., P. Nijkamp, E, Pels and P. Rietveld (2008): A meta-analysis of the price elasticity of gasoline demand. A SUR approach, *Energy Economics* 30 (5), 2105–2122.

Climate Cure 2020 (2010): Tiltak og virkemidler for å nå norske klimamål mot 2020, Klima- og forurensningsdirektoratet, Norges vassdrags- og energidirektorat, Oljedirektoratet, Statistisk sentralbyrå, Statens vegvesen. Rapport TA2590

Dahl, C. (2006): Survey of Econometric Energy Demand Elasticities Progress Report, August 2006, Unpublished report.

Dahl, C. (2012): Measuring global gasoline and diesel price and income elasticities, *Energy Policy* 41, 2–13.

Dahl, C. and T.E. Duggan (1998): Survey of Price Elasticities from Economic Exploration Models of US Oil and Gas Supply, *Journal of Energy Finance & Development* 3, Number 2, 129-169.

Ellis, J. (2010): The Effects of Fossil-Fuel Subsidy Reform: A review of modelling and empirical studies, International Institute for Sustainable Development (IISD), March 2010. http://ssrn.com/abstract=1572397.

Fæhn. T, E. Isaksen, K. Jacobsen and B. Strøm (2013a): MSG-TECH: Analysis and documentation of a general equilibrium model with endogenous climate technology adaptations, Reports 47/2013, Statistics Norway.

Fæhn, T., C. Hagem, L. Lindholt, S. Mæland and K. E. Rosendahl (2013b): Climate policies in a fossil fuel producing country- demand versus supply side policies, Discussion paper 747, Statistics Norway.

Farzin, Y.H. (2001): The impact of oil prices on additions to US proven reserves, *Resource and Energy Economics*, 271–291.

Fournier, J. I. Koske, I. Wanner and V. Zipperer (2013): The Price of Oil – Will it Start Rising Again?, OECD Economics Department Working Papers, No. 1031, OECD Publishing. http://dx.doi.org/10.1787/5k49q186vxnp-en

Golombek, R., C. Hagem and M. Hoel (1995): Efficient incomplete international climate agreements, *Resource and Energy Economics* 17 (1), 25-46.

Griffin, J.M. (1985): OPEC behavior: a test of alternative hypotheses, *American Economic Review* 75, 954–963.

Hagem, C. (1994): Cost-effective climate policy in a small country, *Energy Journal* 15 (4), 119-139.

Hansen, P.V. and L. Lindholt (2008): The Market Power of OPEC 1973–2001. *Applied Economics* 40(22), 2939–59.

Harstad, B. (2012): Buy Coal! A Case for Supply side Environmental Policy, *Journal of Political Economy* 120 (1), 77-115.

Hoel, M. (1994): Efficient Climate Policy in the Presence of Free Riders, *Journal of Environmental Economics and Management* 27 (3), 259-274.

Hoel, M. (1996): Should a carbon tax be differentiated across sectors? *Journal of Public Economics* 59 (1), 17-32.

Hoel, M. (2013): Supply side climate policy and the green Paradox, CREE Working Paper 2/2013

Hotelling, H. (1931): The economics of exhaustible resources, *The Journal of Political Economy* 39, 137-175.

International Energy Agency (IEA) (2007): World Energy Outlook 2006, International Energy Agency, Paris.

Krichene, N. (2002): World crude oil and natural gas: a demand and supply model, *Energy Economics* 24, 557–576.

Markusen, J. R., E. R. Morey and N. D. Olewiler (1993): Environmental Policy when Market Structure and Plant Locations Are Endogenous, *Journal of Environmental Economics and Management* 24 (1), 69-86.

Markusen, J. R., E. R. Morey and N. Olewiler (1995): Competition in regional environmental policies when plant locations are endogenous, *Journal of Public Economics* 56 (1), 55-77.

Ministry of Finance (2012): Skatter, avgifter og toll 2013. http://www.regjeringen.no/nb/dep/fin/ dok/ regpubl/ prop/2012-2013/prop-1-ls-20122013/11/9/2.html?id=702766

Ministry of Petroleum and Energy (2011): An industry for the future – Norway´s petroleum activities, Meld. St. 28 (2010–2011) Report to the Storting (white paper). http://www.regjeringen.no/upload/OED/Petroleumsmeldingen_2011/Oversettelse/2011-06_White-paper-on-petro-activities.pdf

Ministry of Petroleum and Energy (2013): Facts 2013 (Faktaheftet 2013). The Norwegian Petroleum Sector. http://npd.no/Global/Engelsk/3-Publications/Facts/Facts2013/FACTS_2013.pdf

Mohn, K. and P. Osmundsen (2008): Exploration economics in a regulated petroleum province: the case of the Norwegian Continental Shelf, *Energy Economics* 30, 303–320.

OGP (2012): Environmental performance indicators. 2011 data, Report No. 2011e, October 2012, International Association of Oil & Gas Producers. http://www.ogp.org.uk/publications/environment-committee/environmental-performance-indicators/environmental-performance-indicators-2011-data/

Ramcharran, H. (2002): Oil production responses to price changes: an empirical application of the competitive model to OPEC and non-OPEC countries, *Energy Economics* 24, 97–106.

Rauscher, M. (1997): International Trade, Factor Movements, and the Environment, Oxford: Oxford University Press.

Ringlund, G. B., K. E. Rosendahl and T. Skjerpen (2008): Does oilrig activity react to oil price changes? An empirical investigation, *Energy Economics* 30, 371-96.

Rystad (2013): Petroleum production under the two degree scenario (2DS), Report for The Ministry of the Environment.http://www.regjeringen.no/pages/38425303/2013_Rystad_Energy_Climate_report_Norwegian Ministry_of_the_environment.pdf

Sinn, H.-W. (2008): Public policies against global warming: a supply side approach, *International Tax and Public Finance* 15 (4), 360-394.

Smith. J. (2005): Inscrutable OPEC? Behavioral tests of the cartel hypothesis, *The Energy Journal*, 26 (1), 51-82.

The Economist (2009): Norway and the environment - Binge and purge. http://www.economist.com/node/12970769

The Norwegian Oil Company (2012): Konsekvensutredning for Ivar Aasen (Impact study for Ivar Aasen (in Norwegian).

Venables, A. J. (2011) : Depletion and development: Natural resource supply with endogenous field opening, CESifo working paper: Resource and Environment Economics, No. 3608. http://hdl.handle.net/10419/52473

World Bank (2008): Climate Change and the World Bank Group: Phase I: An Evaluation of World Bank Win-Win Energy Policy Reforms. World Bank: Washington, DC.

Österle, I. (2012): Fossil Fuel Extraction and Climate Policy: A Review of the Green Paradox with Endogenous Resource Exploration. FEEM Working Paper Series 13.2012.

Appendix A:

Derivation of equation (18):

$$E'_{y_i} = \tilde{E}'_{y_i} + \frac{\partial \sum_{j=o,c,g} \beta_j(X_j)}{\partial y_i} = 1 - L^D + \sum_{j=o,c,g} \beta'_{X_j} \frac{\partial X_j}{\partial y_i}$$

$$= 1 - L^D + \beta'_{X_i} \cdot (1 + \sum_{k=o,c,g} D'_{ik} \frac{\partial f_k}{\partial (y_i - x_i)}) + \beta'_{X_s} \cdot (\sum_{k=o,c,g} D'_{sk} \frac{\partial f_k}{\partial (y_i - x_i)}) + \beta'_{X_h} \cdot (\sum_{k=o,c,g} D'_{hk} \frac{\partial f_k}{\partial (y_i - x_i)})$$

$$= 1 - L^D + \beta'_{X_i} - \sum_{j=o,c,g} \beta'_{X_j} \cdot l^D_{ji}, \qquad s \neq i, h \neq i, s \neq h,$$

and

$$E'_{x_i} = \tilde{E}'_{x_i} + \alpha'_{x_i} + \frac{\partial \sum_{j=o,c,g} \beta_j(X_j)}{\partial x_i} = L^D_i + \alpha'_{x_i} + \sum_{j=o,c,g} \beta'_{X_j} \cdot \frac{\partial X_j}{\partial x_i}$$

$$= L^D_i + \alpha'_{x_i} + \beta'_{X_i} \cdot (-1 - \sum_{k=o,c,g} D'_{ik} \frac{\partial f_k}{\partial (y_i - x_i)}) + \beta'_{X_s} \cdot (- \sum_{k=o,c,g} D'_{sk} \frac{\partial f_k}{\partial (y_i - x_i)}) + \beta'_{X_h} \cdot (- \sum_{k=o,c,g} D'_{hk} \frac{\partial f_k}{\partial (y_i - x_i)})$$

$$= L^D_i + \alpha'_{x_i} - \beta'_{X_i} + \sum_{j=o,c,g} \beta'_{X_j} \cdot l^D_{ji}, \qquad s \neq i, h \neq i, s \neq h.$$

Appendix B:

Price responsiveness on the demand side

There is a large empirical literature on direct price elasticities. However, the estimation results vary quite substantially. Using a meta-analysis of 43 primary studies of gasoline demand from different countries, Brons et al. (2008) find a mean long-run price elasticity of -0.84. However, all the primary studies were published before the year 2000. Carol Dahl has developed a large database with inter alia 247 studies of gasoline and diesel demand studies from around the world. According to her summary statistics, the median long-run price elasticities are -0.55 and -0.33 for gasoline and diesel, respectively.[21] In Dahl (2012) she presents an analysis 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.[22] Dahl finds that elasticities tend to increase with both prices and income. Ellis (2010) reviews empirical literature on price elasticities, and refers e.g. to studies by the World Bank (2008) and the IEA (2007). Whereas the World Bank estimates long-run price elasticities for gasoline and diesel at -0.61 and -0.67, respectively, the IEA estimates the long-run price elasticity for crude oil demand at -0.15. Fournier et al. (2013) estimate the average medium- to long-run price elasticity in OECD and BRIICS (Brazil, Russia, India, Indonesia, China and South Africa) countries to be around -0.2.[23] Askari and Krichene (2010) find very low elasticities: Their estimates of long-run demand *and* supply elasticities are both around 0.01 in absolute value.

Most empirical studies of oil demand focus on gasoline and diesel demand. As stated by Ellis (2010), demand tends to be less elastic in the transport sector than in other sectors due to fewer viable alternatives. This is confirmed by an unpublished survey by Dahl (2006), based on the database referred to above, reporting a mean long-run elasticity for fuel oil at -0.9.

As is evident, a consensus estimate of the long-run price elasticity of oil demand is difficult to nail down. As mentioned in Section 3.2.1, we use -0.5 as our benchmark case estimate. However, we use other estimates as well in the sensitivity simulations.

Whereas estimates of direct price elasticities vary quite a lot, estimates of cross-price elasticities are rarely reported (none of the studies mentioned above do so). Instead, we will rely on simulations on a large-scale CGE model building on the extensively used GTAP database and using benchmark GTAP parameters for crucial elasticities in production and consumption of goods and services.[24] By simulating an exogenous increase in the crude oil price, we find that global consumption of coal and gas (measured in carbon) increases by respectively 0.10 and 0.09 units for every unit

---

[21] The database contains studies dating from the 1970's up until today. The standard deviation for the long-run gasoline elasticity is 6.37! See http://dahl.mines.edu/courses/dahl/dedd/.

[22] 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.

[23] It is reasonable to assume that price elasticities for crude oil are lower than for oil products, as oil products are higher priced than crude oil (Fournier et al., 2013). At least this is the case if the markup, i.e., the difference between the product and the crude oil price, is independent of the crude oil price itself. Own estimations suggest that the markup and the crude oil price is somewhat correlated, but a 1 percent increase in the crude oil price will in general increase the product price by less than 1 percent.

reduction in oil consumption.[25] This corresponds to cross-price elasticities of around 0.08 for both fuels, which we use as our benchmark case estimates.

Price responsiveness of Non-OPEC supply

As opposed to oil demand price elasticities, there exist rather few empirical studies of oil supply price elasticities. This is also pointed out by Fournier et al. (2013), who set the price elasticity of supply equal to the (absolute value of the) estimated demand elasticity (-0.2) in their simulations. Above we referred to a study by Askari and Krichene (2010), who estimates long-run demand *and* supply elasticities around 0.01 in absolute value. In an earlier study, Krichene (2002) reports a long-run supply elasticity of 0.1 for the period 1973-1999. Importantly, however, all these studies consider *world* supply of oil, not Non-OPEC supply. Ramcharran (2002) finds an average price elasticity of 0.11 for Non-OPEC over the period 1973-1997. In a study of OPEC behaviour, Alhajji and Huettner (2000) find support for a model where Saudi Arabia acts as a dominant producer – with this specification oil supply price elasticity from the rest of the world (Non-OPEC + OPEC minus Saudi Arabia) is found to be 0.20. In a similar study, Hansen and Lindholt (2008) find a long-run supply elasticity of 0.38 for the period 1974-2001.

Empirical studies that focus on oil drilling tend to find higher price elasticities. For instance, Ringlund et al. (2008) find an average long-run elasticity of 0.99 for oilrig activity in Non-OPEC, with elasticities ranging between 0.51 and 1.86 in different regions. Dahl and Duggan (1998) find elasticities for oil exploration in the U.S. above one, whereas Mohn and Osmundsen (2008) find a long-run elasticity of 0.41 for exploration drilling in the Norwegian Continental Shelf. Farzin (2001) finds even lower elasticities for reserve additions of known fields in the U.S. (0.16 in the long run).

Again, it is difficult to pin down the exact price elasticity of Non-OPEC supply. As a benchmark case estimate, we will use 0.5, i.e., the same absolute value as for the demand price.

---

[24] The model has been used in e.g. Böhringer et al. (2010, 2012a,b). The GTAP database is available at www.gtap.org.

[25] Obviously, from the same simulations we can derive the implicit direct price elasticity for oil, which turns out to be -0.45 for crude oil, i.e., quite close to the estimate of the benchmark case.