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Demand versus supply side policies

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Abstract:
In absence of joint global action, many jurisdictions take unilateral steps to reduce carbon emissions, and the usual strategy is to restrict domestic demand for fossil fuels. The impact on global emissions of such demand side policies is found by accounting for carbon leakage, i.e. changes in emissions abroad induced by the domestic action. Another domestic option for fossil fuel producers, that is yet not well explored, is to reduce own supply of fossil fuels, again accounting for leakages. We explore analytically and numerically how domestic demand and supply side policies affect global emissions, contingent on market behaviour in the fossil fuel markets. Next, we combine this with costs of demand- and supply side policies to find the cost-effective combination of the two types of policies. Norway is the case in our numerical analysis. Our results indicate that given a desire for domestic action and a care for global emissions, the majority of emission reductions should come through supply side measures, i.e., by downscaling Norwegian oil extraction.

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

JEL classification: H23; Q41; Q54

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Sammendrag

I fravær av en internasjonal klimaavtale har mange land satt i verk nasjonale tiltak for å redusere karbonutslippene. Det vanligste tiltaket er å begrense eget forbruk av fossil energi. For å beregne den globale utslippseffekten av denne type etterspørselstiltak må man ta hensyn til karbonlekkasjen, dvs endringer i utslipp i utlandet som følge av de nasjonale tiltakene. Land som utvinner fossil energi har også mulighet til å påvirke de globale utslippene gjennom redusert produksjon av slik energi. Denne type tiltak er mindre utforsket, og også her må man ta hensyn til karbonlekkasjen for å beregne virkningen på globale utslipp. For å finne den optimale kombinasjonen av de to politikkalternativene undersøker vi analytisk og numerisk hvordan etterspørsels- og tilbudssidepolitikk påvirker globale utslipp. Dette avhenger av markedsresponsen i de fossile energimarkedene. De numeriske beregningene av kostnadene ved politikkalternativene er basert på tall fra Norge. Våre resultater indikerer at dersom det tas hensyn til globale utslippsreduksjoner, og det er ambisjoner om innenlandske tiltak, bør størstedelen av reduksjonene komme gjennom tilbudssidetiltak, dvs. nedskalering av Norges oljeutvinning.

1. Introduction

In 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 on the global level. In this first best situation, demand and supply side policies coincide. However, with limited participation in a climate agreement, or with unilateral action by a single or a coalition of countries, demand side versus supply side policies matters. Many jurisdictions show willingness to restrict domestic demand for fossil fuels, even though economic reasoning calls for picking the *globally* most cost effective abatement options.

Domestic supply side policies are less frequently discussed, let alone pursued. The purpose of this paper is to assess what is the cost-effective combination of the two types of policies, given a country's target for own contributions to global emission reductions. The result hinges critically on how domestic demand side and supply side policies affect global emissions. 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.

Policy measures that reduce fossil fuel demand lead to lower international energy prices, and may also reduce competitiveness 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 conserve 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 ignore the options of purchasing both foreign fossil fuel deposits and international emission quotas (e.g. EU ETS quotas or CDM credits) and look at domestic measures, only.

Our case in the numerical analysis is Norway, which accounts for around 2 percent of global oil production. Norway has an ambitious target for domestic emission reductions by 2020 and has so far not considered using supply side measures. Our findings indicate that the *global* effect of the domestic demand side ambitions is likely to be around 30-40 per cent lower than the domestic emission

reductions, because of carbon leakages. The main conclusion of our paper is that the most cost-effective domestic policies for obtaining these global reductions would be to substitute around two thirds of the planned domestic demand side abatement with supply side measures, that is, reduced oil extraction.

The 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). Previous literature on optimal 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 the fossil fuel market as one aggregate 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). Hagem (1994) compares numerically the costs of pure demand side policy with pure supply side policy for 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, we review the empirical literature on the 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 shown 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 quite clear 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 depends on the expected, future price path (Hotelling, 1931). If they 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 analyzing fossil fuel policies in a static framework as ours even if some intertemporal redistribution 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. Unilaterally introducing demand side instruments such as carbon taxes or permits reduces the international competitiveness of domestic, emission-intensive firms and causes carbon leakages. 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 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, $\overline{A}$, where W is utility of consuming fossil fuels net of production and net import costs:

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

where 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:

$$\text{(2)} \qquad B'_{y_i} = P_i + P'_{y_i}(y_i - x_i) + \lambda E'_{y_i}$$

$$\text{(3)} \qquad c'_i(x_i) = P_i - P'_{x_i}(y_i - x_i) + \lambda E'_{x_i}\ .$$

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 welfare impacts of the global fossil fuel price changes can be considered minor for the small home country. Note that this is not a sufficient condition for

disregarding the global emission effects of the price changes, which must be compared to the home country's own emission cuts; see next subsections. From (2) and (3), we then find:

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

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 profit and net benefit, it is shown in Golombek et al. (1995) that the optimal outcome can be achieved by introducing a consumer tax, $t^c = \lambda E'_{y_i}$, and a producer tax, $t^p = \lambda E'_{x_i}$, for all fuel types.

We will proceed by deriving expressions for E'_{y_i} and E'_{x_i} in a partial fossil fuel market model. We distinguish between impacts on global emissions stemming from combustion of fossil fuel traded in markets and used as input in extraction, respectively, and explore them in each of the two subsequent subsections.

2.2. Global emissions from combustion of fossil fuels traded in markets

Let capital letters denote foreign production and consumption of the three fossil fuels (X_i and Y_i, $i = o,c,g$). Total global emissions from combustion of fossil fuels, $\tilde{E}$, equals global fossil fuel production, which again must equal global consumption:

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

To simplify the analytical derivations, we treat domestic consumption (y_i) and production (x_i) as exogenous variables, set by the domestic regulator. 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 ($Y_i = D_i(P_o, P_c, P_g)$, 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 energy market, foreign production must equal foreign consumption plus net import from the home country:

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

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

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

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

(8) $$X_o = Z + S_o(P_o),$$

where Z is output from the dominant oil producer, and $S_o(P_o)$ 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:

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

Our default assumption is that the dominant oil producer maximises net income. However, we also consider other objective functions. In 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.

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

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

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

(11) $$P_o + P_{oZ}' \cdot Z - C'(Z) = 0.$$

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

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

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 CO_2) following from a unit *decrease* in domestic consumption of fuel *i*:

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

To simplify the discussion, we make the following reasonable assumption:[1]

(14) $$0 < L_i^D < 1.$$

We define marginal supply side leakage of fuel *i* (L_i^S) as the *increase* in total fossil fuel production abroad (measured in CO_2) 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:

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

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

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

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

[1] (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. (15) is satisfied in our numerical model.

($\tilde{E}'_{y_i}$ -$\tilde{E}'_{x_i}$ > 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 only accounted for emissions from the use of fossil fuels traded in markets. However, as argued above, there are also emissions due to extraction of the fuels, as fossil fuels are used as inputs in the extraction processes, 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):

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

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

(18) $$E'_{y_i} = \tilde{E}'_{y_i} + \frac{\partial \sum_{j=o,c,g} \beta_j(X_j)}{\partial y_i} = 1 - L^D + \beta'_{X_i} - \sum_{j=o,c,g} \beta'_{X_j} \cdot l_{ji}^D,$$
$$E'_{x_i} = \tilde{E}'_{x_i} + \alpha'_{x_i} + \frac{\partial \sum_{j=o,c,g} \beta_j(X_j)}{\partial x_i} = L_i^D + \alpha'_{x_i} - \beta'_{X_i} + \sum_{j=o,c,g} \beta'_{X_j} \cdot l_{ji}^D,$$

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

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

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 market 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:

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

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

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^D_{ji}), the differences in emission intensities 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:

(22) $$E'_{y_i} - E'_{x_i} = 1 - 2L^D_i + 2\beta'_X \cdot (1 - L^D_i) - \alpha'_{x_i} .$$

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

3. Numerical analysis

We estimate marginal costs of Norwegian unilateral reductions in fossil fuel demand and supply in Section 3.1. This means quantifying $B'_{y_i}\text{-}P_i$ and $P_i\text{-}c'_i(x_i)$, respectively; see Eq. (4). Demand side abatement is assessed by means of a CGE country model. Supply side measures are quantified by identifying representative, marginal cuts in oil production. Norway is also a significant producer of gas. In 2011, Norway accounted for 2.3 percent of global oil production and 3.1 percent of global gas production (BP, 2012). 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. Thus, we do not consider this supply side option in our analysis.[2]

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

Demand side policies

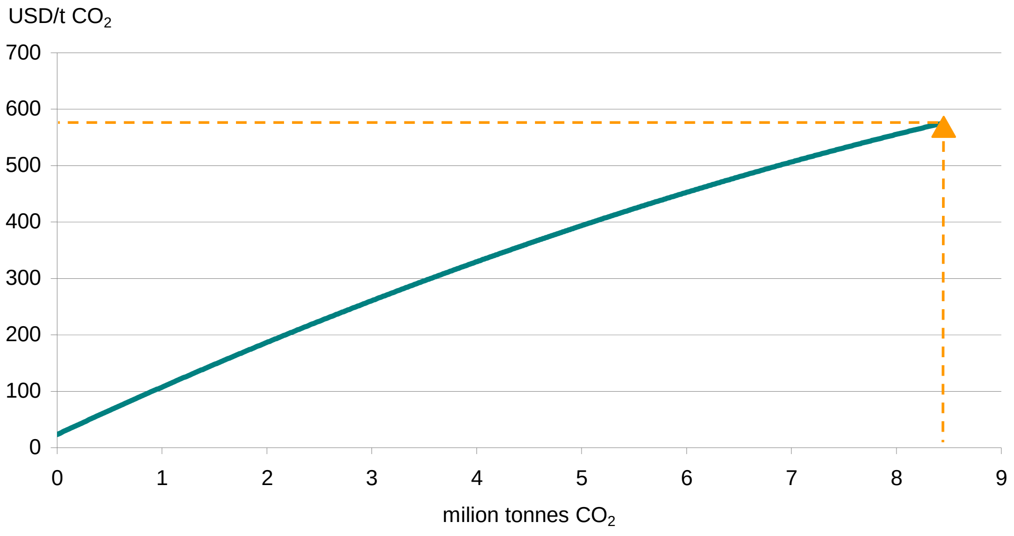
The starting point for our policy analysis is the ambition on domestic greenhouse gas (GHG) abatement set by the Norwegian Parliament.[3] By 2020, unilateral action corresponding to a 30 per cent reduction from Norwegian 1990 emissions is pledged, and about two thirds of the reductions relative to a defined 2020 reference level is to be taken domestically through demand side measures. The officially appointed expert group Climate Cure 2020 (2010) carried out macroeconomic computations of necessary, cost-effective demand side measures. (Climate Cure 2020) derives what we may term a reference scenario, whitch includes policies already implemented, approved, or promised for the years up to 2020. To obtain a marginal cost function for demand side measures, we compare this reference

[2] We abstract from the technical challenges of separating oil and gas extraction, but return to this issue in section 3.3.

[3] The agreement is available at http://www.regjeringen.no/Upload/MD/Vedlegg/Klima/avtale_klimameldingen.pdf

scenario with a unilateral climate policy scenario where demand side policies are only imposed on sectors outside the EU ETS. This choice is consistent with our assumption that the home country (Norway) is concerned with *global* emissions; as there is a cap on total emissions in the EU ETS, additional cuts in Norwegian ETS sectors would merely displace emissions to ETS-regulated installations in other European countries.[4]

Figure 1. Marginal costs of foregone fossil fuel consumption for Norway



The reduction of CO_2 emissions from fossil fuel consumption compared with the reference scenario amounts to 15 per cent of total GHG emissions in 2020, corresponding to a domestic abatement of $\overline{A}_D$ = 8.4 million tonnes (Mt) of CO_2.[5] The estimated marginal costs in terms of foregone fossil fuel consumption (the value of B'_{y_i} -P_i for all fuels) to achieve the domestic target is USD 576 per ton CO_2, which are considerable as virtually all abatement will have to take place within transportation. In road transportation, the abatement amounts to more than half of the reference emissions. The cuts almost exclusively take place as reduced oil consumption.

[4] This comparison of scenarios is identical to comparing scenarios B and C in Climate Cure 2020 (2010). The scenario C used as our reference includes participation in the EU ETS, a differentiated carbon tax system in the non-EU ETS sector, deployment of CCS technologies on all gas power installations, and considerable energy efficiency improvements. In scenario B, the differentiated carbon tax system is replaced by a uniform GHG tax.

[5] The Climate Cure 2020 computations also allows for forest conservation and other GHG abatement, which we disregard here. Total abatement is therefore 21 per cent in 2020, where 15 percentage points represent demand side CO_2 abatement.

Based on a number of simulations using the same hybrid CGE model and assumptions as Climate Cure 2020 (see Fæhn et al., 2013), we have estimated the following marginal cost curve for Norwegian demand side measures: [6]

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

The curve is depicted in Figure 1; the marked point is the Climate Cure 2020 unilateral policy scenario, where $\overline{A}_D$ = 8.4 Mt of CO_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 $P_o - c'_o(x_o)$; see nominator of the second fraction of Eq. (4). We need to single out oil fields which can be characterized as marginal, in the sense that reducing or terminating extraction involves as small profit loss per unit CO_2 extracted as possible. 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 declines. In addition, IOR activities (Improved Oil Recovery) can involve new investments. Typically, these fields also have higher emission intensities.

For the years 2009-2011, we have singled out nine Norwegian fields where oil constituted a major or total part of the petroleum production. In addition, these fields were in, or close to, the decline phase. For some of these fields investment costs for drilling purposes were increasing during one or more of our covered years, which may be characterized as IOR-activities. We have data from Statistics Norway on production volume and variable costs, costs that would not accrue if oil production were reduced or terminated. Based on these data we can construct the marginal production cost curve shown in Figure B1 in Appendix B.

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), subtracted by the production costs in Figure B1; see Figure 2.[7] The supply side cost curve, where A_S is reduced extraction measured in CO_2, is:

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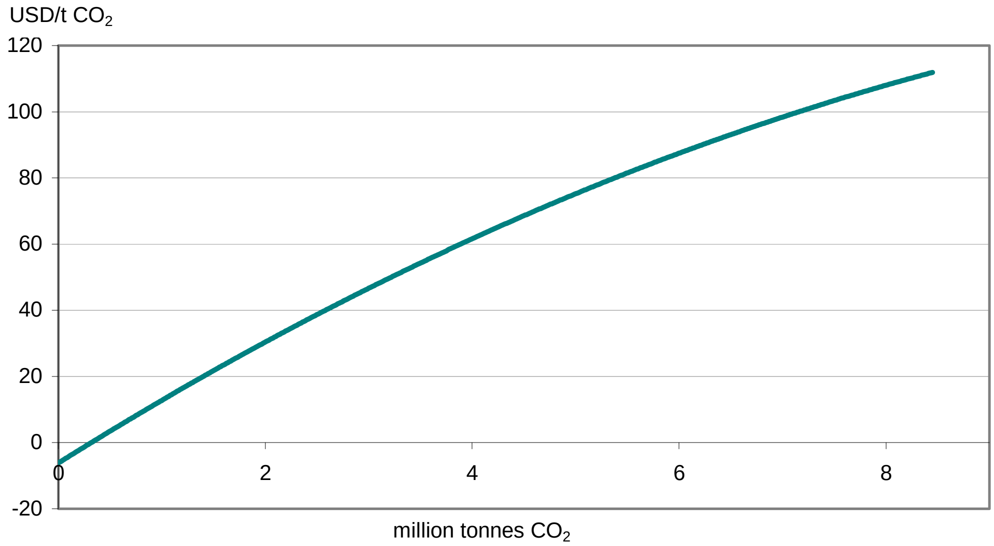
[6] The intersection point with the vertical axis is the uniform tax rate that yields the same abatement as obtained with the differentiated tax system in the reference scenario.

[7] While costs and production are measured in USD/barrel and million Sm^3 in Figure B1, respectively, we now measure these variables in USD per ton CO_2 and Mt of CO_2. One million Sm^3 of oil leads to 2.65 tonnes of CO_2 emitted when the oil is combusted.

(24) $$P_o - c_o'(x_o) = -0.7A_S^2 + 19.6A_S - 6.1.$$

We see that it is actually profitable to reduce 0.3 Mt of CO_2, irrespective of climate benefits, due to high production costs of some of the smaller fields.

Figure 2. Marginal foregone profits of reduced oil extraction for Norway



As we only have included variable costs in the decline phase of the fields, and not field development costs in the initial years (due to lack of data), we have probably underestimated the total costs of production, i.e., overestimated the costs of reducing production. Moreover, we do not have specific information about costs of IOR projects, which are often projects with limited profits per unit of extraction. Most probably this contributes to overestimate the costs of the supply side measures depicted in Figure 2.

In our study we are more interested in future abatement options. Thus, the relevant question is to what extent the cost function depicted in Figure 2 is representative for coming years such as 2020. On the one hand, the future oil price may be higher than the average for the years 2009-2011 (84.5 USD per barrel), suggesting 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 higher oil price on forgone profits could be moderated. 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 by 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.

To help assessing the relevance of the marginal foregone profit curve in Figure 2, we have also gathered information on a future, not yet started, oil field named Ivar Aasen. Here we have access to information about both expected annual development and operating costs, as well as production (The Norwegian Oil Company, 2012). Investments for this field will start 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.[8] With an average production of 1.4 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 B1 in Appendix B for the years 2009-2011 (i.e., the upper third part of the curve).[9]

To sum up, we believe that Figure 2 could be quite representative for the year 2020, although the uncertainties are rather large. From the discussion above, it seems more likely that the supply side abatement costs lie below than above the curve shown in Figure 2.

3.2. Numerical analysis of global fossil fuel markets

The partial fossil fuel market model

Based on the exposition in Section 2.2, 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 climate 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 C contains a detailed discussion of the main drivers, in particular a review of

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[8] 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.

[9] According to Aftenposten (2013), several other undeveloped fields have break-even prices around 60-80 USD per barrel.

existing demand and supply elasticity estimates from the literature. Here we only present our benchmark assumptions, 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 equipments. 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 projects to increase oil recovery (IOR) rates of fields in production. 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.[10] 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 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% of the oil price, which is within the range of production costs reported by IHS CERA

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

for OPEC countries (see e.g. Figure 3.9 in Ministry of Petroleum and Energy, 2011).[11] When we model OPEC as a competitive producer, we assume the same supply elasticity as for Non-OPEC.

Although the lion's share of carbon 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 greenhouse gas (GHG) emissions per unit production worldwide in 2011 were 159 tonnes CO_2e (CO_2 equivalents) per 1,000 toe hydrocarbon produced. However, the marginal emission intensities will typically exceed the average. Emission intensities for the Middle East are much lower than the global average, which is also the case for Norway. Hence, average Non-OPEC emissions are higher than the global average. As explained in appendix C, we set the benchmark emission intensities in Norway, OPEC and Non-OPEC equal to respectively 90, 76 and 300 tonnes CO_2e per 1,000 toe.[12] For comparison, emissions from consuming (i.e., combusting) 1,000 toe of oil is about 3,070 tonnes of CO_2. Although of minor importance here, we also account for emissions from extracting other fossil fuels, and assume that emission intensities for coal and gas are equal to the emission intensity for oil in Non-OPEC (outside Norway).

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. (5). 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 competitive or a dominant 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).

[11] 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. We return to this issue below when we do sensitivity analysis with respect to elasticities.

[12] 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). As seen in the following subsection, however, these emissions are of less importance.

We first notice that leakage through the oil market is around 50 percent 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. Still, supply side leakage through the oil market is 55 percent, compared to 45 percent for demand side leakage (given the benchmark assumptions).

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 percent of the gross emission reduction.

Finally, we see that the importance of emissions from fossil fuel extraction is more modest, as these emissions account for less than ten per cent of total emissions from extracting and consuming oil. The effects are highest for demand side policy, as under supply side policy emissions from oil extraction only matters to the degree that emissions outside Norway exceed Norwegian emissions.

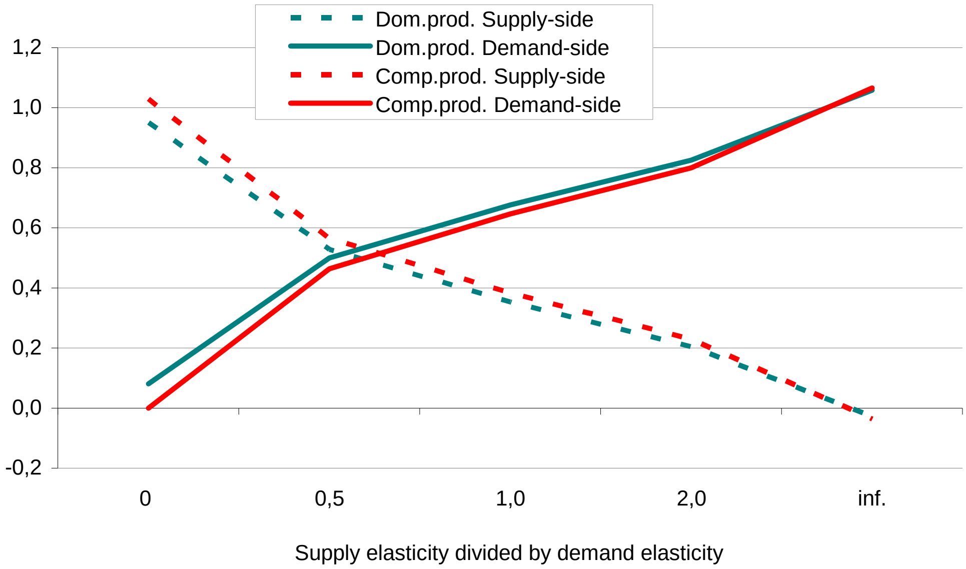
Table 1. Net global emission reduction from reduced Norwegian oil extraction or consumption by one unit of carbon. Benchmark assumptions.

	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, the net emission reductions depend heavily on the assumed elasticities, which affect leakage through the fossil fuel markets. In the competitive model variant, we can freely alter any elasticity and recalibrate the model to base year data. In the dominant producer model, however, a change in elasticities will typically alter the calibrated production costs in OPEC that are consistent with base year data. Hence, in order to keep OPEC production costs unchanged while checking the effects of different elasticities, we search for combinations of elasticities that comply with this

restriction.[13] Intuitively, higher supply elasticity must then be accompanied with less elastic demand (to keep the residual demand elasticity quite unchanged). Figure 3 shows the results of either more elastic supply and less elastic demand, or vice versa.[14] We see that when supply is twice as elastic as demand, net emission reductions from supply side policies drop to 20 percent of the gross emission reduction, while for demand side policies net emission reductions are around 80 percent. On the other hand, if demand is twice as elastic as supply, supply side policies are slightly more effective in reducing global emissions than demand side policies. These findings apply both in the competitive setting and when OPEC acts as a dominant producer. We notice, however, that OPEC tends to adjust its supply somewhat more in the latter case, implying slightly higher supply side and lower demand side leakage in the dominant producer variant.

Figure 3. Net global emission reductions (per cent) with demand or supply side policy when OPEC acts as dominant or competitive producer



If OPEC decides to keep the oil price fixed at the BAU-level, there is of course no demand side leakage through the fossil fuel markets. Hence, net global emission reductions under demand side policy equal the gross reductions in Norway, plus reduced emissions from extraction, while supply side policy has negligible impacts on global emissions.

[13] If we relax this restriction, and multiply all elasticities with a factor $k > 1$ ($k < 1$), the calibrated OPEC unit costs increase (decrease). This leads to higher (lower) emission reductions with demand side policy and lower (higher) emission reductions with supply side policy. In the competitive setting the results are unchanged.

[14] All fossil fuel supply and demand elasticities are adjusted, except for OPEC in the dominant producer model.

On the other hand, if OPEC decides to keep its oil extraction fixed at the BAU-level, net global emission reductions are about half of the gross reduction in Norway both under supply- and demand side policy. The explanation is that the price response by Non-OPEC is quite similar to the net price response for fossil fuel demand (coal and gas demand change in the opposite direction of oil demand).

We noticed above that emissions from oil extraction have relatively modest impacts on the net emission reductions from reduced oil extraction or consumption. Still, it might be useful to see the consequences of changing the benchmark assumptions about emission intensities of oil extraction. If we e.g. assume that Norway cuts back on its most emission-intensive extraction activities (e.g., improved oil recovery projects), we may be talking about fields with emissions of 300 tonnes of CO_2 per 1,000 tonnes of oil (cf. Figure C1). Then the net emission reduction from supply side policy increases to 0.418 (0.448) when OPEC behaves as a dominant (competitive) producer. If we instead assume that the marginal oil extraction outside OPEC has emissions around 500 tonnes of CO_2 per 1,000 tonnes of oil, which could be the case if oil sand in Canada constitutes a major share of marginal extraction, then net emission reduction from supply side policy drops to 0.33 (0.358) when OPEC behaves as a dominant (competitive) producer. Net reduction from demand side policy, on the other hand, increases to 0.699 (0.671). Hence, emissions from oil extraction should not be ignored, and their importance depends quite much on which oil resources that are (not) extracted.

3.3. Optimal balancing of demand and supply side policies

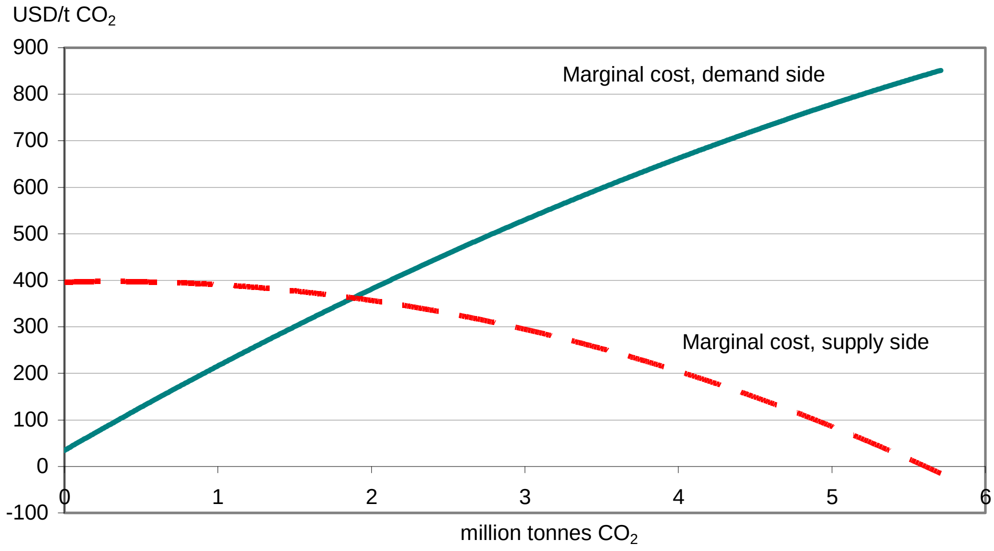
The equilibrium solution

When we account for the net global emission effects displayed in Table 1 (with OPEC being a dominant producer), the demand side measures in Climate Cure 2020 (2010), i.e., reducing domestic emissions by $\overline{A}^D$ = 8.4 Mt of CO_2, correspond to a global emission cut of $\overline{A}$ = 5.7 Mt of CO_2. The marginal cost of reducing *global* CO_2 emissions (i.e., λ in Eq. (4)) is then 850 USD per ton. The corresponding marginal abatement cost curve for demand side measures is depicted in Figure 4, along with the corresponding marginal abatement cost curve for supply side measures (also accounting for net global emission effects).

The intersection point in Figure 4 reveals that the optimal combination of demand and supply side abatement for Norway, given a global emission reduction target of $\overline{A}$ = 5.7 Mt, involves 35 per cent demand side measures, while the remaining emission cuts should be carried out as reduced oil

extraction. The corresponding marginal costs of reducing global CO_2 emissions are 367 USD per ton, i.e., less than half of the marginal cost with only demand side measures.

Figure 4. Leakage-adjusted domestic demand side marginal abatement cost curve and the marginal supply side abatement cost curve



Implementing this combination of demand and supply side measures would mean that domestic CO_2 emissions should be reduced by almost 3 Mt of CO_2, e.g., through a domestic CO_2 tax on non-EU ETS sectors of 248 USD per ton CO_2 (cf. Figure 1).[15] Almost 90 per cent of the measures that are profitable to carry out relate to transportation, of which reduced private transport accounts for 20 per cent and transition to climate friendly vehicles accounts for the rest.

Moreover, Norwegian oil extraction should be reduced by 3.8 million Sm^3, which is 3.4 percent 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 53 per barrel,[16] i.e., around half of the current crude oil price. As mentioned in Section 3.1, the break-even price of the Ivar Aasen oil field, which can be characterized as relatively profitable, is around USD 60 per barrel.

[15] The domestic CO_2 tax is found by multiplying the marginal cost of reducing global CO_2 emissions (367 USD per ton) with the net effect on global emissions of reduced Norwegian consumption (0.676 – see Table 1).

[16] The production tax is found by multiplying the marginal cost of reducing global CO_2 emissions (367 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).

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 3.4 percent calculated above. The reason is that, as underlined in Section 3.1, we most likely overestimate the costs of reducing oil extraction. 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 our benchmark assumptions. Note that to be consistent with the domestic emission reduction target in Climate Cure 2020 (2010), we have to adjust the global emission reduction target $\overline{A}$ in the same way as before. This adjustment in the global target has small impacts on the distribution between demand and supply side measures, but obviously affects the optimal tax levels.

We notice from Table 2 that assuming competitive behaviour by OPEC gives more or less the same results as above. Besides that, we see that the shares of supply and demand side measures depend 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 more effective in reducing global emissions, and the share of supply side measures increases to around 90 percent. Nevertheless, the optimal production tax does not change much. On the one hand, the global emission effects of reduced oil extraction (E'_{x_i}) are increased, shifting the supply side curve in Figure 4 downwards. Moreover, the global target has been reduced due to higher demand side leakages. This reduces the shadow price of reducing global emissions (λ), even though the demand side curve in Figure 4 shifts upwards. On the other hand, the optimal production tax is proportional to E'_{x_i} (cf. Section 2), and (as just stated) this rate 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 36 percent. 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 depicted in Figure 4. 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 percent, supply side measures should account for 84 percent of total abatement, with the optimal domestic CO_2 price and production tax being 131 USD per ton CO_2 and 29 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 percent. Moreover, for 8 of the 13 fields currently under development on the Norwegian shelf, more than 90% of recoverable reserves are oil (Ministry of Petroleum and Energy, 2013).

The higher oil price, the less profitable is the supply side policy. However, it is very unlikely that it is cost effective to rely only on demand side measures. Given the benchmark 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 field is less than 126 USD per barrel.

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

	Net emission reduction*		Target ($\bar{A}$) Mt of CO_2	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	5.7	66%	34%	53	243
Competitive OPEC	0.383	0.646	5.5	71%	28%	53	211
Fixed OPEC supply	0.49	0.539	4.6	87%	13%	45	119
Fixed oil price	0.005	1.025	8.7	0%	100%	-	576
Supply two times more elastic than demand	0.204	0.825	7.0	36%	64%	45	436
Demand two times more elastic than supply	0.528	0.5	4.2	90%	10%	42	94
50% lower supply side costs	0.353	0.676	5.7	84%	16%	29	131

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

Policy alternatives and discussion

So far we have taken for granted that the Norwegian government will impose sufficiently strong measures to reach the global 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 ton CO_2.[17] Using the benchmark value

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

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 value of E'_{x_i}), cf. Eq. (4). That is, supplementing a domestic CO_2 price of 66 USD per ton 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 tonne.

A more ambitious alternative could be to spend as much on an optimally balanced demand and supply side strategy as would be the total cost of the demand side policies announced by the Parliament. As shown above, the marginal costs of reducing global CO_2 emissions are more than halved when the optimal combination is chosen instead of a pure demand side strategy. These savings could alternatively be invested in further global emission cuts. We still restrict the analysis to domestic measures, despite that allowing for offset or deposit purchases abroad would render abatement cheaper. Calculations then show that spending the same total amount on abatement as foregone in the demand side strategy, would yield a total global abatement of more than 10 Mt of CO_2, of which 3 Mt would be optimally abated through demand side measures and the remaining through contracted oil production.

In our benchmark case, the derived marginal costs of emission reductions translate into a shadow price on oil production equal to 53 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 and 2.7 billions USD with demand side policies, only. 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 planned extraction from developed fields.

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. Moreover, this global perspective should be included when the authorities are considering measures to increase the recovery rate on the Norwegian shelf.[18]

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 from Norwegian oil production, as well as a transparent model of international fossil fuel markets. We find that a majority of the measures should be implemented on the supply side, that is, by reducing Norwegian extraction of oil. Given our benchmark assumptions, the optimal combination of demand and supply side measures involves annual cuts in Norwegian oil

[18] Norwegian authorities are generally concerned about increasing recovery rates of Norwegian oil extraction. For instance, the Norwegian Petroleum Directorate (NPD) states on its website that "The NPD shall be a driving force for realising the resource potential by emphasising long-term solutions, upside opportunities, economies of scale and joint operations, as well as ensuring that time-critical resources are not lost." (http://npd.no/en/About-us/). Moreover, increasing recovery rates was the main objective of the so-called "Utvinningsutvalget", initiated by the Ministry of Petroleum and Energy (2010).

extraction of around 3.8 million Sm^3 (3-4 percent of current Norwegian oil production), and annual domestic reductions in CO_2 emissions of almost 3 million tonnes of CO_2 (6-7 percent of current Norwegian CO_2 emissions). This combined policy will give the same *global* emission reductions as the *domestic* emission reductions suggested by the Norwegian government, but at a cost of only one third of using only demand side measures. However, it should be noted that our numerical information is not integrated in a common model framework. As we focus on the long run, transaction costs of reallocating resources to the new equilibrium are not assessed. These can be significant, and 2020 is most likely too short a horizon to disregard transaction costs.

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

We emphasize that there are a number of uncertainties in our calculations. However, the conclusion that a majority of the global emission reductions should be taken through supply side measures, is quite robust.

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Appendix A

OPEC operates as a competitive price taker:

If OPEC operates as a price taker, we find aggregate supply of oil as a function of the price of oil:

(25) $$X_o = S_o(P_o).$$

It thus follows from (6), (7) and (25) that all equilibrium prices are functions of net demand from the home country:

(26) $$P_i = g_i(y_o - x_o, y_c - x_c, y_g - x_g), \quad i = o,c,g.$$

OPEC keeps oil price constant:

If oil price is kept constant at a level equal to $\overline{P}_o$, OPEC must set *Z*, such that

(27) $$\overline{P}_o = P_o(y_o - x_o - Z, y_c - x_c, y_g - x_g).$$

Hence,

(28) $$Z = Z(y_o - x_o - Z, y_c - x_c, y_g - x_g),$$

and prices of coal and gas are functions of net import from the home country:

(29) $$P_i = h_i(y_o - x_o, y_c - x_c, y_g - x_g), \quad i = c,g.$$

OPEC keeps production constant:

Z constant($Z = \overline{Z}$), gives

(30) $$P_i = q_i(y_o - x_o - \overline{Z}, y_c - x_c, y_g - x_g), \quad i = o,c,g.$$

Derivation of equations (18):

$$E'_{y_i} = T'_{y_i} + \frac{\partial \sum_{j=o,c,g} \beta_j(X_j)}{\partial y_i} = 1 - L^D + \sum_{j=o,c,g} \beta'_{X_j} \frac{\partial X_j}{\partial y_i}$$
$$= 1 - L^D + \beta'_{X_i} \cdot (1 + \sum_{k=o,c,g} D'_{ik} \frac{\partial f_k}{\partial (y_i - x_i)})$$
$$+ \beta'_{X_s} \cdot (\sum_{k=o,c,g} D'_{sk} \frac{\partial f_k}{\partial (y_i - x_i)}) + \beta'_{X_h} \cdot (\sum_{k=o,c,g} D'_{hk} \frac{\partial f_k}{\partial (y_i - x_i)})$$
$$= 1 - L^D + \beta'_{X_i} - \sum_{j=o,c,g} \beta'_{X_j} \cdot l^D_{ji}, \qquad s \neq i, h \neq i, s \neq h,$$

and

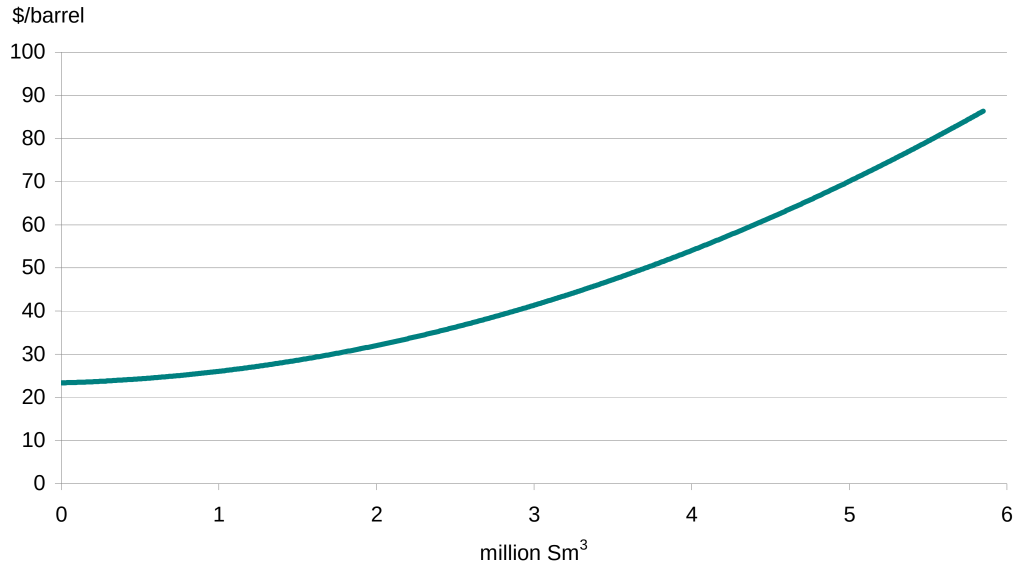
$$E'_{x_i} = T'_{x_i} + \alpha'_{x_i} + \frac{\partial \sum_{j=o,c,g} \beta_j(X_j)}{\partial x_i} = L^D_i + \alpha'_{x_i} + \sum_{j=o,c,g} \beta'_{X_j} \cdot \frac{\partial X_j}{\partial x_i}$$
$$= L^D_i + \alpha'_{x_i} + \beta'_{X_i} \cdot (-1 - \sum_{k=o,c,g} D'_{ik} \frac{\partial f_k}{\partial (y_i - x_i)})$$

(31)

$$+ \beta'_{X_s} \cdot (- \sum_{k=o,c,g} D'_{sk} \frac{\partial f_k}{\partial (y_i - x_i)}) + \beta'_{X_h} \cdot (- \sum_{k=o,c,g} D'_{hk} \frac{\partial f_k}{\partial (y_i - x_i)})$$
$$= L^D_i + \alpha'_{x_i} - \beta'_{X_i} + \sum_{j=o,c,g} \beta'_{X_j} \cdot l^D_{ji}, \qquad s \neq i, h \neq i, s \neq h.$$

Appendix B

Figure B1. Variable costs and corresponding production for nine Norwegian oil fields 2009-2011[19]



Source: Statistics Norway

[19] The fields are Glitne, Gungne, Gyda, Jotun, Norne, Sygna, Ula, Varg and Veslefrikk from 2009 to 2011. Hence, we have 27 observations of costs and production. We arrange our observations according to cost level. We find no connection between vintage and the cost level, i.e. the cost level of a field in 2011 is generally not higher than in 2009. We downscale production in each year to one third, so that the figure represents an average year in 2009-2011. We are not allowed to disclosure operating costs for single fields in 2011, and therefore we only show the fitted curve and not how the single fields are placed in the figure. The marginal cost curve is $1.5x^2 + 2.0x + 21.7$, with R^2=0.98. The production volume for these fields is 5.3 per cent of total Norwegian liquids production in 2012.

Appendix C

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.[20] 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.[21] 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.[22] 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.

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[20] 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/.

[21] 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% above the elasticities found in static studies.

[22] 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% increase in the crude oil price will in general increase the product price by less than 1%.

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 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.[23] 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 reduction in oil consumption.[24] This corresponds to cross-price elasticities of around 0.08 for both fuels, which we use as our benchmark 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

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

[24] 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 our benchmark estimate.

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 estimate, we will use 0.5, i.e., the same absolute value as for the demand price.

OPEC's response

OPEC's response to a change in supply from a Non-OPEC producer depends on how OPEC exploits its market dominance in the oil market. As discussed in the theoretical part in Section 2, our default assumption is that OPEC behaves as a dominant producer, but we also consider alternative assumptions.

As seen in Eq. (11) OPEC's response as a dominant producer depends on the residual demand function (i.e., global demand minus Non-OPEC supply) and the production costs of OPEC. The residual demand has been discussed above. The production costs of OPEC are calibrated in our model so that our reference simulation is consistent with base year data (2011).

Differences in emission intensity in oil extraction

When it comes to emissions from oil extraction, there are quite large differences across extraction fields. According to OGP (2012), the average greenhouse gas (GHG) emissions per unit production worldwide in 2011 were 159 tonnes CO_2e 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 to be 60 tonnes CO_2e per 1,000 toe.[25] A closer look at Norwegian fields shows that CO_2-emissions from oil fields were in fact 4-5 times higher than CO_2-emissions from gas fields both in 2011 and 2012, see Figure C1. This is partly because the two largest Norwegian gas fields use electricity rather than gas, and partly because oil fields in Norway to a larger degree are in their final phases of extraction. Energy use per unit oil or gas extracted typically increases as the natural pressure in the reservoir declines. Finally, the average oil field in Norway tends to be smaller than the average gas field, and smaller fields have historically had higher emissions than larger fields (at least in Norway, cf. NHO,

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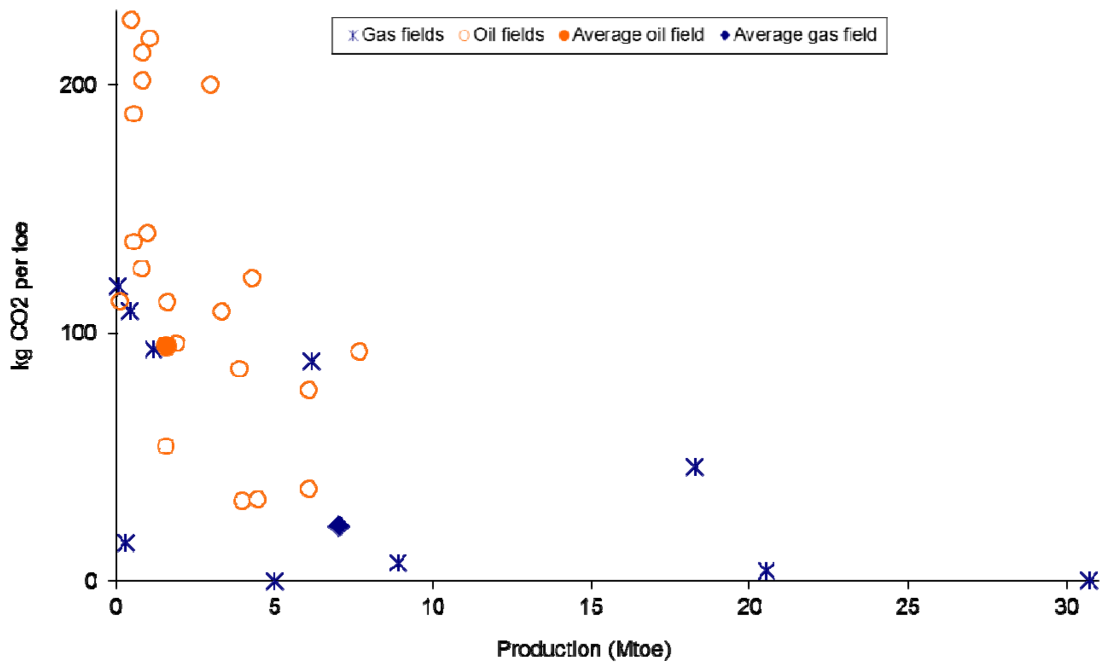
[25] https://www.ssb.no/en/statistikkbanken

2009). The average CO_2-emission intensity at Norwegian oil fields in 2012 were 95 tonnes CO_2 per 1,000 toe. In addition comes CH_4-emissions amounting to around 5 tonnes CO_2e per 1,000 toe.

Figure C1. Production and CO_2-emission intensities in Norwegian oil and gas fields in 2012*



Source: Own calculations based on Norwegian Petroleum Directorate (OD) and Norway's Climate and Pollution Agency (Klif)

* An oil (gas) field is defined as producing at least 50% crude oil (natural gas) in 2012. In some cases it has been necessary to group several fields in the calculations of emission intensities. In those cases production from the largest field is shown. Two small oil fields with emission intensities above 400 kg CO_2 per toe is not shown.

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.[26]

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, cf. the discussion and Figure 1 for Norway above. 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.

[26] 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.

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 as 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 assumption is that marginal emission intensities are 50% 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. From the discussion of Figure C1 above, this may be a too conservative increase when it comes to Norway. 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.

B

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