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Does Increased Extraction of Natural Gas Reduce Carbon Emissions?[a]

Finn Roar Aune[b], Rolf Golombek[c] and Sverre A. C. Kittelsen[d]

Abstract

Without an international climate agreement, extraction of more natural gas could reduce emissions of CO_2 as more “clean” natural gas may drive out “dirty” coal and oil. Using a computable equilibrium model for the Western European electricity and natural gas markets, we examine whether increased extraction of natural gas in Norway reduces global emissions of CO_2. We find that both in the short run and in the long run total emissions are reduced if the additional quantity of natural gas is used in gas power production in Norway. If instead the additional quantity is exported directly, total emissions increase both in the short run and in the long run. However, if modest CO_2-taxes are imposed, increased extraction of natural gas will reduce CO_2 emissions also when the additional natural gas is exported directed.

JEL Classification: D58, Q38, Q48

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1 Introduction

A key question in the literature on carbon emission abatement is how measures implemented in one region have an impact on emissions in other regions. If some countries reduce their demand for fossil fuels, the international prices of fossil fuels decrease and hence emissions in other countries increase, see, e.g., Felder and Rutherford (1993), Golombek *et al.* (1995) and Jacoby et al. (1997). Such carbon leakage effects could also come into play through international prices of energy-intensive goods: If production of energy-intensive goods is reduced in some countries (e.g., due to taxes on fossil fuels), prices of these goods will increase and hence emissions in other countries will increase, provided that some of the increased production is based on additional use of fossil fuels, see, e.g., Hoel (1996).

So far the literature has focused on how abatement in some countries could increase emissions in other countries. However, it is also possible that measures taken in some countries could *lower* emissions in other countries: Because the carbon emission coefficient of natural gas is lower than those of coal and oil, a pure substitution of coal and oil with natural gas (made available through increased extraction of natural gas) will benefit the environment (the substitution effect). However, increased extraction of natural gas will also increase total energy consumption, and hence, *ceteris paribus*, increase total emissions of CO_2 (the quantity effect). If increased extraction of natural gas has a (total) positive environmental effect, due to the present lack of a ratified international climate agreement major suppliers of natural gas – like Norway – may increase their extraction as a means of reducing global emissions.

The impact of more natural gas on total emissions of CO_2 depends on a number of factors such as market structure, the demand system, the efficiencies of electricity plants, the time horizon (the short-term effect may differ from the long-term effect), and the energy and environmental policy domestically and internationally. If an international climate agreement of the Kyoto type is established, that is, an agreement where each participating country (signatory) is assigned a specific number of (internationally tradable) quotas, increased extraction of natural gas will not change total emissions of CO_2 among the signatories as the Kyoto agreement dictates the level of total emissions.[1] Hence, the present study is not of interest if the Kyoto agreement is signed and enforced. However, other types of international climate agreements than the Kyoto type are possible. One example is an agreement imposing all signatory countries to use a common policy domestically, e.g. a carbon tax set at a common level. Under such an agreement, the rate of extraction of natural gas could be considered as a national measure to reduce total emissions.[2]

In general, theory cannot predict whether increased extraction of more natural gas will lower total emissions of CO_2. Without an international climate agreement of the Kyoto type, it is an empirical question whether total emissions will decrease. The purpose of the present paper is to examine - using a computable equilibrium model and assuming there is no Kyoto agreement - whether increased extraction of natural gas reduces total emissions of CO_2, that is, whether the substitution effect dominates the quantity effect.

If extraction of natural gas increases, the price of natural gas decreases. Hence, in the new equilibrium both gas power producers and end users of natural gas have in general increased their consumption of natural gas. The key factors determining the effect on total emissions of CO_2 may be as follows:

- *Decreased production of electricity from other plants.* Increased gas power production (through increased use of natural gas) will increase total production of electricity, which will lower the price of electricity. Hence production of electricity from some other power plants decreases. The more inelastic the demand, the more the price of electricity drops and hence the more electricity production in other plants drops. There is full crowding out in the special case of completely inelastic demand, that is, the increase in “new” gas power production equals the decrease in initial production of electricity.

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[1] While increased extraction of natural gas will have impact on emissions from the non-signatories through international energy prices, this effect will be modest or even negligible.

[2] There has been intense debate in Norway – not always very clear from a professional point of view - on whether increased extraction of natural gas will lower total emissions if the additional quantity of natural gas is used in gas power production in Norway. Due to environmental concerns, in 2000 the government wanted *de facto* to reject an application to set up a gas power station in Norway, but was forced to resign. The plant will be set up if the private investors expect it to be profitable, which depends, for example, on domestic and foreign carbon taxes.

- *Reduced production of electricity by technology*. The marginal electricity plants, that is, those units cutting back on production when the price of electricity drops, differ between countries, between seasons and between day and night. If the marginal plants are not fossil fuel based (e.g., nuclear and hydro), emissions of CO_2 will increase as new gas power production drives out "clean" initial production of electricity. A more interesting case is that of reduced production in fossil fuel based plants due to more new gas power. As a rule of thumb, total emissions will increase if the new gas power competes out "old" gas power, as total consumption of power has increased. On the other hand, total emissions may decrease if the marginal plants use oil or coal as fuels (oil and coal have higher CO_2 emission coefficients than natural gas, cf. above).

- *Plant efficiency*. An inefficient plant uses an excessive amount of fossil fuels in order to produce one unit of electricity. For each fossil fuel, the least efficient plants will, at the margin, generally be the least profitable ones. Hence, if plants cutting back on production have low efficiency, total emissions of CO_2 may fall significantly (for a given reduction in power production).

- *Substitution in final demand*. A lower price of natural gas changes the relative prices in disfavour of coal and oil. End users will then increase consumption of natural gas and decrease consumption of oil and coal. While the two effects have different impacts on emissions of CO_2, the second may be the weakest as cross-price elasticities in final demand are probably low.

In order to examine - in the absence of a Kyoto agreement - whether increased extraction of natural gas lowers emissions of CO_2 we need a numerical model that provides answers to such questions as to what extent "new" gas power drives out "dirty" initial production of electricity, what is the plant efficiency of marginal units, what is the degree of substitution in final energy demand, etc. To this end we use a computable equilibrium model with competitive markets for electricity and natural gas in Western Europe, competitive world markets for oil and coal, and competitive markets for transportation of energy. The four energy goods (natural gas, oil, coal and electricity) are produced, traded and consumed in each of 13 Western European countries. There are a number of technologies available to produce electricity. For each technology (and country), efficiency varies across plants.

Below we limit our attention to the case of increased extraction of natural gas in Norway, which is one of the major European suppliers of natural gas. We first examine the impact on emissions of CO_2 in the short run, that is, when all capacities in the numerical model are given. In the short-run analysis we distinguish between whether the incremental quantity of natural gas is

i) used for gas power production in Norway, or
ii) exported directly (At present there is *de facto* no demand for natural gas in mainland Norway).

Note that under i) the allocation of natural gas abroad between gas power production and final consumption is determined by the model. Next, we study the impact on CO_2 emissions in the long run, that is, all capacities are determined by the model.[3] In the long-run study, the allocation of the incremental quantity of natural gas between gas power production in Norway and direct export is endogenously determined by the numerical model.

We find that if the increased quantity of natural gas is used in a (new) gas power plant of standard size in Norway, total emissions of CO_2 *decrease* in the short run. The drop in total emissions reflects that i) a substantial share of the increased production of electricity in Norway is exported, ii) production of electricity abroad decreases significantly (inelastic demand in the short run) and iii) primarily coal plants lower their production. If instead the incremental quantity of gas is exported directly in the short run, part of the additional amount of natural gas is used in gas power production abroad, whereas the remaining quantity is used by the end-users abroad. We find that total emissions *increase* when the incremental quantity is exported directly in the

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[3] An alternative definition of long run could be related to the non-renewability of natural gas, see Hoel and Kverndokk (1996) and Berg *et al.* (2002) for the relationship between non-renewable resources (fossil fuels), emission of carbon and climate measures. In the present paper, the non-renewability of fossil fuels is disregarded as the numerical model is only run for hypothetical long-run equilibria in the base year.

short run. Increased emissions reflect that the substitution effect among end users is much lower than in production of electricity, in fact emissions from the end-user sectors increase. In addition, emissions in the electricity industry decrease less than in the previous case because in the countries importing natural gas from Norway, coal power is infrequently the marginal technology.

In the long run, the effect on total emissions is dependent on whether it is (politically) feasible to increase capacities for nuclear power production. If this is not the case, increased extraction of Norwegian natural gas will *decrease* emissions as production of coal power abroad is reduced. On the other hand, if investments in nuclear power are feasible, increased extraction of natural gas raises total emissions of CO_2 because increased investments in gas power will reduce investments in, and hence production of, nuclear power.

The rest of the article is organized as follows. In Section 2 we present the numerical equilibrium model in more detail. In Section 3 we report on the short-run effects following from increased extraction of natural gas, both when the additional quantity of natural gas is used in gas power production in Norway, and when natural gas is exported directly. We also discuss to what extent the findings are robust relative to shifts in key parameters (price elasticities, a uniform tax on CO_2 emissions and amount of natural gas extracted). In Section 4 we report on the long-run effects when capacities are endogenous (although investments in nuclear are not feasible). Section 5 sums up our main findings and discusses the importance of investments in nuclear power.

2 A numerical model

The past 15 years have seen various initiatives to liberalise the natural gas and electricity industry in Western Europe. The process has been driven both at the national level and by the EU Commission, which has worked out several proposals to enhance competition at all levels in the energy markets. The objective of the Commission is to transform heavily regulated national markets into efficient European markets through regulatory reforms, see Thackeray (1999) and IEA (2000).

In this study we assume that the EU succeeds in establishing efficient internal markets for natural gas and electricity. Below we present a static computable equilibrium model of competitive energy markets in Western Europe.[4] In Section 3 and 4 this model is used to identify the impact of increased extraction of natural gas on total emissions of CO_2.

In our computable equilibrium model all markets are competitive and there is inter-fuel competition. In equilibrium all arbitrage possibilities are exploited and thus (for each good) price differences reflect cost differences only. The main features of the model are as follows:

- *Countries*. There are 13 countries with endogenous production, trade and consumption. These are termed model countries, and are Austria, Belgium, Denmark, Finland, France, Germany, Great Britain, Italy, the Netherlands, Norway, Spain, Sweden and Switzerland. All other countries are included in the model as aggregate regions with mainly exogenous behaviour (see below).

- *Goods*. There are four energy goods: coal, electricity, natural gas and oil.

- *Markets*. Natural gas and electricity are traded in competitive Western European markets. Coal and oil are traded in competitive world markets.

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[4] For a mathematical description of the model, as well as an explanation of calibration and data sources, see Aune *et. al.* (2001a).

- *Periods*. All fossil fuels are traded in annual markets, whereas electricity is traded in four time periods (summer vs. winter, and night vs. day).

- *Demand for energy*. There are three types of agents using energy: households, manufacturing and power producers. The first two groups (end users) demand all four energy goods. For each country and each type of end user, demand is derived from a multi-goods, multi-period CES utility function. This functional form ensures that regularity conditions derived from economic theory are fulfilled globally ("everywhere"). Five nest levels, with associated substitution and share parameters, are necessary to achieve the desired own- and cross-price elasticities. The structure of nests is designed to facilitate meaningful economic interpretations.

  At the top nest level there are substitution possibilities between energy-related goods and other consumption. At the second level the consumers face a trade-off between consumption based on the four different energy sources. Each of these is a nest describing complementarity between the actual energy source and the consumption goods that use this energy source (e.g., electricity and light bulbs). Finally, the fourth and fifth levels are specific to electricity in defining the substitution possibilities between summer and winter (season), and between day and night in each season. Structural differences in demand are treated by allowing price elasticities to differ across countries, energy goods and end users. In calibrating the model, price elasticities are transformed into substitution and share parameters.

  Fossil fuel based power producers demand fossil fuels if production is profitable. Hence, for this group as well, demand for, e.g., natural gas is decreasing in the price of natural gas. Finally, non-model countries have standard downward sloping demand functions for coal and oil.

- *Production of electricity.* In each model country there is production of electricity by various technologies (some are not available in all countries): coal power, gas power, oil power, pumped storage power, reservoir hydro power, nuclear, waste power and renewables. In general, for each technology and each country, efficiency varies across electricity plants. However, instead of specifying heterogeneous plants, we model – along the lines of the standard assumption of a representative agent – supply of electricity from each type of technology as if there were one single plant with decreasing marginal efficiency in each country.

- *Short-run supply of fossil fuel based electricity*. Each producer of fossil fuel based electricity (coal power, gas power and oil power) maximizes profits given the following constraints:

  i) Maintained power capacity should not exceed installed capacity (which is exogenous in the short run, but endogenous in the long run).
  ii) In each period, production should not exceed maintained energy capacity (number of hours times maintained capacity).
  iii) All plants need some down time for technical maintenance.
  iv) For each season there is a constraint related to start-up costs. This type of cost is incurred if electricity production varies between day and night.

  Short-run profits equal total revenues (following from production of electricity) minus costs: fuel costs, operating costs, maintenance costs (related to maintained power capacity) and start-up costs (related to magnitude of capacity started each day).[5] In the Appendix we provide a detailed description of the optimisation problem of a fossil fuel based power producer.

- *Short-run supply of non-fossil fuel based electricity*. Each producer of non-fossil fuel based electricity solves a similar problem to the one above. For *pumped storage* producers[6], the only difference is that electricity – not a fossil fuel – is used as an input. However, for the other non-fossil fuel based producers there are

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[5] Because all cost elements are included in the Lagrangian of the electricity producers, we can derive optimal capacity utilisation over time at the plant level. This is an improvement relative to the traditional "load duration" approach, see, e.g., Kahn *et al.* (1992), in which the start-up cost is a variable cost and the composition of technologies in high load periods does not fully reflect the nature of start-up costs.

[6] A pump storage producer typically pump the water to a reservoir (at a high altitude) during the night (when electricity prices are low), and let the water flow down during the day, thereby producing power when electricity prices are high.

additional constraints. First, for *nuclear*, the start-up capacity is set at zero (production is not varied between day and night due to prohibitive costs). Second, for *reservoir hydro*, the reservoir filling at the end of a season cannot exceed the reservoir capacity (exogenous in the short run). Moreover, total use of water, that is, total production in a season plus the reservoir filling at the end of that season should not exceed total supply of water, that is, the sum of the reservoir filling at the end of the previous season and the seasonal inflow (exogenous). Finally, for *waste power*, production in each season is constrained by the available waste in that season (zero reservoir size).[7]

- *Supply of coal and oil*. There is competitive supply of coal and oil in all countries.

- *Supply of natural gas*. In order to facilitate the examination of whether more natural gas lowers total emissions of CO_2, in each model country extraction of natural gas is exogenous (equal to observed extraction in the data year of the model). For all other countries, net exports of natural gas to the region of the 13 model countries are equal to observed net exports in the base year.[8]

- *Trade*. There is trade in all energy goods. Transport of goods from producers to end users takes place on three levels: international transport (transmission), national transport and distribution (to households). Each country is represented by a central node, as illustrated in Figure 1. For each country, coal and oil is transported from the world market to the central node, at a given cost. Electricity and natural gas is traded via international transmission lines (pipelines) that run between the nodes. All lines have given capacities in the short run. For each line, the (endogenous) transport tariff ensures that demand for transport does not exceed supply.

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[7] For renewables (solar, geothermal, etc.), in each period production is exogenous (equal to observed supply in the data year). Even if it were possible to increase the capacities of renewables, there would be no investments in the base case long-run equilibrium as prices of electricity are significantly lower than anticipated costs of renewables, see e.g. Chakravorty *et al.* (1997). Moreover, with a uniform carbon tax of 100 USD/ton CO_2 imposed on all fossil fuel users in all model countries (see the discussion on robustness in Section 4) and no nuclear investments, the producer price of electricity would be about twice as high as in the base case equilibrium, but still it might no be profitable to invest in renewable electricity production.

[Figure 1 about here]

- *Capacities*. In the short-run version of the model, installed power capacity and reservoir capacity (in hydro plants) are exogenous. Moreover, transmission capacities for natural gas and electricity are also exogenous in the short run. In the long-run, these (four types of) capacities are determined by profitability (there are revenues and costs associated with expanding each type of capacity).

- *Data year*. The calibration of all functions uses 1996 data, see Aune *et al* (2001a). However, for reservoir hydro we impose that the seasonal inflow of water equals the inflow in a hydrological normal year.

- *Equilibria*. The short-run equilibrium is the hypothetical 1996 outcome if markets had been radically liberalised in 1996, and the 1996 capacities were given. The long-run equilibrium is the hypothetical 1996 outcome if markets had been radically liberalised in 1996, and all capacities were adjusted (through investments) in 1996.

For each model country, the model determines all energy quantities. Hence, emissions of CO_2 (total and by type of energy and power technology) are also determined. Moreover, the model determines trade in energy and (producer and consumer) prices of all energy goods.

In order to illustrate the main driving forces of the model, we now discuss effects of increased exports of natural gas from Norway in the short run and in the long run. Suppose Norway increases its extraction of natural gas, and the entire additional quantity is exported. Further, suppose there is idle capacity in only one of the international transmission lines of natural gas from Norway, say the one to Germany.

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[8] Also for electricity net exports to the region of the 13 model countries are equal to observed net exports in the data year. However, we do not model the natural gas and electricity markets in the non-model countries.

Increased exports of natural gas from Norway to Germany will push down the price of natural gas in Germany as supply of natural gas has increased in Germany. A lower price of natural gas is accompanied by increased use of natural gas in Germany, both by the end users and by gas power plants. Increased use of natural gas among the end users will decrease their use of oil and coal, but not by very much because the cross-price elasticities in final demand are assumed to be low. Increased use of natural gas by gas power plants will increase supply of electricity in Germany, which will push down the price of electricity in Germany. A lower price of electricity implies that production of electricity from other plants will decrease. In general, production from a number of technologies (e.g., coal power and gas power) may decrease. The magnitude and composition of decreased production will in general vary between day and night, and between seasons.

As the price of natural gas has decreased in Germany, the price difference between Germany and some of its neighbouring countries, say France and Belgium, may be larger than costs of transporting natural gas between Germany and France and between Germany and Belgium. These arbitrage possibilities will be exploited by traders. In our model the transport tariff consists of two parts; one exogenous term, which is set by the regulator (e.g., to ensure a minimum remuneration of capital to owners of transmission lines), and one endogenous part that ensures that demand for transport does not exceed supply (the fixed capacity).

Assume there is no idle capacity in the transmission line to Belgium, but idle capacity to France. Then the endogenous tariff term of the Belgian transmission line will increase by so much that demand for transport services from Germany to Belgium is still equal to the given capacity. However, there will be no increase of exports of natural gas from Germany to Belgium (in the short run) as there is no idle capacity. On the other hand, exports from Germany to France will increase. Hence, in France the price of natural gas will decrease, all users of natural gas will in general increase its consumption and part of the increased imports may be re-exported to e.g. Spain, and so on. Through general equilibrium effects the price of natural gas will in general decrease in all model countries, and in the new equilibrium the differences in the producer prices of natural gas (one in each country) reflect costs of transmission (in particular the endogenous tariff terms) only.

Similarly, a lower price of electricity in Germany will generate exports of electricity from Germany to its neighbouring countries. Hence, in the neighbouring countries the price of electricity falls, domestic production of electricity drops, and part of the increased imports may be re-exported to other countries. Again, in the new equilibrium the differences in the producer prices of natural gas (one in each country) reflect costs of international transmission of electricity. The changes in electricity production, both the magnitude of the decrease as well as the altered composition by technologies, will in general differ between countries and time periods.

In the long run model it may be profitable to increase the capacity of transmission lines that have no idle capacity (e.g., the pipeline between Germany and Belgium). Our model provides shadow values for all natural gas and electricity transmission lines, and these are compared with the annualised unit capital cost for expansion of transmission lines, given that lines might be used in both directions (exports from Germany to Belgium in one time period, and exports from Belgium to Germany in another time period).

Although the price of electricity drops due to increased exports of natural gas from Norway, it may still be profitable to invest in new power capacity as the efficiency of new power plants may be much higher than the efficiency of existing plants. In our model it is assumed that for coal power, gas power and oil power all agents are in a position to invest (unlimited) in the most efficient (new) technology without costs of adjustment. Under our assumptions the long-run costs of coal power are lower than for gas power and oil power, and hence in the long run the price of electricity is heavily influenced by the main features of new coal power (efficiency, costs of investments and the price of coal).[9] This is why coal power is the main marginal technology in the long run, and that an increase in gas power will to a large extent crowd out $C0_2$-intensive coal power, see the discussion in Section 3 and 4.

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[9] Note that although the long-run costs are lower for coal power than for gas power it may still be profitable to set up some new gas power plants because this technology has some cost advantages compared with coal power, e.g. lower costs of maintenance and lower start-up costs.

3 Short run effects

In Section 1 we argued that increased extraction of natural gas will lower total emissions of CO_2 i) the more initial production of electricity decreases, ii) the more the phased-out electricity production is based on fossil fuels, iii) the lower the efficiency of the phased-out plants and iv) the more substitution takes place from coal and oil among the end users. In this section we use the numerical model to identify these effects in the short run.

Below we distinguish between two cases with respect to how the additional quantity of Norwegian natural gas is used. First, we examine the case in which the additional quantity of natural gas is used in gas power production in Norway ("gas power"). Note that gas power production is imposed in the model, independent of whether it is profitable. We assume that the gas is used in a standard new gas power plant with 58 per cent efficiency, 10 per cent down-time, and annual production of 6 TWh electricity.[10] Under these assumptions the new gas power plant uses 0.88 Mtoe natural gas each year, that is, the additional quantity of extracted Norwegian natural gas is set equal to 0.88 Mtoe.

Next, we study the case in which the additional quantity of natural gas (0.88 Mtoe) is not used in gas power production in Norway. As there is *de facto* no end-user demand for natural gas in Norway, in this case the additional quantity of natural gas is exported ("direct export"). Note that direct export of natural gas is imposed in the model, independent of whether it is more or less profitable than alternative uses of the gas.

In both cases the initial state - henceforth termed the (short-run) base case- is characterized by a competitive outcome, reflecting that a radical liberalisation of the Western European energy markets has taken place. Moreover, extraction of natural gas is equal to observed extraction in the data year of the model – 1996. In the base case, that is, the hypothetical short-run equilibrium with 1996 data used to calibrate all functions in the model, the user price of electricity and natural gas (averaged over

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[10] In Norway two firms have applied for licence to set up gas power plants to date. Planned annual production is around 6 TWh for each firm.

all users in Western Europe) is roughly 50 per cent and 20 per cent, respectively, lower than in the data year of the model. Moreover, total production of electricity is 20 per cent higher than in 1996. The increase in production is mostly due to more coal power, see Aune *et al.* (2001b) for more details.

3.1 Gas power

Increased gas power production in Norway raises electricity supply in Norway. However, because Norway presently has no fossil fuel based electricity plants, emissions of CO_2 in Norway from other electricity plants than the new (imposed) gas power station is still zero. On the other hand, a share of the increased electricity production in Norway is exported, thereby lowering the price of electricity also in Western Europe. As part of the electricity supply in Western Europe is fossil fuel based, electricity from Norway can drive out fossil fuel based electricity production in Western Europe. Thus total emissions will decrease more the higher the share of the increased electricity production in Norway that is exported.

According to our model, increased gas power production in Norway (6 TWh) raises electricity consumption in Norway by 0.3 TWh. Hence, net export of electricity from Norway increases by 5.7 TWh. Consumption of electricity outside Norway increases, however, by only 0.9 TWh. The difference between increased exports from Norway (5.7 TWh) and increased consumption outside Norway (0.9 TWh) results from lower production of electricity in the 12 model countries by 4.8 TWh. The substantial crowding-out effect reflects inelastic demand in the short run (average direct short-run price elasticity for electricity is –0.21).

Increased gas power production in Norway reduces production of coal power in the other model countries by as much as 4.8 TWh. For the other technologies, the changes are negligible or even zero. In Norway, emissions of CO_2 increase by around 2 million tons due to increased gas power production. On the other hand, emissions of CO_2 fall significantly in Finland (2.6 million tons; reduced coal power) and Sweden (1.1 million tons; reduced coal power). Because emissions in Norway increase by 2 million tons, whereas total emissions in the other model countries decrease by 3.7

million tons, in Western Europe (the 13 model countries) total emissions *decrease* by 1.7 million tons CO_2.[11]

Robustness

We now examine the impact of more natural gas on total emissions of CO_2 under different assumptions of the key parameters of the model; the price elasticities, the tax on emission of CO_2 and the amount of increased extraction of natural gas.

i) Price elasticities

In calibrating the nested CES demand functions, we have used data on consumption and prices along with estimates of (direct and cross) price elasticities to determine all substitution and share parameters in the nests. By changing the share and distribution parameters on the second level of the CES functions (that is, the level in which consumers face a trade-off between consumption based on the four different energy sources), all direct and cross price elasticities between energy goods are changed (the third level of the CES function).

Figure 2 shows the results of increased extraction of natural gas (0.88 Mtoe) on CO_2 emissions under different values of average price elasticities. The horizontal axis measures the weighted average of the direct price elasticities for all model countries, energy goods and end-user groups, using value shares as weights. Each point on a curve shows, for a given weighted average of direct price elasticities, the net increase in total emissions of CO_2 in the model countries following from increased extraction of natural gas in Norway by 0.88 Mtoe. In our base case equilibrium, the weighted direct price elasticity equals –0.23.

As seen from Figure 2, increased extraction leads to lower emissions of CO_2 for all the tested price elasticities.[12] The drop in emissions of CO_2 (due to increased

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[11] Emissions in the non-model countries increase by 0.5 million tons CO_2 because both the price of coal and oil have decreased, although marginally.

[12] In calibrating the model we imposed some restrictions such as non-negativity on the parameters. By keeping these restrictions while changing the share and distribution parameters on the second level of the CES function, we find that the weighted average direct price elasticity cannot be lower than –0.18, see Figure 2. Note that for this value the weighted average cross price elasticity is negative: when demand is inelastic, a 1 % increase in the price of an energy good leads to an almost 1 % increase in the cost of that good. Because there is not much substitution away from non-energy goods, demand for

extraction) is roughly 1.5 million tons (1.7 million tons in the base case where the weighted direct price elasticity equals –0.23). As demand becomes more elastic (higher absolute value of the weighted average price elasticity), the distribution of natural gas between gas power production and end-user demand changes only marginally. On the other hand, coal power production first decreases (hence emissions decrease) and then increases (hence emissions increase) as demand becomes more elastic (and extraction is increased by 0.88 Mtoe). This is the dominating effect in Figure 2.

[Figure 2, 3 and 4 about here]

ii) Uniform tax rate

Next we study how changes in emissions of CO_2 – following from increased extraction of 0.88 Mtoe natural gas – are related to the tax on emissions. In the base case, all users of fossil fuels pay the observed emission taxes in the data year of the model (1996). While these taxes in general differed between countries, fuels and users, for most users they were zero (or very small). We now replace the 1996 CO_2 taxes by a uniform CO_2 tax imposed on all fossil fuel users in the model countries.

In Figure 3 each point on a curve shows, for a given uniform CO_2 tax, the *change* in total emissions in the model countries due to increased extraction of natural gas in Norway by 0.88 Mtoe. The curve was constructed as follows: We first pick a uniform tax rate. Next we run the model i) with extraction equal to observed extraction in 1996, and ii) with extraction of natural gas in Norway that exceeds the observed extraction in 1996 by 0.88 Mtoe. The difference between i) and ii) w.r.t. total CO_2 emissions for the model countries is shown in Figure 3. Without any tax, total emissions in the model countries drop by 1.2 million tons CO_2 when extraction in Norway increases by 0.88 Mtoe and the additional quantity of natural gas is used in gas power production in Norway. (With 1996 CO_2 taxes, the drop was 1.7 million tons, cf. above.) Figure 2 shows that the change in emissions is related to the tax in a

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other energy goods has to decrease in order to meet the budget constraint, that is, cross price elasticities are negative.

complex way, but for all tax rates between 0 and 100 USD/tons CO_2, total emissions are *lower* than without the additional quantity of natural gas.[13]

iii) More natural gas

The discussion above is based on increased extraction of 0.88 Mtoe natural gas in Norway (which corresponds to annual use of natural gas in a new gas power plant with annual production of 6 TWh electricity, cf. above). We now examine how the *change* in total emissions depends on the amount of additional gas. As we increase the quantity of additional natural gas, in general terms, total emissions first decrease and then increase, cf. Figure 4. For all additional quantities above 7 Mtoe (50 TWh gas power), total emissions are higher than in the base case.

In the base case there is idle capacity in the electricity transmission line between Norway and Sweden in all time periods. Norway exports to Sweden in all time periods except on winter day (no trade). As extraction of natural gas is increased, exports from Norway to Sweden increase, and there is no idle capacity in transmission in any time period when the additional extraction exceeds 2 Mtoe. When Sweden imports electricity from Norway, the price of electricity in Sweden falls and Swedish coal power production decreases. With an additional extraction of 2 Mtoe natural gas, coal power is almost phased out in Sweden.

Without increased extraction, the transmission line between Norway and Finland is fully utilized in all time periods (Norway exports to Finland). However, as extraction of natural gas is increased in Norway, Finland imports more electricity from Sweden (the price in Sweden has been pushed down due to higher imports from Norway). As the price of electricity drops in Finland, domestic coal power production is reduced (until there is no idle capacity in the electricity line between Finland and Sweden).

Turning to trade between Norway and Denmark, in the base case Norway imports from Denmark at night, whereas there is negligible trade during the day. As extraction

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[13] For all tax rates the additional quantity of natural gas raises emissions from natural gas by about 2 million tons CO_2, but lowers emissions from oil slightly. Hence, Figure 2 primarily reflects how *changed* emissions from coal are dependent on the uniform tax rate (total use of coal, as well as total coal power production, is decreasing in the tax rate). With no tax, the additional quantity of natural gas reduces emissions from coal by almost 4 million tons.

is increased, imports from Denmark to Norway are first reduced and then turned into exports. As Denmark increases its power imports from Norway, Danish production of gas power decreases. When the additional extraction in Norway exceeds 3 Mtoe, Danish coal power production starts decreasing as well.

Let us now take a closer look at Figure 4. First, total emissions decrease as Norway increases natural gas extraction. The bottom is reached for around 2 Mtoe more natural gas. The drop mainly reflects lower coal power production in Sweden and Finland (dominating over increased emissions in Norway due to more gas power production). As Norway increases its extraction by another 2 Mtoe natural gas, total emissions increase, mainly due to more gas power production in Norway (Swedish coal power has already been phased out). However, additional extraction of 1 Mtoe then lowers total emissions, the dominating effects being lower coal and gas power production in Denmark. When the additional extraction exceeds 5 Mtoe, total emissions increase: above 5 Mtoe the electricity transmission line between Norway and Denmark has no idle capacity, and therefore additional extraction is used to produce gas power that is entirely consumed in Norway.

3.2 Direct export

In this subsection we assume that the additional natural gas is exported directly. As in the previous subsection, we mainly focus on the case in which the additional quantity of natural gas equals 0.88 Mtoe (which corresponds to annual use of natural gas in a new gas power plant with annual production of 6 TWh electricity, cf. above).

Increased exports of natural gas from Norway push down the price of natural gas. Hence (outside Norway), household (0.13 Mtoe), manufacturing (0.16 Mtoe) and gas power plants (0.57 Mtoe) increase their use of natural gas. In our model, increased use of natural gas by *end users* leads to only negligible substitution from coal and oil (0.02 Mtoe). Hence, total emissions from the end-user sectors increase.

Increased use of natural gas raises gas power production outside Norway (by 2.8 TWh). Therefore the price of electricity drops, and part of the initial production of electricity decreases; oil power production decreases by 0.9 TWh and coal power production decreases by 0.1 TWh. For the other technologies there are small or even no changes (total electricity production increases by around 2 TWh). Note that the increase in gas power production reflects that the price of natural gas has decreased more (in per cent) than the price of electricity. As gas power plants differ in efficiency, increased gas power production implies that plants with lower efficiency are phased in, which requires – ceteris *paribus* – that the fuel price drops significantly.

Emissions of CO_2 increase in Great Britain (0.6 million tons; increased gas power), Italy (0.4 million tons; increased gas power) and Belgium (0.2 million tons; increased gas power). On the other hand, emissions in Germany drop (0.3 million tons; decreased oil power that is dominant over increased gas power). For the other countries changes in emissions are small. For the 13 model countries, total emissions *increase* by 1.1 million tons of CO_2.

Why do total emissions increase when the additional quantity of natural gas is exported, whereas total emissions decrease when the additional quantity is used for gas power production in Norway? Under “direct export” the additional quantity can be transported to Belgium, Germany and Great Britain and distributed between end users and gas power plants (or re-exported).[14] While there might be substantial substitution from coal and oil towards gas in the power sector, the substitution among end users is marginal as our cross price elasticities are of standard magnitudes – in our model they are on average 0.025 in the household sector and 0.05 in the manufacturing sector (more flexibility in choice of fuel in the manufacturing sector). In the power sector the substitution between fossil fuels depends on the marginal power technology. If i) coal power is the marginal technology, ii) gas power production increases by 1 TWh, and iii) the direct price elasticity of electricity is –0.2 (as in our calibration point), production of coal power will roughly decrease by as much as 0.8 TWh. Because part of the additional natural gas is used by the end-users under “direct export”, emissions tend to increase least in this scenario.

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[14] In the base case there is no idle capacity in the gas pipeline between Norway and Great Britain. Hence, under “direct export” Great Britain increases its consumption of natural gas by exporting less

Second, countries differ. In some countries, coal power plants are marginal power producers, whereas in other countries they are not. In Belgium, Germany and Great Britain (importers of natural gas from Norway), coal power is not the marginal technology. On the other hand, under gas power production in Norway more electricity can be exported from Norway to Denmark, Finland and Sweden. In Finland and Sweden, coal power is the marginal technology and increased import of electricity from Norway lowers production of coal power in these two countries significantly. Hence, emissions drop radically under "gas power".

Robustness

We now test the robustness of whether increased exports of natural gas will increase total emissions of CO_2 in Western Europe. As in Section 3.1 we start with price elasticities. When the weighted average direct price elasticity is less (in absolute value) than 0.20 ("inelastic demand"), total emissions drop if more natural gas (0.88 Mtoe) is extracted, see Figure 2. As demand becomes more elastic, increased extraction leads to higher total emissions. The increase is slightly above 1 million tons of CO_2 for price elasticities in the range of –0.2 to –0.4.

Both in the base case and the case of additional natural gas (that is exported), more elastic demand leads to increased use of gas in power production, and thus lower consumption of gas among the end users. However, the (positive) difference between use of natural gas in power production in the case of additional natural gas and in the base case decreases as demand becomes more elastic. Correspondingly, the (positive) difference between use of natural gas among the end users in the case of additional natural gas and in the base case increases as demand becomes more elastic. This reflects that the (positive) difference between the price of natural gas in the base case and with more natural gas increases as demand becomes more elastic. As the relative position of gas power is weakened when demand becomes more elastic, the position of coal power is enhanced, and hence emissions increase, see Figure 2.

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natural gas to Belgium, since the price of natural gas has decreased in Belgium due to increased imports from Norway.

Figure 3 shows how the *change* in total emissions is dependent on the uniform tax on CO_2 emissions. If the 1996 taxes are removed, additional extraction of natural gas (0.88 Mtoe) will increase total emissions by 1.0 million tons CO_2. However, as the uniform tax is increased from zero, the change in total emissions rapidly becomes negative, but then turns positive again. Figure 3 shows that for most tax rates, the change in total emissions is roughly around zero.

The impact of increased extraction on total emissions of CO_2 is shown in Figure 4. For some additional extraction levels (3.5 to 9 Mtoe), more natural gas reduces total emissions. More importantly, for all levels of increased extraction, total emissions are higher than in the base case.

As the additional extraction of natural gas is increased to 13 Mtoe (see below), total production of both coal power and oil power decrease, whereas gas power production increases. Total power production increases because the latter effect dominates, but national effects differ. In Germany and Belgium, coal power is unaffected as extraction of natural gas is increased (to 13 Mtoe), gas power increases and oil power decreases. While total emissions decrease in Germany, in Belgium total emissions increase. In Great Britain, coal power decreases whereas gas power increases (no oil power production even in base case). Total emissions in Great Britain first increase and then decrease. In countries without a pipeline from Norway, in general emissions increase slightly.

The shape of the curve in Figure 4 summarizes these national effects. The curve also reflects that i) there is no idle capacity in the pipeline from Norway to Great Britain even without any additional extraction (base case), ii) Norway exports more natural gas to Germany as long as the additional extraction is less than 8 Mtoe, and iii) Norway exports more natural gas to Belgium as long as the additional extraction is less than 18 Mtoe. Note that when the additional extraction exceeds 13 Mtoe, the producer price of Russian gas is zero, that is, costs of transport of Russian gas determine the equilibrium price of natural gas. Hence, increased additional extraction in Norway above 13 Mtoe lowers Russian supply correspondingly, and therefore has only a negligible effect on emissions, see Figure 4.

4 Long run effects

In the previous section we identified short-run effects of increased extraction of natural gas on total emissions of CO_2. We found that if the additional quantity of natural gas (0.88 Mtoe) is used in gas power production in Norway, total emissions will decrease. If instead the additional quantity of natural gas is exported directly, total emissions will increase. Hence, with respect to the environment, the additional natural gas should be used in gas power production. On the other hand, our calculations reveal that it is more profitable to export natural gas directly than to use it in gas power plants in Norway. Hence, for Norway there is a trade-off in the short run between environmental concern and profitability.

We now turn to examine long-run effects of increased extraction of natural gas in Norway. Because investments in all capacities are now endogenous (in Section 3.1 the capacity of gas power production in Norway was increased exogenously)[15], we let the model allocate the additional natural gas between gas power production in Norway and direct export according to profitability.

The long-run base case (no additional extraction) is characterized by no investments in nuclear (see Section 5 for the opposite case). Moreover, as in Section 3, the outcome is competitive, reflecting that the energy markets in Western Europe have been radically liberalised. In the long run base case, the user price of electricity and natural gas (averaged over all users in Western Europe) is roughly 55 per cent and almost 20 per cent, respectively, lower than observed in 1996, that is, fairly similar to the short-run base case. However, due to investments in capacities for power production and energy transmission, the supply of electricity is around 45 per cent higher than in 1996. As in the short-run base case, in which power production is 20 per cent higher than in 1996, the increase in production of electricity primarily reflects increased coal power production.

Increased extraction of natural gas in Norway (by 0.88 Mtoe) raises exports of natural gas from Norway by almost the same quantity (The remaining amount reflects losses in transmission). Consumption of natural gas by the end users (outside Norway) increases by 0.35 Mtoe, and hence use of natural gas by electricity plants increases by around 0.45 Mtoe. As in the short-run case, the substitution effect in the household and manufacturing sector from coal and oil is tiny (0.01 Mtoe). Hence, emissions in the end-user sectors increase.

The increased exports of natural gas from Norway are primarily transported to Belgium, while only a small share is exported to Germany. There are no additional exports from Norway to Great Britain because this pipe has no idle capacity (investments in capacity are not profitable). In Belgium, part of the additional quantity of natural gas is used in gas power production. Increased gas power production in Belgium pushes down the price of electricity, and production in coal power plants is decreased significantly (1.9 TWh). Through general equilibrium effects, the price of electricity falls in all model countries, and the composition of electricity production changes. In France coal power production decreases slightly, whereas gas power production increases in the Netherlands (decreased export of natural gas to Belgium), Great Britain (increased import of natural gas from Belgium) and Finland (increased import of natural gas from Norway through Sweden). For the other technologies, the changes are negligible or zero. Total production of electricity increases by only 0.5 TWh (in Section 3 total production under “gas power” and “direct export” increased by 1.1 TWh and 2.0 TWh, respectively).

Emissions decrease significantly in Belgium (1.1 million tons; decreased coal power), but increase in the Netherlands (0.7 million tons; increased gas power) and Great Britain (0.4 million tons; increased gas power). For the sum of the model countries, total emissions *increase* by 0.4 million tons of CO_2. To sum up, in the long run, where distribution of the additional quantity of natural gas is endogenously determined, the additional amount of natural gas is exported, and as in the short-run case “direct export” total emissions increase.

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[15] All elasticities differ between the short-run and the long-run model.

Robustness

Figure 2 shows that for weighted average price elasticities in the range of –0.70 to-0.85 (the long-run base case value is –0.79), total emissions increase as more natural gas (0.88 Mtoe) is extracted. However, more elastic demand lowers the increase in total emissions. For weighted average price elasticities below –0.85, total emissions even drop, and the decrease is roughly 1.5 million tons of CO_2.

As demand becomes more elastic, the (positive) *difference* between use of natural gas in power production in the case of additional natural gas and in the long-run base case increases (the opposite was the case under "direct export", see Section 3.2). Correspondingly, the (positive) difference between use of natural gas among the end users in the case of additional natural gas and in the base case decreases as demand becomes more elastic. This reflects that the (positive) difference between the price of natural gas in the long-run base case and the case of more natural gas decreases as demand becomes more elastic. Because the relative position of gas power is enhanced when demand becomes more elastic, the position of coal power is weakened, and hence emissions decrease, see Figure 2.

As seen in Figure 3, when the 1996 CO_2 taxes are removed and extraction is increased by 0.88 Mtoe, total emissions increase by around 0.5 million tons. As the uniform tax rate is increased, the *change* in total emissions is quite turbulent. In general terms, total emissions increase for low tax rates (below 5 USD), whereas total emissions decrease for "medium" tax rates (5-45 USD). In most countries coal power production is phased out for "medium" tax rates. For most tax rates exceeding 45 USD, total emissions increase because the additional natural gas is used in gas power production (outside Norway) but there is no remaining oil power and coal power (no substitution possibilities). Note that for all tax rates it is optimal for Norway to export the entire additional amount of natural gas.

Finally, when extraction of natural gas is increased, most of the additional natural gas is used in gas power production (primarily in Belgium and Norway). While oil power production remains almost unchanged, coal power production decreases. Total production of electricity increases moderately, reflecting that the increase in gas power production is almost neutralized by the drop in coal power production. Figure 4 shows the total effect on emissions in the model countries. Increased extraction up to 3 Mtoe raises emissions, but emissions fall as extraction is increased further. Emissions are lower than in the long-run base case provided that the additional extraction exceeds 4 Mtoe.

5 Concluding remarks

The purpose of the present paper is to examine whether increased extraction of natural gas lowers total emissions of CO_2 in Western Europe through substitution from "dirty" coal and oil towards "clean" natural gas. Using a computable equilibrium model for the Western European electricity and natural gas markets we examine whether increased extraction of natural gas in Norway decreases total emissions of CO_2. We find that in the short run, total emissions are reduced if the additional quantity of natural gas (0.88 Mtoe) is used in gas power production in Norway, see Table 1. If instead the additional quantity of natural gas is exported, total emissions increase in the short run. Roughly, these short-run effects are robust, in their ordering if not in their magnitude, with respect to level of the uniform CO_2 tax and amount of additional extraction.

Table 1: Effects on total emissions of CO_2 in Western Europe due to increased extraction of natural gas (0.88 Mtoe).

	Short run	Long run No nuclear investments	Long run Nuclear investments
Imposed gas power	-	-	-
Imposed direct export	+		
No restrictions		+	+

In the long run, increased extraction (0.88 Mtoe) will increase total emissions if investments in nuclear power production are not feasible and the use of the incremental natural gas is determined by profitability ("no restrictions", "no nuclear investments"). However, because the increased quantity of natural gas is exported (gas power production in Norway is less profitable than direct export), we have also examined the case in which the entire additional quantity of natural gas (0.88 Mtoe) is imposed to be used in gas power production in Norway (in the long run). Under this restriction, total emissions decrease as coal power production (primarily in Finland and France) is crowded out.

So far we have assumed that it is not possible to invest in nuclear power. If, alternatively, investments in nuclear power are feasible, new nuclear power obtains a market share of 10 per cent in the long-run base case equilibrium (with investments in nuclear). Compared with the long-run equilibrium without nuclear investments (Section 4), total electricity production changes only marginally, and hence also total electricity consumption changes only marginally. Investments in nuclear replace investments in coal power, which reflects that long run costs of new nuclear do not differ much from long run costs of new coal power.[16]

With nuclear investments, increased extraction of natural gas in Norway ("no restrictions", "nuclear investments") will increase total emissions (relative to the long-run base case equilibrium with nuclear investments). Also in this case the additional quantity of natural gas is mainly used in gas power production outside Norway. Increased gas power production reflects increased investments in gas power, which drive out investments in nuclear power, and hence total emissions increase (like in the case of no nuclear investments, see Table 1).

Finally, if the entire additional quantity of natural gas (0.88 Mtoe) is reserved for use in gas power production in Norway, and investments in nuclear are feasible ("imposed gas power", "nuclear investments"), primarily coal power (but also some investments in nuclear power) are crowded out. Hence, like in the other cases in which the additional amount of natural gas is used to produce gas power in Norway, total emissions decrease, cf. Table 1.

To sum up our main findings, the environmental effect of increased natural gas extraction depends crucially on whether the extra gas is used for production of electricity in Norway, or exported directly. If no new gas power capacity is built in Norway, total emissions increase. We find that both in the short run and in the long run total emissions are reduced if the additional quantity of natural gas is used in gas power production in Norway. If instead the additional quantity is exported directly, total emissions increase both in the short run and in the long run. However, if modest

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[16] Under our assumptions, a small increase in costs of new nuclear makes investments in new nuclear not profitable.

CO_2-taxes are imposed, increased extraction of natural gas will reduce CO_2 emissions also when the additional natural gas is exported directed.

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Appendix Supply of Electricity

Production of electricity takes place in each model country through various technologies (some are not available in all countries): gas power, oil power, coal power, pumped storage power, reservoir hydro power, nuclear, waste power and renewables. In all countries in our model, electricity is produced in two seasons (summer and winter); within each season there are two periods (day and night). In general, for each technology and each country, efficiency varies across electricity plants. However, instead of specifying heterogeneous plants within each category of electricity production (technologies and countries), in the short-run version of the model we model the supply of electricity from each category *as if* there were one single plant (producer) with increasing marginal costs. In the long-run version of the model, from each category of electricity production (technologies and countries) there is an additional producer that may set up new power plants with "high" efficiency.

Below we explain the optimisation problem solved by a (sector) electricity producer that use a fossil fuel, e.g. natural gas, as an input. In the short run (given capacity), total costs are given by:

$$C = \sum_{t \in T} \left(\overline{\nu}_t P^f + c^O \right) y_t + c^M K^M + \sum_{t \in T} c^S K_t^S \qquad (1)$$

There are four types of costs involved in the operating decisions. First, there are costs directly related to combustion of the fossil fuel. Let $\overline{\nu}_t$ be the average amount of the fossil fuel required to produce one unit of electricity in period t ($\overline{\nu}_t$ is increasing in electricity production, which reflects decreasing efficiency – less efficient plants are phased in as production increases). Then fuel costs in period t are given by $\overline{\nu}_t P^f y_t$, where P^f is the (annual) user price of the fossil fuel, $f = \{coal, natural\ gas, oil\}$ and y_t is sales of electricity in period t (T is the set containing all four time periods). Second, in addition to fuel costs, there are other inputs (with exogenous prices) that are assumed to vary proportionately to production, implying a constant unit operating cost c^O. Third, the producer is assumed to choose the level of power capacity maintained (K^M), thus incurring a unit maintenance cost c^M per power unit. Finally, if the producer chooses to produce electricity in only one of the periods in each season (e.g. during the day), he will incur a daily start-up cost. In this model the start-up cost c^S is expressed as a cost per start-up power capacity (K^S) in each season.

Profits for fossil-fuel based power production are:

$$\Pi = \sum_{t \in T} (P_t y_t + P_t^R K_t^R) - \sum_{t \in T} \left(\overline{\nu}_t P^f + c^O\right) y_t - c^M K^M - \sum_{t \in T} c^S K_t^S \tag{2}$$

Revenues consist of two parts: income from ordinary sales of electricity and income from sales of capacity to the system operator, who ensures that there is always a reserve power capacity available. Ordinary income in period t is given by $P_t y_t$, where P_t is the price of electricity in period t. Moreover, the producer sells K_t^R of his (maintained) capacity to the system operator at the price P_t^R.

The producer maximises profits, given several constraints. Below, the restrictions on the optimisation problem are given in solution form, where the Kuhn-Tucker multiplier – complementary to each constraint – is also indicated. The first constraint requires that maintained power capacity (K^M) should be less than or equal to total installed power capacity (K_0):

$$K^M \leq K_0 \perp \lambda \geq 0, \tag{3}$$

where λ is the shadow price of installed power capacity.[17]

Second, in each period, production of electricity is constrained by the maintained energy capacity, net of the capacity sold as reserve capacity to the system operator. The (net) power capacity is transformed to electric energy production capacity by multiplying by the number of hours in each period (ψ_t):

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[17] In general, the notation $a \leq 0 \perp b \geq 0$ is shorthand for $a \leq 0 \text{ and } b \geq 0 \text{ and } ab = 0$, where *a* is the derivative of the Lagrangian w.r.t. *b*.

$$y_t \le \psi_t (K^M - K_t^R) \perp \mu_t \ge 0. \tag{4}$$

All power plants need some down-time for technical maintenance. Hence, total annual production cannot exceed a share (ξ) of the rated capacity:

$$\sum_{t \in T} y_t \le \xi \sum_{t \in T} \psi_t K^M \perp \eta \ge 0. \tag{5}$$

Finally, as mentioned above, a start-up cost is incurred if electricity production varies between day and night (in the same season). This cost depends on the additional capacity that is started in the peak period, that is, on the difference between capacity use in one period and capacity use in the other period in the same season. The start-up capacity (K_t^S) must therefore satisfy the following requirement:

$$y_t / \psi_t - y_u / \psi_u \le K_t^S \perp \phi_t \ge 0, \tag{6}$$

where y_t / ψ_t is actual capacity used in period t and y_u / ψ_u is actual capacity used in the other period in the same season. For each pair of periods in the same season there are thus two inequalities, which together imply two different non-negative start-up capacities (only one will be non-zero in equilibrium).

The Lagrangian of the fossil fuel based power producer is

$$\begin{aligned} \mathrm{L} = {} & \sum_{t \in T} \left(P_t y_t + P_t^R K_t^R \right) - c^{inv} K^{inv} \\ & - \sum_{t \in T} \left(\overline{\nu}_t P^f + c^O \right) y_t - c^M K^M - \sum_{t \in T} c^S K_t^S - \lambda \left\{ K^M - K_0 \right\} \\ & - \sum_{t \in T} \mu_t \left\{ y_t - \psi_t \left(K^M - K_t^R \right) \right\} - \eta \left\{ \sum_{t \in T} y_t - \xi \sum_{t \in T} \psi_t K^M \right\} \\ & - \sum_{t \in T} \phi_t \left\{ y_t / \psi_t - \sum_{u \in T} \delta_{tu}^S \, y_u / \psi_u - K_t^S \right\}, \end{aligned} \tag{7}$$

where the selector δ_{tu}^{S} is equal to 1 for the other period *u* in the same season as period *t*, and 0 for all other periods. It is straight forward to find the first-order conditions (see Aune *et al.* (2001a)), and each of these requires, of course, that marginal revenue should be equal to the corresponding marginal costs.

In the long-run model, there are two types of electricity producers; one with existing plants with given capacities (see the discussion above), and one that can set up a new gas power plant with capacity K^{inv}. Let the required amount of natural gas used to produce one unit of electricity in a new gas power plant be v_t. Due to technological progress, the required amount of natural gas used to produce one unit of electricity is lower in a new plant than in old plants. Total costs for the new gas power producer is

$$C = c^{inv}K^{inv} + \sum_{t \in T}\left(\nu_t P^f + c^O\right)y_t + c^M K^M + \sum_{t \in T} c^S K_t^S \tag{8}$$

where c^{inv} is the annualised costs of investment per unit capacity. The optimisation problem of the new gas power producer is similar to the one explained above, except that K_0 in (3) is replaced by K^{inv}.

Figure 1 Natural Gas Transport i Europe

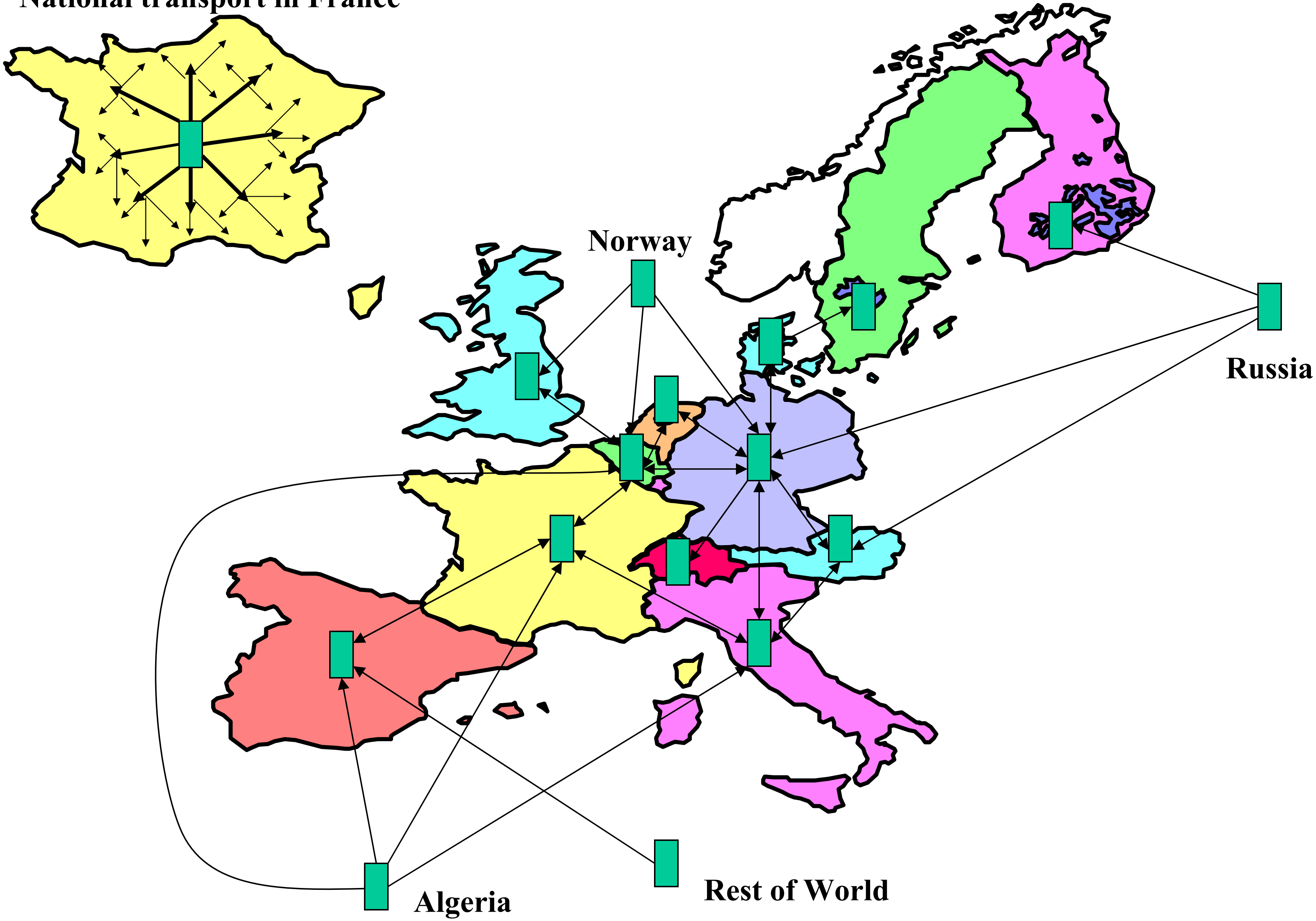

Figure 2 Net increase in total emissions of CO_2 in model countries following from increased extraction of natual gas in Norway (0.88 mtoe). Weighted average of the direct price elasticities.

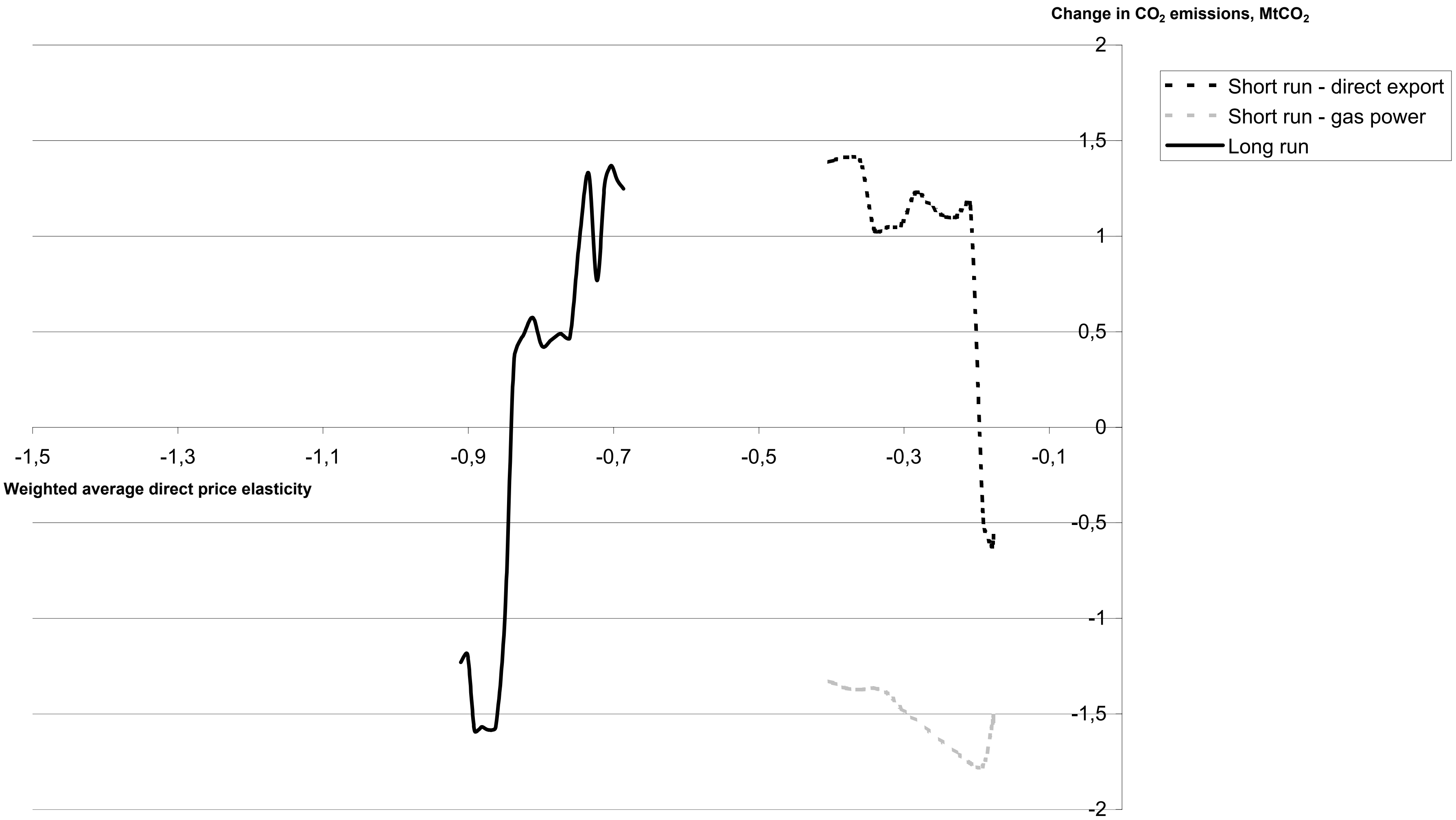

Figure 3 Net increase in total emissions of CO_2 in model countries following from increased extraction of natual gas in Norway (0.88 mtoe). Uniform CO_2 tax.

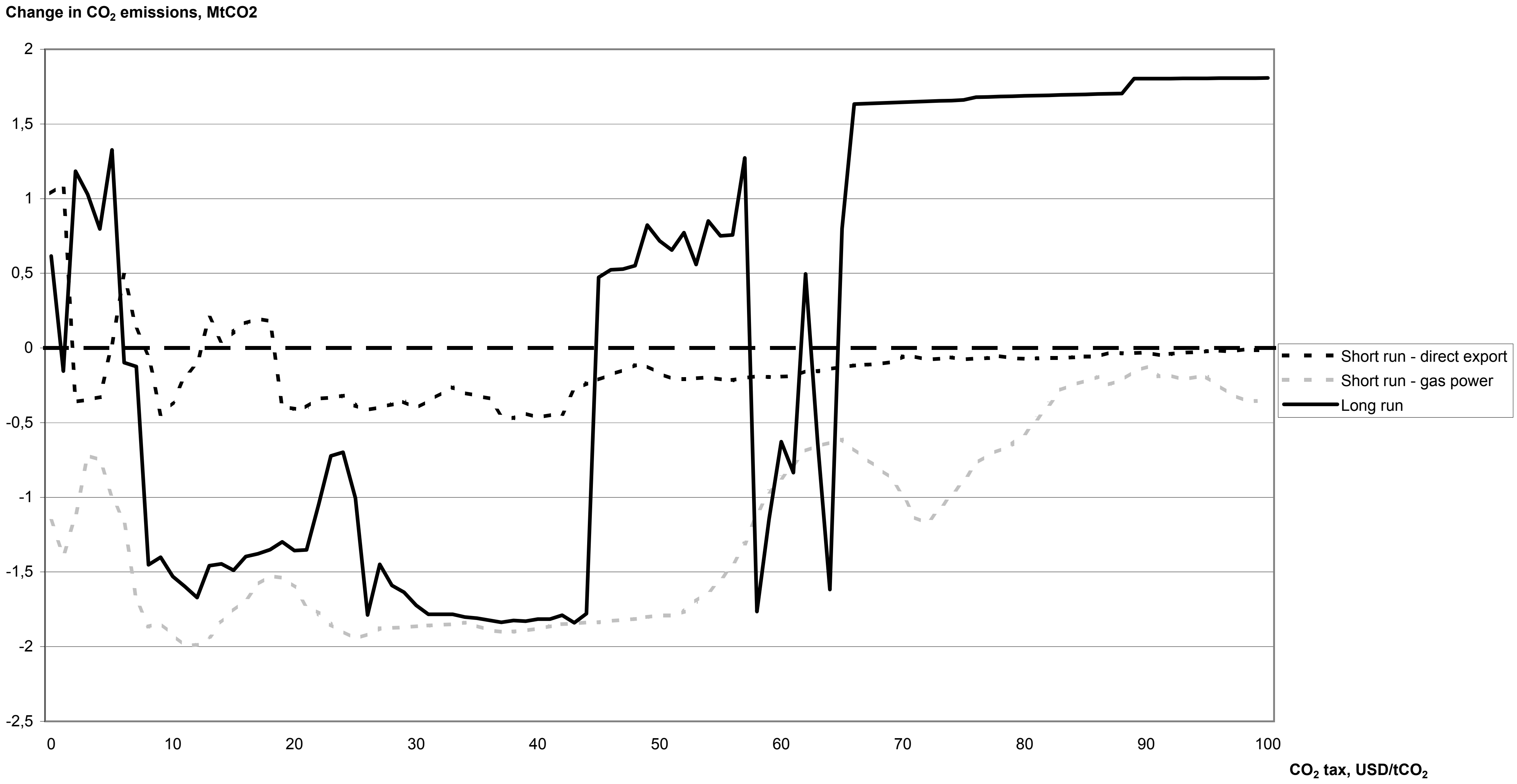

Figure 4 Net increase in total emissions of CO_2 in model countries following from increased extraction of natual gas in Norway.