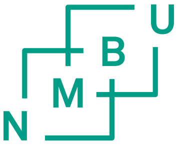

NMBU

Acknowledgement

I would like to express my gratitude to Knut Einar Rosendahl for continuous support and inspiration through the whole writing process. Thank you for **always** finding time to give feedback. Without those valuable comments and discussions the work on the thesis would have been much less enjoyable.

A special thanks to Marius Gavenas for taking care of everything so that I could focus on writing. Your help is highly appreciated.

Dear friends made this quite demanding semester much lighter, thank you for that.

Lastly, I would like to thank my family whose love and support guide me through life.

Any potential weaknesses or mistakes of the thesis are my full responsibility.

Ekaterina Gavenas

Ås, May 13, 2014

Abstract

This study analyses CO_2 emissions and emission intensity on 43 oil and gas fields on Norwegian continental shelf for the period 1997-2012. Secondary data on production, emissions, water and reservoir depth, oil prices, emission prices and electrification were collected for the study from Norwegian Environment Agency, Norwegian Petroleum Directorate, Norwegian Ministry of Finance, Statistics Norway and the U.S. Energy Information Administration. The results of panel data analysis support previous studies and show that there is difference between oil and gas fields when it comes to emissions. Gas production tends to have lower emissions. Emission intensity tends to be higher in the initial and decline phases of a field's lifetime. Emission price seems to have no significant effect on either emissions or emission intensity for the studied period.

Sammendrag

Denne oppgaven analyserer CO_2 utslipp og utslippsintensitet fra 43 olje- og gassfelt på norsk kontinentalsokkel i tidsperioden 1997 – 2012. Det ble samlet inn sekundærdata for produksjon, utslipp, vann- og reservoardybde, oljepriser, utslippspriser og elektrifisering av olje- og gassfelt som videre ble analysert med hjelp av økonometriske modeller. Datakilder som brukes er Miljødirektoratet, Oljedirektoratet, Finansdepartementet, Statistisk Sentralbyrå og Energi Informasjons Tilsynet i U.S. (U.S. EIA). Resultatene av dataanalysen underbygger tidligere forskning på dette området og viser at det finnes forskjeller mellom oljefelt og gassfelt når det gjelder CO_2 utslipp. Gassproduksjon har tendenser til lavere CO_2 utslipp. Utslippsintensitet er høyere i oppstartsfasen og i avslutningsfasen av feltene på norsk kontinentalsokkel. Utslippspris har ingen betydelig påvirkning på verken utslipp eller utslippsintensitet i tidsperioden 1997 – 2012.

Table of Contents

1 Introduction

With each subsequent publication of Intergovernmental Panel on Climate Change (IPCC 2014) report the challenge of emission reductions becomes more acute. We become more and more sure that current climate situation is the result of human activity. Authorities and scientists almost unanimously recognize the necessity for more noticeable emission reductions worldwide. Norway among other countries took on commitment to considerably reduce emissions by 2020, two thirds of emission reductions have to be taken domestically.

Main sources of emissions in Norway are road and coastal traffic, petroleum activities and industry; they account for more than two thirds of domestic emissions.

Oil and gas production requires use of energy inputs, which results in emissions. Those emissions contribute to worsening the climate change problem. In order to correct for this negative externality Norway introduced CO_2 tax offshore in 1991. Since 2008 petroleum industry in Norway is also regulated by European Union Emission Trading Scheme.

One of the possible climate policies for Norway is to slow down domestic petroleum production. This policy suggestion has a number of supporters; it however also provoked active debate in Norwegian politics and media. Opponents of this measure argue that Norwegian petroleum production is a relatively clean one and it is not reasonable to reduce it so that it is substituted by more energy intensive production from other regions. Some also claim that it is too expensive to leave resources unextracted in order to reduce emissions.

In this work we chose to focus on CO_2 emissions from offshore sector, thus we investigate the following research question:

What influences emissions and emission intensity on oil and gas fields on Norwegian Continental Shelf?

The thesis aims to contribute to understanding of emissions offshore and to serve as a support in developing measures in domestic emission reductions. In a previous study emissions from Norwegian fields were examined, however it covered only one year and did not include estimation of several variables (Fæhn et al. 2013). We will study the period of 1997-2012 and evaluate the influence of various field characteristics and external factors. We seek to answer the following sub questions:

Are there differences between oil and gas fields with respect to emissions? Does size of the field matter? Does it matter how deep the water in the field area is? Do emissions drop when output declines? How will CO_2 *price affect emissions offshore?*

The structure of this thesis is as follows: chapter 2 provides background information about Norwegian petroleum sector and overview of Norwegian climate policy; it also frames the political debate concerning domestic emission reductions. Chapter 3 presents theoretical framework and literature review. Chapter 4 describes data collection and method. Chapter 5 presents results and discusses policy implications of the results. Chapter 6 concludes the thesis.

2 Background

The chapter describes the Norwegian petroleum sector, its brief history and the state organization of activities. Further, main aspects of the Norwegian climate policy are presented and the ongoing debate about the validity of reduced oil extraction as a domestic emission reduction measure is mentioned.

2.1 Norwegian petroleum sector

2.1.1 Brief History and Organization

Interest in the North Sea's petroleum potential was encouraged by the gas discovery in the Netherlands in 1959 (NPD 2013). Norwegian government denied request from Philips Petroleum for conducting exploration on the Norwegian continental shelf, the authorities would not allow only one company possess the exclusive rights to exploration in the territory. In May 1963 the government declared sovereignty over the Norwegian continental shelf. The first discovery was the Ekofisk field in 1969, production from which started in 1971 (ibid). Other big fields were discovered in the following thirteen years: Statfjord, Oseberg, Gullfaks and Troll (ibid).

In the beginning foreign companies dominated the petroleum activities. The Norwegian participation increased with the entry of Norsk Hydro and establishment of Statoil in 1972 (ibid).

A predictable and transparent framework is necessary for the oil companies to operate optimally. The framework should meet the incentive compatibility criterion of the resource allocation mechanism by stimulating actors in petroleum industry to meet the State's objectives while achieving their profit maximization goals.

The general legal basis for the licensing system governing Norwegian petroleum activities is codified in the Petroleum Act (Act of 29 November 1996 No.71) (NPD 2013). The framework for the petroleum activity in Norway is set by the Parliament (Stortinget), which possesses the legislative power (NPD 2013). Stortinget supervises the Government and public administration (ibid). The Government has the executive authority over the petroleum policy and answers to Stortinget (ibid). The Government is supported by the ministries, underlying directorates and supervisory authorities (ibid).

Ministry of Petroleum and Energy has the overall responsibility for managing the petroleum resources on the Norwegian continental shelf. It must ensure that the activities are performed in accordance with the guidelines set by Stortinget and the government (NPD 2013). The Ministry of Petroleum and Energy is assisted by the Norwegian Petroleum Directorate, which has the administrative authority over exploration and production on the Norwegian continental shelf (ibid).

Figure 1 below summarizes the state organization of the petroleum activities.

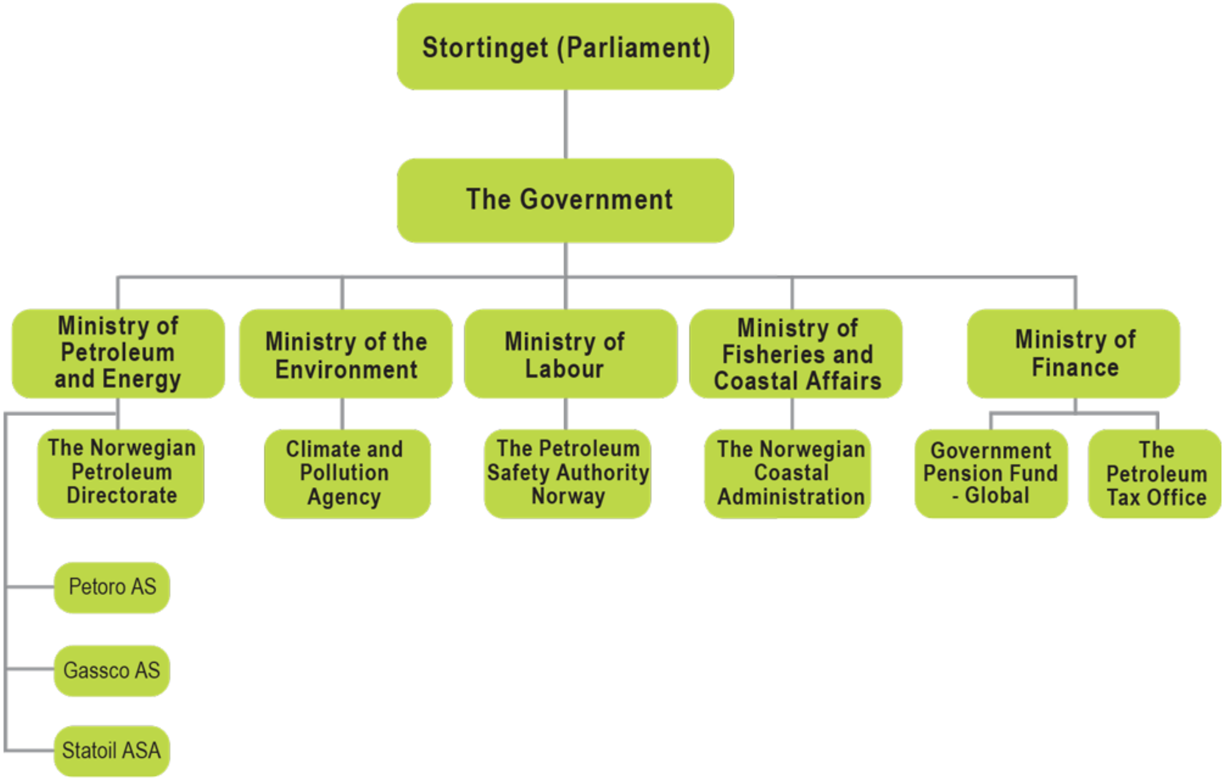


Figure 1. State organization of the petroleum activities. (Source NPD 2013).

2.1.2 Current position

Petroleum industry is the largest sector of Norwegian economy, it accounted for 23% of country’s total value creation in 2012 (Ministry of Petroleum and Energy 2014). According to the BP Statistical Review of World Energy, Norway produced 114.9 billion cubic meters of natural gas in 2012, which is a 12.6% increase compared to 2011; in world’s perspective it constitutes 3.4% of total natural gas production and accounts for around 25% of EU’s gas demand (BP 2013). The oil production in 2012 was 1.9 million barrels daily, which is a 7% decrease compared to 2011, it is 2.1% of global oil production (BP 2013).

2.2 Norwegian climate policy

Thorvald Moe in the policy note evaluating Norwegian Climate Policies 1990-2010 writes that policies have been influenced by the principles developed by OECD, the European Commission and Norway's participation in UNFCCC negotiations (Moe 2010) . He further states that the objective of a climate policy is to find a mix of measures which minimize the economic and social costs of transition towards low GHG economy (Moe 2010). Moe names the key criteria in formulating the policy (Moe 2010:8):

- Effectiveness (reducing emissions on the scale required).

- Cost-Efficiency (achieving emission reduction goals at the least social and economic cost both within and between countries).

- Equity in recognizing differences in incomes, technologies and historical responsibility.

Norway was an early mover in introducing market based instruments in order to achieve the goals of climate policy. The CO_2 tax was introduced in 1991 in Norway (on petrol, auto diesel oil, mineral oil and the petroleum sector offshore). Bruvoll and Dalen (2009) explain that CO_2 taxes on mainland activities are generally levied on the use (more precisely the purchase or import) of mineral oils and petrol, while the CO_2 taxes on the Norwegian offshore sector are levied on the burning of petroleum and natural gas. The CO_2 tax for petroleum activities is 400 NOK per ton CO_2 effective 1 January 2013 (NPD 2013). The fee (NOK 0.96 per unit) is paid per standard cubic meter (Sm_3) of gas that is burned or released directly, and per liter of petroleum burned (NPD 2013).

Norway joined the EU's emission trading scheme by adopting the Directive 2003/87/EC (EU Comission 2007). As of 1 January 2008, the petroleum activities are subject to both CO_2 tax and mandatory emissions allowances. CO_2 tax and the CO_2 price in the ETS have varied over time and we will return to this in chapter 5.

The Norwegian Government's strategy document on Climate policy (Klimaforliket) was adopted by Stortinget in 2008. The document specified that Norway's goal was to reduce emissions equal to 15-17 million tons of CO_2 equivalents by 2020, regardless of other countries' commitments, and two thirds of these reductions have to be achieved domestically (Climate Agreement 2008).

2.3 Emissions from petroleum sector

In 2011 53.3 million tons CO_2e were emitted from Norwegian territory (SSB 2014). In world's perspective it constitutes only 0.16% of total emissions[1]. Almost one third of domestic emissions were caused by petroleum activities, see Figure 2 below.

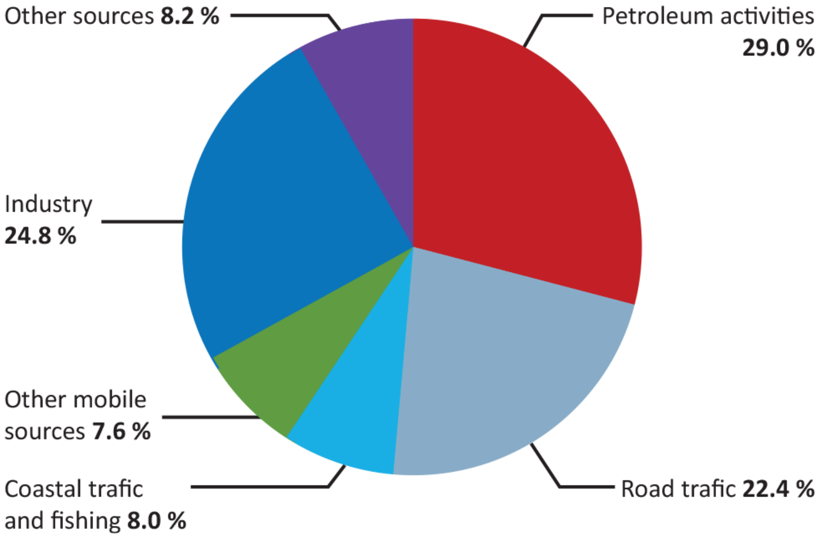


Figure 2. Sources of Norwegian CO2 emissions, 2011. (Based on data from Statistics Norway).

Main source of emissions offshore is the burning of gas in the turbines to supply electricity (Norwegian Environment Agency 2014). Gas flaring, burning of diesel in engines and well testing also contribute to total emissions caused by petroleum sector.

Emission intensity varies considerably across fields and countries. According to data by Oil and Gas Producers, average global emission intensity was 132 tons of CO_2 per thousand tons of hydrocarbon production in 2012 (OGP 2013). Lowest reported emission intensity is 58 tons of CO_2 per 1000 tons of production in the Middle East, while the highest numbers are for North

---

[1] Global CO_2 emissions in 2011 were, according to PBL Netherlands Environmental Assessment Agency report, 34 billion tons CO_2 (excluding land use, land use change and forestry).

America, i.e. 214 units (ibid). Such high average values for North America must be influenced by the production of synthetic crude oil from oil sand through surface mining and upgrading, or in situ and upgrading. Both processes are highly energy intensive (Charpentier et al. 2009).

A team of researchers from Statistics Norway commented that coverage for the Middle East in OGP report is less comprehensive than for other regions and real values can be higher (Fæhn et al. 2013). They calculated the average intensity for Norway in 2011 to be 60 tons of CO_2e per 1000 tons of production (Fæhn et al. 2013). Fæhn et al. (2013) also mentioned that emissions from oil fields were 4-5 times higher than emissions from gas fields for 2011 and 2012. One of the possible explanations for this was that two largest gas fields were electrified and that more of oil fields than gas fields are in the final phase of extraction (Fæhn et al. 2013). In our paper we want to go deeper into studying emissions and emission intensity on petroleum fields in Norway. We will extend analysis to sixteen years and will include several variables in estimation.

2.4 Political debate

On the Durban climate change conference in 2011 the question about how Norway can further contribute to the mitigation of GHG emissions (domestic reductions and not only buying cheap quotas from abroad) was raised. Erik Solheim, the former Norwegian minister of the Environment and International Development, suggested slowing down the tempo of oil production in Norway. This was supported, among others, by a researcher Knut Einar Rosendahl (Rosendahl 2011). Opponents of this measure did not stay silent. For instance, professor Petter Osmundsen pointed out that Norwegian CO_2 emissions are so insignificant in the world's perspective that the climate benefits from reducing oil production will be unnoticeable (Osmundsen 2011). He also mentioned that the reduced Norwegian production will be replaced by a more energy intensive production like Canadian oil sands, thus the GHG reduction will be neglected (Osmundsen 2011).

This discussion was renewed in 2013 when Jens Ulltveit-Moe, a Norwegian investor, wrote an article saying that oil, coal and gas are the energy sources of the past, while wind, water and solar energy are our future. Bård Vegar Solhjell, the minister of the Environment at that time, supported this view. He also agreed that expertise from petroleum sector in Norway should be gradually moved to marine, “green” industry and renewable energy. In addition, he said that reduction in oil extraction in Norway was an effective climate policy (Solhjell 2013). However, Ola Borten Moe, the former Oil and Energy minister, was quite critical towards this position and by no means could agree to keep mineral resources remain unextracted (Moe 2013).

The debate on this topic has not been settled yet; the discussion is still active in Norwegian media.

In the earlier mentioned study researchers investigated analytically and numerically how domestic demand and supply side policies affect global emissions (Fæhn et al. 2013). Their main conclusion 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” (Fæhn et al. 2013:5). This conclusion supports Solheim’s suggestion.

In the light of the ongoing discussions about the emissions from petroleum activities, it seemed interesting to take a closer look at what these emissions are determined by; whether it is the type of a field (oil or gas), the size of a field, age or location that influence the emissions.

3 Theoretical framework

This chapter opens with a profit maximizing firm's behavior when environmental regulation is introduced. Then we will take a closer look at environmental taxes and tradable permits, how they function, and how to decide which instrument to choose. The chapter concludes with the combination of price and quantity instruments.

Here by a term *firm* we mean a unit which produces oil or gas and adjusts its behavior so that profit is maximized. Petroleum fields on Norwegian continental shelf which we study in this paper are considered firms[2].

Oil and gas extraction is energy-intensive industry, and, as was mentioned in chapter 2, it accounts for large share of Norway's emissions. Considerable part of emissions offshore is due to fossil fuel (gas and diesel) used as input in oil and gas production, partly via electricity generation. In addition, there are some emissions not directly connected with oil and gas production, e.g. well-testing, and some emissions related to flaring.

The idea behind any environmental regulation is to correct negative externality, in our case this externality are emissions induced by oil and gas production offshore. Emission tax or tradable emission permits are aimed at reducing emissions by influencing firm's behavior. Environmental regulation may reduce company's profit. A firm can adjust by reducing usage of fossil fuels and increasing usage of other inputs, it can alternatively scale down production; both choices will result in fewer emissions. This mechanism fails when emission price is too low.

3.1 Profit maximization

In modelling there is always a dilemma between realism and theory (Sadoulet & De Janvry 1995). Assumptions that we make simplify reality considerably, however models are useful to explain the main economic mechanisms behind the real life economy.

---

[2] Petroleum fields in Norway are typically owned by several firms and it is usual that a petroleum company owns several fields, partly or completely. To simplify the modelling we disregard this since it does not influence the analysis.

A simple profit maximization model is chosen to describe a behavior of a single firm. We base our analysis on theories presented in “Microeconomic analysis” by Hal Varian (Varian 1992) and “The structure of economics” by Silberberg and Suen (Silberberg & Suen 2001).

Economic profit is designed to be the difference between the revenue a firm receives and the costs it incurs (Varian 1992). Assumptions for the model: a firm seeks to maximize its profits by choosing *n* actions so that the difference between revenues and costs is maximized: R$(a_1, \dots, a_n)$ - C$(a_1, \dots, a_n)$. The profit maximization problem can be written as:

$$\max_{a_1,\dots,a_n} R(a_1, \dots, a_n) - C\,(a_1, \dots, a_n)\,.$$

From this follows that an optimal set of actions **a*** = (a_1^*,…, a_n^*) should satisfy the condition:

$$\frac{\partial R(a^*)}{\partial a_i} = \frac{\partial C(a^*)}{\partial a_i} \qquad i=1, \dots, n\,.$$

Varian calls it the “fundamental condition of profit maximization” (Varian 1992). A firm decides how much to produce and how much of each input to use. The fundamental condition of profit maximization implies that the level of output should be chosen such that the marginal revenue of production equals to the cost of production one extra unit; revenue earned by one extra unit of input should be equal to the cost of employing an extra unit of input.

The second fundamental condition of profit maximization, as Varian mentions, is the condition of equal long-run profits (ibid).

In our case we deal with firms that are under environmental regulation. To reflect this, we incorporate cost of environmental regulation of emissions caused by production into the problem of profit maximization by Silberberg and Suen (Silberberg & Suen 2001).

We assume that producers are price taking firms that have an objective of maximizing profit subjected to production function (technology) constraint and environmental regulation. Let us simply say that a firm employs only two inputs in production, where $\boldsymbol{x_1}$ is fossil fuel and $\boldsymbol{x_2}$ can be labeled as other inputs. Let $\boldsymbol{y}$ be output quantity choices of the firm’s primary product (in our case oil, gas). The output quantities are connected to input through a production function: $\boldsymbol{y = f(x_1,\ x_2),\ f'(x_i)} > 0$. Let $\boldsymbol{p}$ be the scalar output price and $\boldsymbol{w}$ be a vector of input prices,

$\boldsymbol{w} = (\boldsymbol{w_1}, \boldsymbol{w_2})$**.** Energy employed in production induces emissions $\boldsymbol{e}$, which are linked to the use of fossil fuels through an emission function $\boldsymbol{e} = \boldsymbol{g}(\boldsymbol{x_1}),\ \boldsymbol{g}'(\boldsymbol{x_1}) > 0$**.** Let ***z*** be the scalar emission price (the cost of emission tax or permit to a firm). Thus, the firm maximizes the following profit function:

$$\pi = pf(x_1, x_2) - w_1x_1 - w_2x_2 - zg(x_1). \qquad (3.1)$$

The test conditions of the model are the particular values of input prices, output price and emission price. The objective of this model is to make it possible to state the adjustments in the level of output when the test conditions change.

The first order conditions for profit maximization are:

$$\frac{\partial \pi}{\partial x_i} = p\frac{\partial f}{\partial x_i} - w_i - z\frac{\partial g}{\partial x_i} = 0.$$

or

$$p\frac{\partial f}{\partial x_i} = w_i + z\frac{\partial g}{\partial x_i}.$$

We can interpret the FOCs in a following way: a profit maximizing firm will employ resources up to the point where the marginal revenue per each factor employed equals the cost of purchasing this input and the cost of environmental regulation per unit of input. Note that employment of what we called other inputs, according to our assumptions, does not produce emissions and hence the cost of emissions is not relevant when deciding how much of other inputs to use ($z\frac{\partial g}{\partial x_2} = 0$).

Different oil and gas fields have different characteristics, e.g. emission intensity, which we mentioned in chapter 2. Depending on the production function fields employ different quantities of inputs. The profit equation suggests that profit declines if price of 1 ton of CO_2 increases. In this case a firm can choose to use less fossil fuel and more of other inputs or it can decrease production. If emissions are regulated by quotas that are auctioned off or by emission taxes, then a relatively clean firm (the one which emits less per produced unit compared to other firms) can benefit if the output price increases. Alternatively, when emission price is very low, it will most likely not affect the decision of the firm about energy use.

3.1.1 Environmental regulation and producer surplus

Profit maximizing equation 3.1 suggests that tax fee or auctioned off emission quota reduces firms' profits. The graphical analysis below illustrates how environmental regulation influences producer surplus.

Suppose we have a market which consists of identical profit maximizing firms which produce some good. Production causes a negative externality, e.g. CO_2 emissions. In Figure 3 we can see an initially unregulated market presented by the sum of all firms' supply curves S_0 and market demand curve D. Equilibrium price (p_0) and quantity (q_0) are set by the intersection of S_0 and D. In this market producer surplus equals to the area f+g+h.

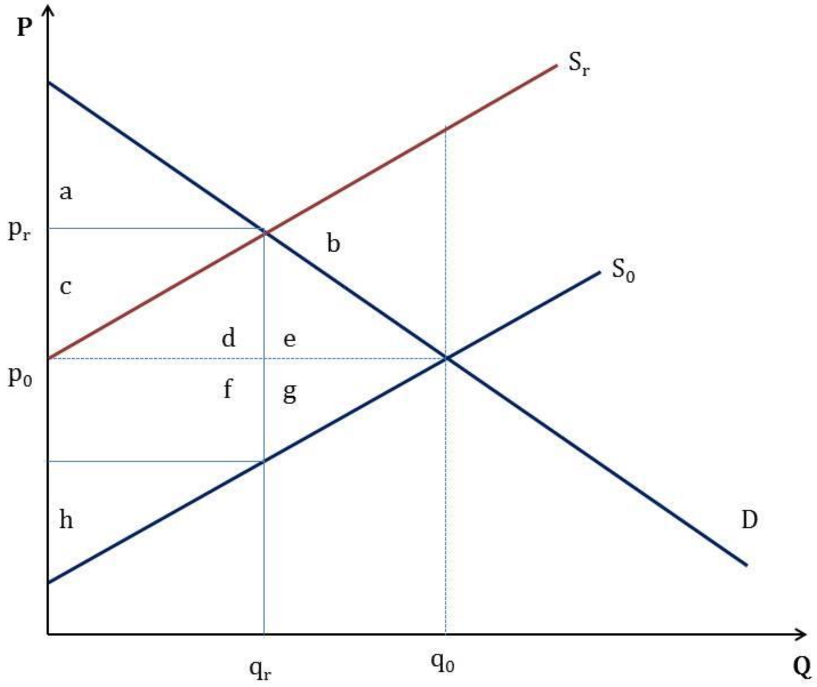


Figure 3. Change in producer surplus due to environmental regulation.

We now assume that emissions per output are unchanged. When government introduces environmental regulation, e.g. a CO_2 tax, the supply curve shifts upwards, new supply curve is now $S_{r,}$ which can also be interpreted as marginal social cost curve of production of the good. The new equilibrium is set by the intersection of the demand curve D and the new supply curve S_r. The new price p_r is higher than the initial price ($p_r > p_0$) and the new quantity q_r is lower than the initial quantity ($q_r < q_0$). This supports Karp and Zhao (2009) who write that a regulation that increases firms' costs typically reduces their incentives to supply that good, so the market price of the good increases.

The producer surplus is now presented by the area h. Government receives the revenue from the tax payment equal to the area c+d+f. The avoided external cost of the environmental regulation is the area b+e+g.

Initial producer surplus (f+g+h) is bigger than the surplus after environmental regulation is introduced (h), thus the graphical analysis supports the analytical one.

3.2 Environmental Tax

Taxes, due to Arthur Cecil Pigou, have been recommended as a way to correct negative externalities at least since 1920 (Howe 1994). As Howe writes, taxes are preferred due to efficiency and revenue reasons (Howe 1994).

When tax is set, firms adjust their emission levels according to the tax and thus reveal their abatement cost evaluated at this emission level. Thus, those actors for whom it is cheaper to abate, reduce emissions more than those with higher marginal abatement costs, as we can see in the Figure 4 ($z_3 > z_2 > z_1$). Taxes satisfy the equi-marginal principle, according to which all actors face the same marginal abatement cost evaluated at a chosen level of emissions:

$$tax = MAC_1(z_1) = MAC_2(z_2) = MAC_3(z_3)$$

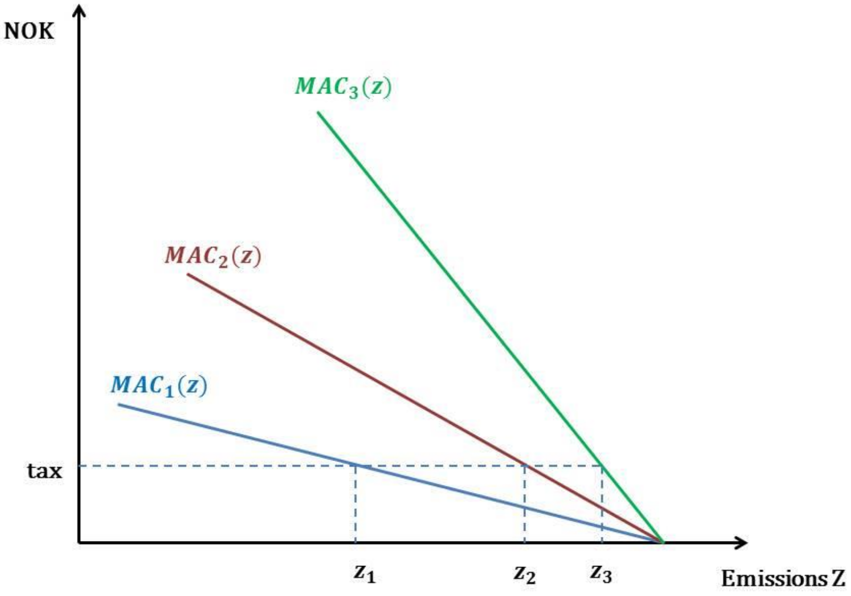


Figure 4. Equi-marginal principle.

This principle allows to achieve environmental goal at least cost, satisfying condition for cost-effectiveness for homogeneous emissions reductions (Hoel 1998).

Another argument in favor of taxes is the double dividend. The double dividend means that environmental taxes not only help in achieving environmental goal, but also generate the revenue which can be used to reduce other distortionary taxes in the economy, like labor or revenue tax, see e.g. Bovenberg and Mooij (1994), Goulder (1995) and Hoel (1998) for details. Taxes in some cases are also reported to be easier than quantity restrictions to negotiate and monitor (Karp & Zhao 2009).

Main critique of taxes stems from political economy. Karp and Zhao (2009) claim that it is easier to succeed in environmental negotiations based on quantity targets rather than a tax. The authors also say that taxes are less likely to get industry support than quantity based policies (ibid).

3.3 Tradable Emission Permits

Another policy instrument to internalize externalities is tradable emission permits. The idea of cap and trade was introduced in the classic work of Ronald Coase (1960) on how well-defined property rights can assure efficient outcomes, despite the presence of externalities (Goulder 2013).

In the cap and trade system the focus is on achieving a certain quantitative target. However, if the target is set too loose, the system will fail. In Figure 5 we can see that a loose quota yields low price on emission allowances, the tighter the quota is, the higher will the price be and the more expensive it will be for firms to produce emissions. If the quota is bigger than current emissions, then the quota constraint becomes non-binding and price on permission allowances falls to zero.

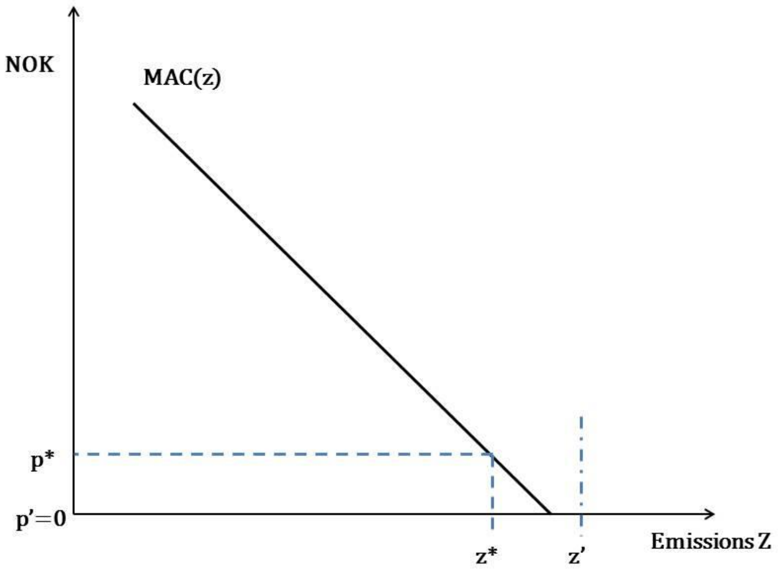


Figure 5. Non-binding quota.

Karp and Zhao dwell upon introduction of price floor and price ceiling into emission permit system in order to manage price fluctuations (Karp & Zhao 2009). They assume that permits are traded internationally and that a Central Bank is a regulatory body. When price on permits is too low, reaches the floor, Central bank buys back permits. When, on the contrary, price gets too high, Central bank sells permits (ibid).

Strong lobbying from the industry makes emission permit system more appealing in terms of political economy (Böhringer & Lange 2005). There is, however, more room for corruption and wasteful expenditures to capture "rents" (Karp & Zhao 2009).

How to allocate emission allowances has for several years been an issue in the environmental literature. Free allocation of emission permits is inconsistent with polluter pays principle, since the companies producing emissions are allocated emission quotas free of charge (Sorrell & Sijm 2003). Moreover, when gratis allocation exceeds company's demand, they can be sold, thus the polluter earns windfall profits on producing externality (Woerdman et al. 2008).

Another issue frequently discussed with quota allocation is incentive to innovate. Some argue that free allocation does not incentivize innovation as much as auctioning off permits (Cramton & Kerr 2002). Fischer et al. (2003) on the contrary state that "in the case of high imitation, steeply sloped marginal environmental benefits, low innovation costs, a small number of firms, and high benefits/abatement[…]" grandfathering is preferable and not auctioning (Fischer et al. 2003:545).

3.4 Prices versus quantities

There is an ongoing discussion about taxes and tradable permits, which instrument is better in terms of political, legal and revenue concerns (see e.g. McKibbin and Wilcoxen (1997), Goulder et al. (1997), Karp and Zhao (2009)). Another venue for comparison is research and development and incentives for technology innovation (see e.g. Fischer et al. (2003), Rosendahl (2004), Pizer and Popp (2008), Greaker and Pade (2009)). However, there are situations when price and quantity instruments lead to the same result.

In case of certainty about marginal abatement costs and marginal environmental costs (marginal damages), emission taxes and tradable emission permits yield the same aggregate emission level and satisfy both cost-effectiveness ($MAC_i(z_i) = MAC_j(z_j)$) and efficiency ($MAC(z)=MD(z)$) criteria. The intersection of aggregate marginal abatement costs and marginal damages sets the optimal aggregate emission level ($\bar{Z}$), the optimal emission price then equals the tax, see Figure 6.

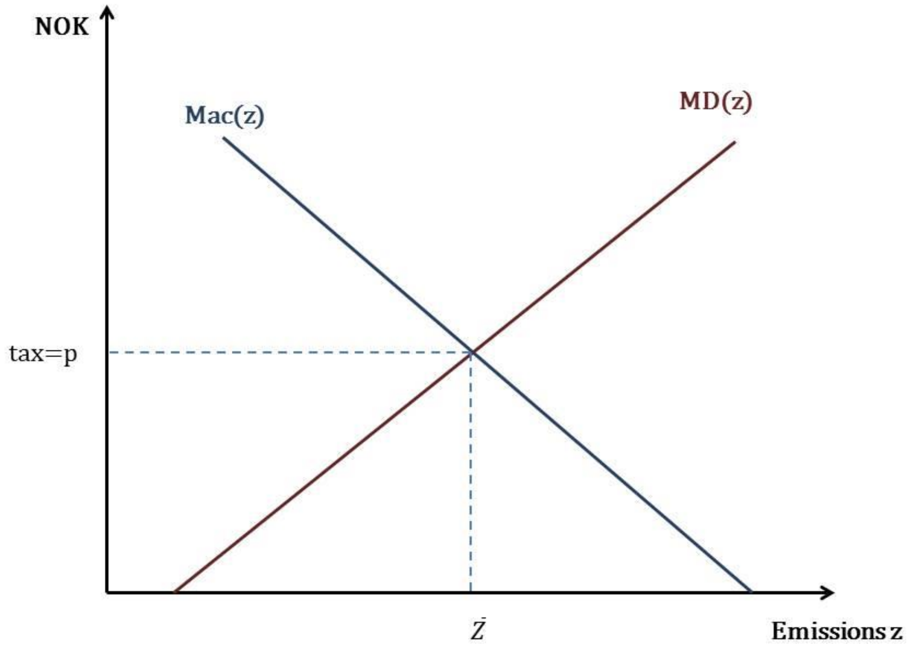


Figure 6. Optimal price and aggregate emission level.

However, the economic activity in a country is not a static condition. There are periods with high economic activity and there are also recession-like periods with low activity. Figure 7 shows how tax and permit trading system interact with economy (Romstad 2014). $\sum MAC_{(z)}$ presents the total marginal abatement costs curve for the all actors in economy, it can be also interpreted as economy's demand for emissions.

In the initial situation taxes and tradable emission permits yield the same result with respect to total emissions $\bar{Z}$ and the emission price (tax=p). When there is boosting activity in the country, economy demands more emissions and the aggregate marginal abatement cost curve shifts clockwise to $\sum MAC^{high\ activity}\ (z)$. If the economy is regulated by environmental tax, emission price will remain the same; the aggregate level of emissions, however, will be higher $Z^{high\ activity}$. In case with emission trading system, the cap will remain the same $\bar{Z}$, but the price will increase to $p^{high\ activity}$.

In the period of recession demand for emissions is lower and the aggregate marginal abatement cost curve rotates counterclockwise to $\sum MAC^{low\ activity}(z)$. The tax regulation will result in lower aggregate emissions level $Z^{low\ activity}$, the price being unchanged. The permit trading system will result in lower emission allowance price $p^{low\ activity}$, the total cap is unchanged ($\bar{Z}$).

As we can see from the graphical analysis, when there are fluctuations in economic activity, tax regulation results in volatility in aggregate emissions level, allowing for more emissions in periods with high economic activity and less emissions in periods with lower economic activity. Quota regulation in turn keeps the aggregate emissions level constant, but allows for price volatility.

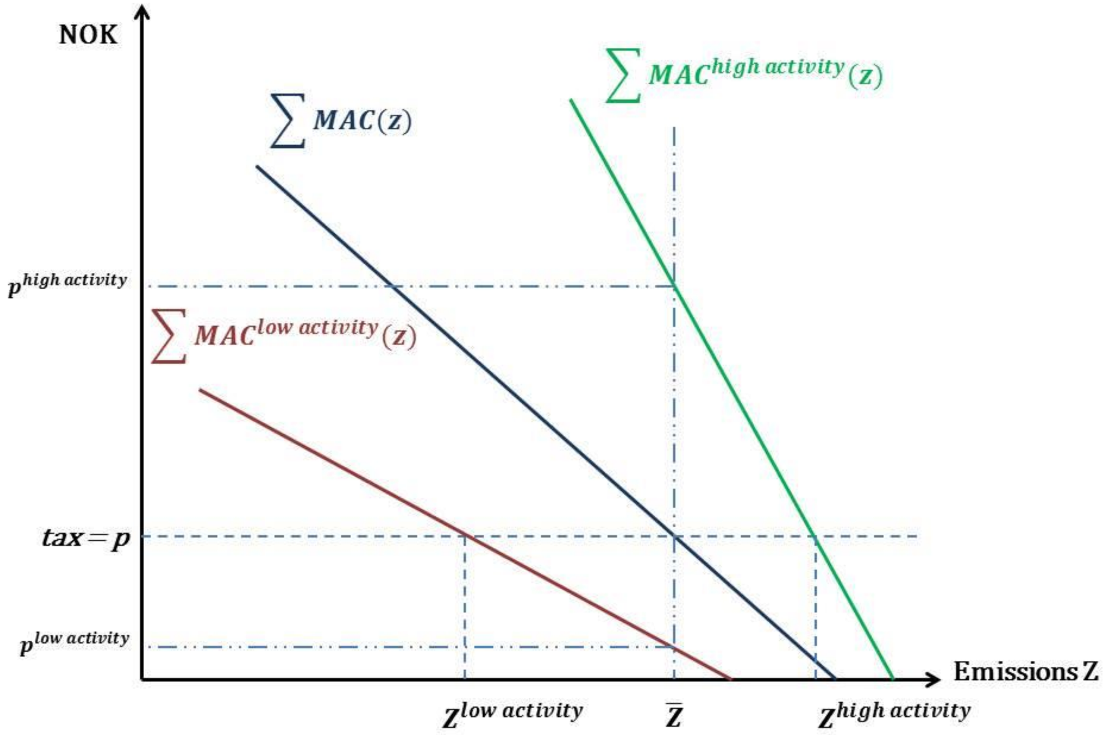


Figure 7. Economic activity and environmental regulation.

3.4.1 Uncertainty in marginal abatement costs

In 1974 Weitzman in his seminal paper compared prices and quantities under uncertainty (Weitzman 1974). By quantities Weitzman means emission standard, but it could also be interpreted as quotas (Rosendahl 2013). The main guideline to policymakers from “Prices versus quantities” paper is, when there is uncertainty about marginal abatement costs and they are steeper than marginal damages, to use price based instruments (taxes). In the converse situation, use quantity based instruments. We can present this solution graphically. In reality the difference in dead weight losses is not that dramatic, we only drew it like this for the illustration purposes.

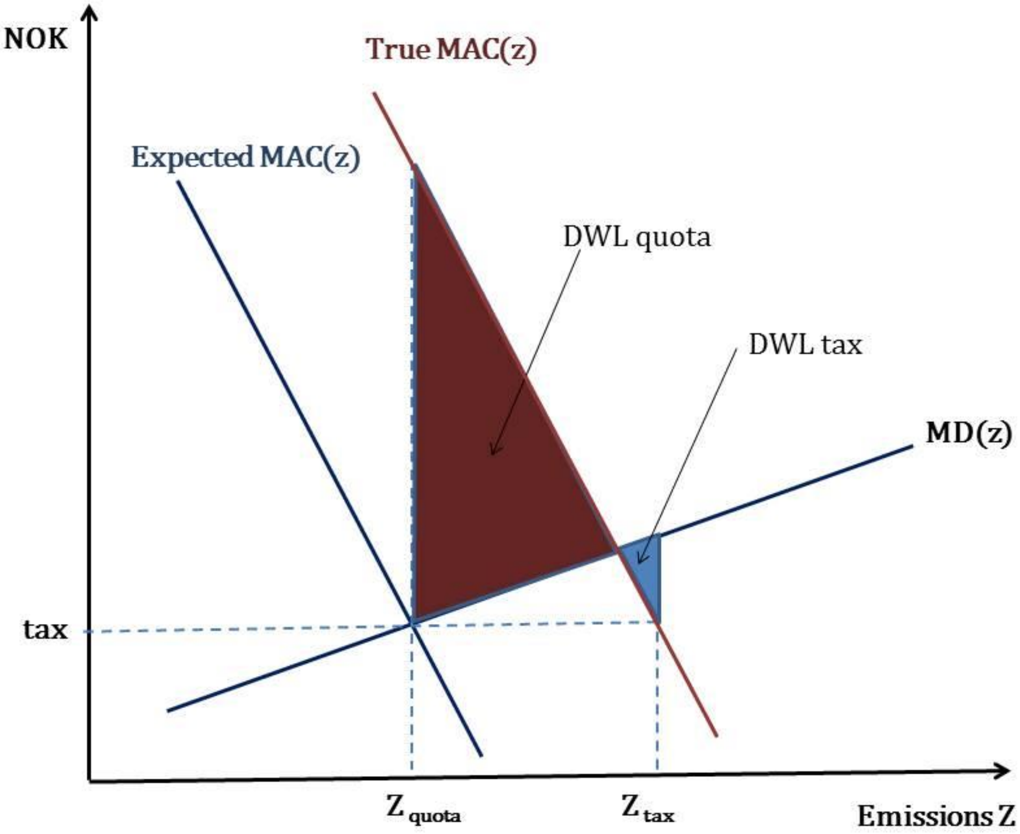


Figure 8. When to choose prices. MAC(z) steeper than MD(z).

Figure 8 illustrates the situation when marginal abatement costs are steeper than marginal damages. Suppose the regulator had estimation of aggregate marginal abatement costs, presented by $Expected\ MAC(z)$ curve and the marginal damages presented by $MD(z)$ curve. According to the expectations, the regulator introduced the optimal policy by either setting a tax or the cap on emissions equal to Z_{quota}. The true marginal abatement costs ($True\ MAC(z)$), however, turned out to be higher than expected. Since the total emission level is set by cap in a quota system, it remains unchanged. The dead weight loss of quantity regulation is shown by the dark red triangle $DWL\ quota$. In case of tax, the total emission level will change to Z_{tax},, while price will stay the same. The dead weight loss from tax regulation is presented by the blue triangle $DWL\ tax$ and we clearly see that it is smaller than the dead weight loss of quantity regulation.

If the true marginal abatement costs were lower than the expected ones, the graphical analysis would give the same result in terms of differences in dead weight losses.

In the situation when marginal damages are steeper than marginal abatement cost, the dead weight loss of the tax will be considerably bigger than the dead weight loss of the quota. Thus, in such case one should apply quantity instruments.

Weitzman has been, however, criticized for the strong assumptions in his proposition (Karp & Zhao 2009). He assumes that the MAC and MD curves are linear and there is uncertainty about the intercept, but not the slope of the marginal abatement cost curve (ibid). The critique nevertheless does not diminish Weitzman's contribution to environmental economics.

3.4.2 Combination

In search for a better climate policy than pure price or pure quantity instruments, several modified or hybrid policies were suggested.

Pizer (2002) in his paper "Combining price and quantity controls to mitigate global climate change" presents a hybrid policy suggested by Weitzman (1978), Roberts and Spence (1976) and McKibbin and Wilcoxen (1997). The suggested mechanism gives producers a possibility of either buying emission permits in the market or obtaining them from the government at a certain "trigger" price (Pizer 2002). This system functions as a permit scheme with a fixed cap and uncertain costs until the marginal costs (allowance price) are below the trigger price. When the trigger price is reached, the costs become certain (equal to the trigger price) but the emissions are not, as in pure tax system. Pizer (2002) states that, if the number of permits is set low enough or the trigger price is set high enough, the hybrid policy will work as pure price or pure quantity system respectively. Since the mechanism works as either tax or tradable permits system, it should perform at least as well as either pure policy (ibid). Besides achieving efficiency in emission reduction, the hybrid system also preserves the political appeal of permit trading, i.e. the flexible distribution of rents associated with emission rights (ibid).

4 Data and Method

This chapter opens with data collection and description. The two models are then formulated and expectations to signs of coefficients are stated. Afterwards the chosen method of analysis is presented and estimations issues are named.

4.1 Data collection and description

The purpose of this thesis is twofold: to study what influences total CO_2 emissions per year per petroleum field on Norwegian continental shelf, and also to analyze what influences emission intensity per year per field. Thus, our dependent variable is total emissions in one model and emission intensity in the other model. Independent variables used in the two models are production, phase of production, share of gas produced per year, share of gas of original recoverable resources, original resources, water depth, reservoir depth, oil price, price of carbon and electrification from the shore. The data is for 43 oil and gas fields for the period from 1997 to 2012.

Yearly data on CO_2 emissions per field were obtained from the Environment Web with the permission from the Norwegian Environment Agency (Miljødirektoratet). The original owner of data is the Norwegian Oil and Gas Association (Norsk Olje&Gass). As already mentioned in chapter 2, main sources of emissions offshore are gas turbines, diesel motors, gas flaring and well testing. The database distinguishes between different sources, we however look at total emissions per field per year, regardless of what they were produced by.

Data on production per field per year were taken from the Statistics Norway (Statistisk Sentralbyrå). Production is reported in common energy units – standard cubic meters of oil equivalents (Sm^3 o.e.), which equals to ca 1000 Sm^3 gas and ca 0.53 tons of natural gas liquids (NGL). Total production in Sm^3 o.e. was converted to tones by a conversion factor of 0.84. Yearly emission intensity for each field was calculated by dividing total emissions reported in tons by the total production for each year. Emission intensity is expressed in tons CO_2 per thousand tons of hydrocarbon production, in line with how carbon dioxide emissions are reported by International Association of Oil and Gas Producers (OGP 2013).

In which phase of production the field is each year, is expressed by the ratio of production per that year to the maximum production in the field's lifetime. Top production level does not necessarily lie in the studied period (1997-2012), but it can take place in earlier years, which is the case for older fields. Some newer fields, on the contrary, might not have reached the peak yet, the highest production number so far is taken for calculations for such fields.

Share of gas produced each year is found by dividing production of gas by total production for the actual year. NGL and condensate are treated as oil.

Original resources, water depth and reservoir depth for each field are taken from the Norwegian Petroleum Directorate (Oljedirektoratet). Share of gas of original recoverable resources is calculated based on data from the Norwegian Petroleum Directorate.

Annual nominal prices per barrel of crude oil Europe Brent in USD were taken from the U.S. Energy Information Administration. Historical annual average of daily exchange rates for US dollars from Norway's central bank (Norges Bank) was used to convert oil prices to Norwegian kroners per barrel. In order to express oil prices in real prices of 2012 producer price index from Statistics Norway was used.

Carbon price is the price of 1 ton of CO_2. As mentioned earlier, until 2008 only carbon tax on Norwegian continental shelf was used, from 2008 petroleum producers are regulated by both CO_2 tax and emission quota. Values for the carbon price were obtained from the Zero Emissions Resource Organization (ZERO). ZERO collected the numbers from various reports from the Norwegian Ministry of Finance.

A dummy variable equal to 1 marks the fields which are supplied with electricity from the shore, 0 otherwise. In our study there are four fields which are electrified, namely Gjøa, Ormen Lange, Troll I and Snøhvit.

When studying the fields we faced one problem. Some smaller fields were tied with bigger fields and emissions caused by their activity were included in the reported emissions of the bigger fields, which would give higher values of emission intensity for the bigger fields and extremely low or absent values for the tied fields. In order to correct for this bias we chose to sum production and emission numbers for the main field and the tied field(s). By *main field* we mean field with highest production. The overview of the tied fields can be found in appendix A. Share of gas produced, phase of production, water depth, reservoir depth and original recoverable resources are reported for the main field for all the combined fields with the exception for Sleipner Øst+Vest for 1997-2002. Sleipner Øst+Vest which consists of two big fields, after thorough considerations, was treated as one field for the period 1997-2002. Recoverable resources were summed up, share of production and share of gas produced were calculated based on common production on Øst and Vest fields, and the average values of water and reservoir depth were taken.

Table 1 below summarizes the variables used in analysis, their sources and main descriptive statistics.

Table 1. Description of the variables.

Variable name	Description	Source	Mean	Std.dev	Min	Max
$emis_{it}$	Total emissions on field i in year t in tons CO_2	Norwegian Environment Agency	335775	331661	1595	1857508
$emispt_{it}$	Emission intensity on field i in year t in tons CO_2 per 1000 tons of production	Own calculations based on total emissions and production per year	98	151	0.07	2 205
$prod_{it}$	Production on field i in year t in thousand tons oil equivalents	Statistics Norway	6 412	6 601	8	31 205
$sharegas_{it}$	Share of gas produced on field i in year t	Own calculations based on production data	0.23	0.30	0	1
$share_{it}$	Phase of production on field i in year t expressed in percentage of maximum production	Own calculations based on production data	0.49	0.31	0.01	1
$size_i$	Original recoverable reserves for field i in million standard cubic meters oil equivalents	Norwegian Petroleum Directorate	225	295	7	1 484
w_i	Water depth for field i in meters	Norwegian Petroleum Directorate	189	153	66	880
res_i	Reservoir depth for field i in meters	Norwegian Petroleum Directorate	2 687	791	1330	4850
oil_t	Oil price in year t in NOK per barrel in 2012 prices	U.S. Energy Information	412	157	150	650

		Administration				
$carb_t$	Price of 1 ton of CO_2 in year t NOK in 2012 prices	ZERO	440	97	265	654
$elect_i$	Dummy variable for electrification from the shore for field i	Norwegian Petroleum Directorate	0.9	0.29	0	1
$gasor_i$	Share of gas of original recoverable resources for field i	Own calculations based on original recoverable resources data	0.31	0.30	0	1

4.2 Expectations to coefficients

4.2.1 Model 1

Natural logarithms were taken of all the variables with the exception for the dummy variable. This transformation helps to correct skewed distribution of residuals. Moreover, it eases interpretation of the results. As Gujarati mentions in double log models, the slope coefficients can be read as elasticities (Gujarati 2011).

Share of produced gas has some zero values. Logarithm of zero is not defined. In order to overcome this we added 1 to share of produced gas before taking logarithm. This will influence interpretation of coefficients in chapter 5.

We assume linear functional form. Our first model with emissions as dependent variable can be formulated in the following way:

$$\log(em_{it}) = \beta_0 + \delta_0 elect_i + \beta_1 \log(prod_{it}) + \beta_2 \log(sharegas_{it}) + \beta_3 \log(size_i) + \beta_4 \log(w_i) + \beta_5 \log(res_i) + \beta_6 \log(carb_t) + \beta_7 \log(oil_t) + c_i + u_{it} \qquad (4.1)$$

where em_{it} is total emissions for field i in year t; β_0 is the intercept parameter; $\beta_{1,\ldots,7}$ are slope coefficients, δ_0 is intercept shift; $elect_i$ is a dummy variable for electrification from the land, it equals to one for those fields which are supplied with electricity from the shore, zero otherwise; $prod_{it}$ is total oil and gas production (including NGL and condensate) for field i in year t; $sharegas_{it}$ is the share of gas produced on field i in year t; $size_i$ presents the original recoverable resources for field i; w_i and res_i show water depth and reservoir depth for field i respectively; oil_t is the oil price in year t; $carb_t$ is the price of 1 ton of CO_2 emissions in year t; c_i is unobserved effect and u_{it} are idiosyncratic disturbances. Variables with subscript *it* vary across fields and time, variables with subscript *i* vary only across fields, but constant over time, and variables with subscript *t* are the same for all fields but vary over time.

Production requires energy as input, hence it is reasonable to assume that increased production implies more energy use and therefore higher emissions, reduced production, on the contrary, implies less energy use and less emissions. Thus, we can expect coefficient for production to be positive. Figure 9 shows one of the fields where total emissions decline with declining production for most of the years, with the exception of 2004-2005.

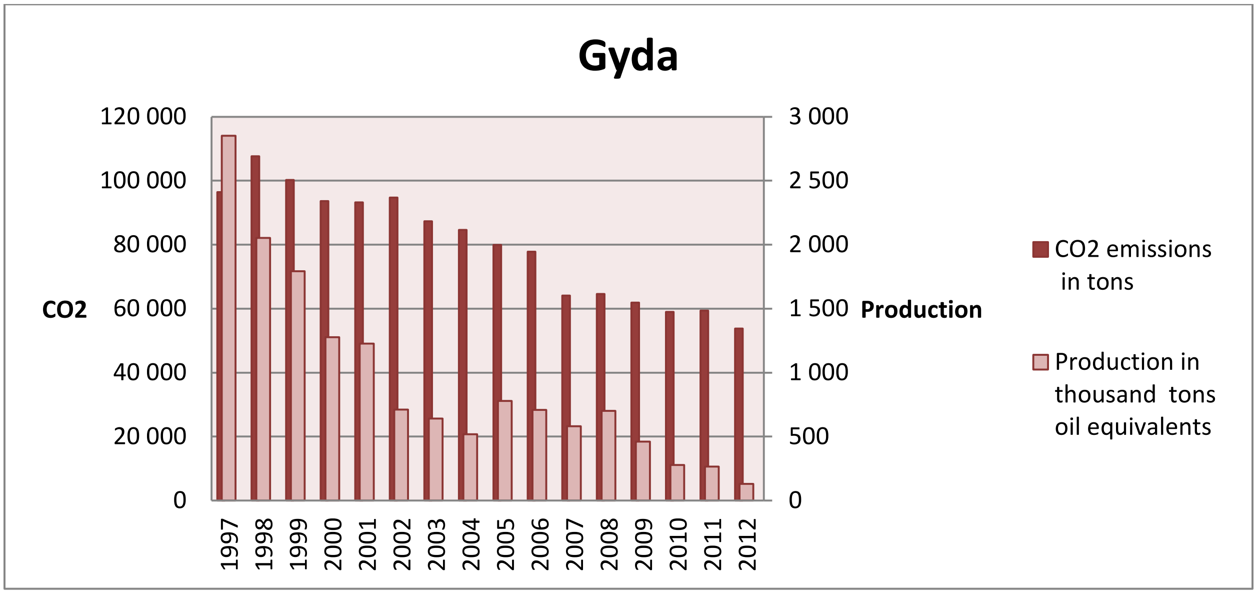


Figure 9. Total production and emissions on Gyda field for 1997-2012.

In some fields, like for example Brage in Figure 10, there seem to be somewhat inverse relation between production and emissions. Production for the years 1997 and 1998 is much higher than for the following years, but emissions are lower than for most of the following years.

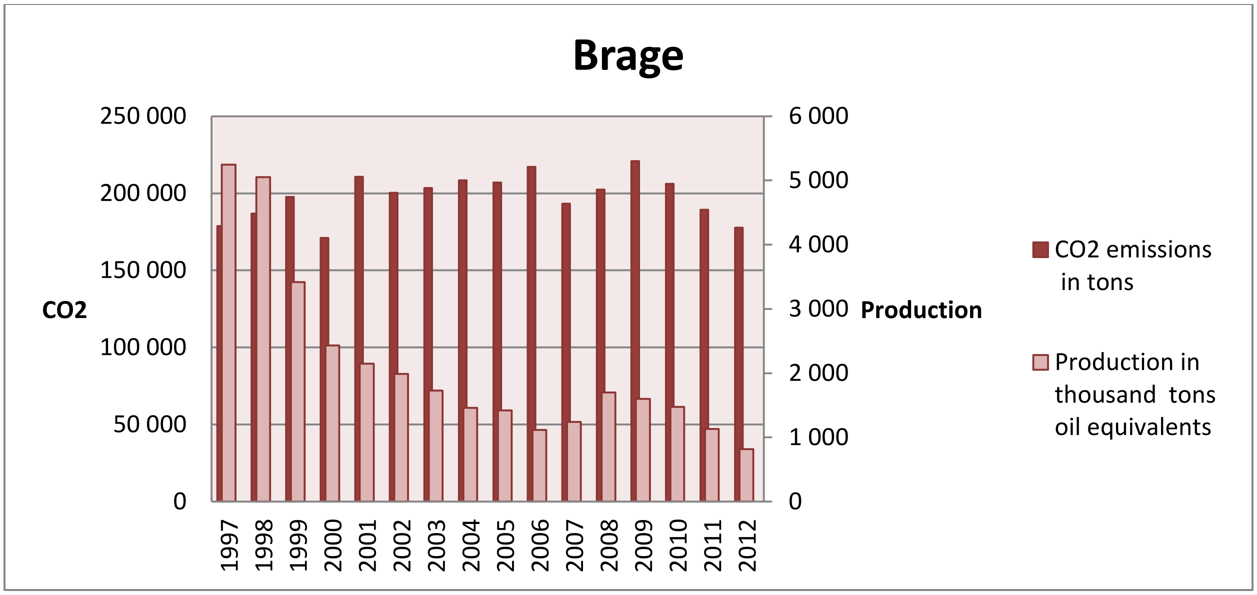


Figure 10. Total production and emissions on Brage field for 1997-2012.

On Njord field, however, there seem to be no observable relations between total production and total emissions, see Figure 11.

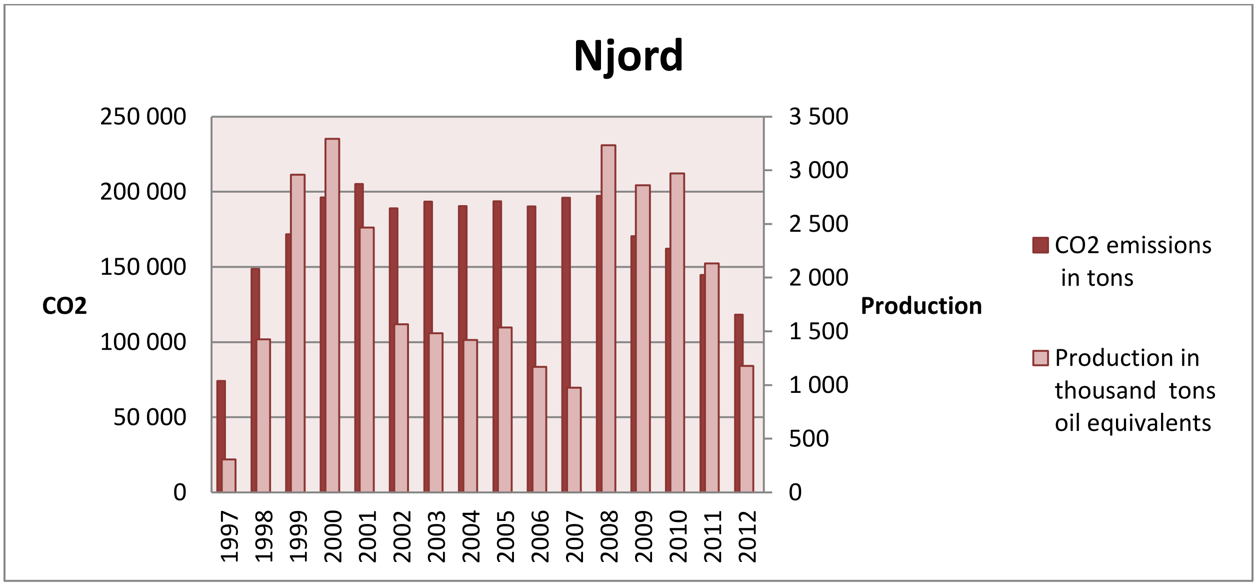


Figure 11. Total production and emissions on Njord field for 1997-2012.

Even though it seems difficult to establish positive or negative relationships between production and emissions by analyzing production/emissions figures, we expect the coefficient on production to be positive. We base our expectation on quite a natural assumption mentioned earlier, namely that more production suggests more emissions.

An earlier study showed that CO_2 emissions from gas fields are lower than CO_2 emissions from oil fields (Fæhn et al. 2013). Thus, we expect a share of produced gas to have a negative sign.

The deeper the reservoir lies, the more energy is needed to develop oil or gas. Thus, we assume that reservoir depth will have a positive sign. The same reasoning is applied for water depth in the area. Alternatively, total depth, which is the sum of water depth and reservoir depth, could have been used, but we decided to study them separately to estimate the effect of each value.

Original recoverable reserves determine how much will be produced in the field in the upcoming years. One might wonder about multicollinearity issue between total production and size of the field and the problem of extrapolating the results to new data. This is a reasonable argument, moreover, correlation numbers are high for production and size of the field see appendix A. We, however, think that it is important to have both variables in the model: original recoverable reserves are time invariant, they capture differences across fields, while production is time variant and captures the effect over a field's lifetime. Therefore, we chose to keep both variables. We find justification for such decision in Gujarati and Porter (2009), according to them, presence of multicollinearity does not affect efficiency of applying estimators to a new dataset if the new data has the same pattern of multicollinearity as the original model. We cannot state with certainty which sign the size of the field will have, but we expect it to have the same sign as production (positive).

As far as oil price is concerned, it can have both, a negative and a positive effect. Gas and diesel are main sources of emissions offshore. Oil and gas prices are usually highly correlated. In the model we view oil price as proxy for diesel and gas consumption cost, thus we expect the coefficient to have a negative sign. However, high oil price makes it profitable even for high-cost producers to develop recourses, which presupposes positive sign on oil price coefficient. Thus, it is hard to say which effect will dominate.

Electrification considerably reduces emissions linked to electricity production offshore, thus we expect the coefficient to be negative.

Carbon price is expected to have a negative effect on total emissions.

4.2.2 Model 2

The model with emission intensity as dependent variable can be formulated in the following way:

$$\log(empt_{it}) = \beta_0 + \delta_0 elect_i + \beta_1 \log(sharegas_{it}) + \beta_2 \log(share_{it}) + \beta_3 \log(size_i) + \beta_4 \log(w_i) + \beta_5 \log(res_i) + \beta_6 \log(carb_t) + \beta_7 \log(oil_t) + c_i + u_{it} \qquad (4.2)$$

where $empt_{it}$ is emission intensity for field i in year t; $share_{it}$ is the percentage of maximum production achieved on field i in year t; annual production per field could not be included in the model because of collinearity; other variables were mentioned in the description of the previous model. We made the same transformation with share of produced gas and share of gas of original recoverable resources as in model 1, i.e. added 1 before taking natural logarithms.

Expectations to the signs of coefficients of share of gas production, water and reservoir depth, electrification oil price and carbon price are the same as in the previous model.

Phase of production is expected to have a negative sign. Both initial and declining phase have low values for share of top production and we expect the fields to have higher emission intensities in these periods. During initial phase, when production is very low, there might be high energy use independent of production volume which becomes noticeable when little volumes are produced. In the decline phase, when pressure in reservoir gets lower, more energy is needed to produce one unit, hence emission intensity is higher (Ministry of Petroleum and Energy 2007). Higher production per field per year yields higher share of top production for that year. We can clearly see the inverse relationship between production and emission intensity in Figure 12. The figure is for the field Balder, but this seems to be the case for most of the fields, see appendix B.

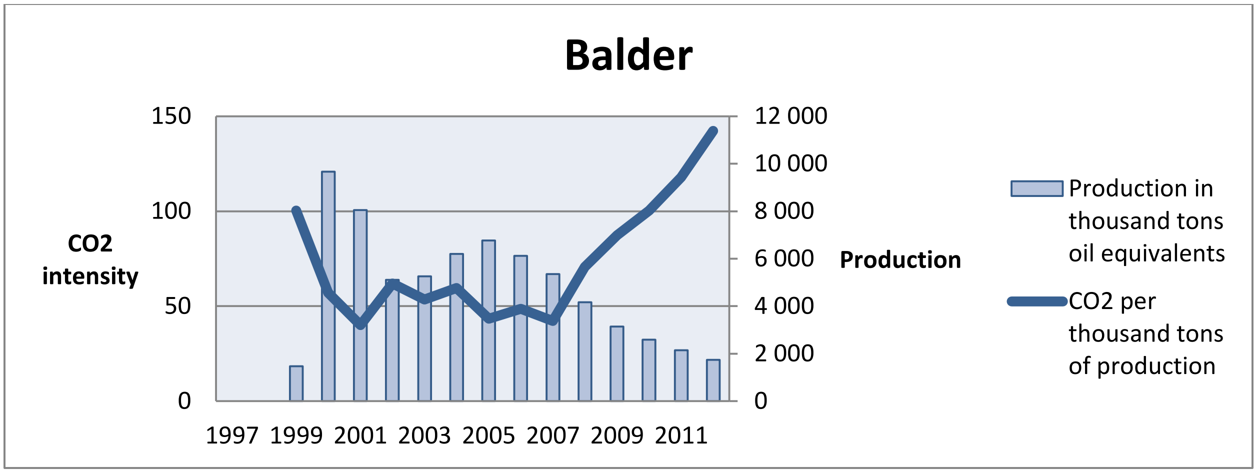


Figure 12. Emission intensity and total production for Balder field 1997-2012.

Also we expect the size of the field to have a negative size. We base our expectation on earlier research which states that, in case of Norway, smaller fields have had higher emission intensity historically (Fæhn et al. 2013).

Expectations about signs of variables' coefficients are summarized in Table 2.

Table 2. A priori expectations for variables' signs.

Variable	Explanation	Expected sign model 1 (emissions)	Expected sign model 2 (emission intensity)
$prod_{it}$	Production in thousand tons oil equivalents for the field i in year t	+	n/a
$sharegas_{it}$	Share of gas produced on the field i in the year t	_	_
$share_{it}$	Phase of production expressed in percentage of maximum production	n/a	_
$size_i$	Original recoverable reserves in million standard cubic meters oil equivalents	+	_
w_i	Water depth in meters	+	+
res_i	Reservoir depth in meters	+	+
oil_t	Oil price in NOK per barrel in 2012 prices	+/ _	+/ _
$carb_t$	Price of 1 ton of CO2 NOK in 2012 prices	_	_
$elect_i$	Dummy variable for electrification from the shore	_	_

4.3 Method

The type of data analyzed in this thesis is panel data, where we study 43 fields for the period 1997-2012. The data set is unbalanced because not all of the fields have been operating during the whole period of study, some, like Edda and Cod, finished production in 1998 and other fields, like Kristin or Gjøa, started production only in 2005 and 2010 respectively. Panel data can be studied using several techniques, three of most commonly used are pooling independent cross sections across time (pooled OLS), using fixed effects model or using random effects model.

As Gujarati and Porter (2009) briefly explain, in pooled OLS model all observations are estimated together, neglecting both, cross section and time series character of the data. The model presupposes that there is no distinction between fields, an assumption which is difficult to maintain. In POLS model the intercept is common for all units.

Main difference between fixed and random effect models lies in the assumption about the unobserved effect. Let us recall the basic unobserved effects model presented by Wooldridge (2002):

$$y_{it} = \beta x_{it} + c_i + u_{it}$$

where x_{it} presents observable variables that change either across time and units or across either of dimensions; β is the slope coefficient, c_i is the unobserved effect (also called unobserved heterogeneity) and u_{it} are idiosyncratic disturbances.

In random effects model zero correlation between the observed explanatory variables and the unobserved effect is assumed (Wooldridge 2002). This is a strong assumption which is difficult to fulfil in real life research.

Fixed effects model allows for arbitrary correlation between c_i and x_{it} (Wooldridge 2002). In this model regression is run on “de-meaned” variables – this does not allow to estimate variables which do not vary over time (Gujarati & Porter 2009).

There can be situations when it is essentially important to estimate the effect of time-invariant variables, even though fixed effects model is the statistically preferred one. In this case, according to Wooldridge (2002), we can either use random effects model or apply instrumental variable regression.

4.3.1 Model 1

As mentioned above, in the first model we study what influences total annual CO_2 emissions per field, for model specification, see equation 4.1.

We started data analysis with running pooled OLS regression with corrected standard errors and tested whether we can use POLS. We tested lagged residuals for significance and ran Breusch and Pagan Lagrange Multiplier test for random effects. The results showed that the model suffers from unobserved effects and POLS was not an appropriate method.

We then ran both, fixed effects and random effects, models with robust standard errors and year dummy variables. In order to decide which model is consistent, we tested the assumption about correlation between observable variables and the unobserved effect. The Hausman test showed statistically significant difference between the random effects and fixed effects estimates, which means the fixed effects model is the statistically correct one. However, the way our model is specified, it has four time-invariant variables (size, water depth, reservoir depth and electrification) which are important for us to estimate. Our options were, as mentioned above, to either state the random effects model results or to run an instrumental variable regression. We chose to run Hausman-Taylor IV estimation which accommodates random effects model with endogeneity of observed variables and generates coefficients for the time-constant variables. We ran post estimation test on overidentifying restrictions. The results of the test showed that the specified subset of the independent variables was uncorrelated with the fixed effect term or, in other words, the assumptions for the validity of HT estimation were not violated. We also ran Hausman test to check if Hausman-Taylor coefficients were consistent, the results of the test showed that the difference in estimators between fixed effects model and Hausman-Taylor regression was not systematic and that Hausman-Taylor coefficients were consistent.

4.3.2 Model 2

Second model estimates how independent variables influence emission intensity, see equation 4.2 for model specification.

Analysis of this model followed the same algorithm as described under model 1. The final estimation was the Hausman-Taylor instrumental variable regression. The post estimation test showed that the chosen instruments were strong and that estimates were consistent.

4.3.3 Estimation issues

We sought to find most statistically correct model to describe what influences emissions and emission intensity. However, one of the fundamental assumptions in statistics is that sample is randomly drawn from a bigger population. This assumption is a priori violated in our case because we were looking at all the oil and gas fields on the Norwegian continental shelf that report emissions and production in Norway. Thus, the estimators we got were inconsistent according to statistical theory. It is worth mentioning though, that violation of this assumption is quite common in empirical studies.

Since Hausman-Taylor regression is modified random effects model we face the potential omitted variables problem and the estimates may be biased.

5 Results and Discussion

5.1 Model 1

Table 3 shows regression results for model 1 using fixed effects, random effects models and Hausman-Taylor regression for comparison[3]. We concluded that HT was the most statistically correct model which allowed us to estimate the variables of interest, both time-variant and time-invariant. We can clearly see from the table that coefficients of HT regression are closer to the fixed effects results, than to the random effects coefficients.

Table 3. Model with emissions as dependent variable, table of results.

Variable	Random effects	Fixed effects	Hausman-Taylor regression
lnprod	**0.25*** **	**0.21*** **	**0.21*** **
	(0.04 /5.94)	(0.05/4.49)	(0.02/9.93)
lnsharegas	**-0.81*** **	**-0.47**	**-0.47** **
	(0.29/-2.76)	(0.30/-1.58)	(0.19/-2.41)
lnsize	**0.41*** **	(omitted)	**0.46*** **
	(0.11/3.74)		(0.11/4.23)
lnw	**0.32** **	(omitted)	**0.38* **
	(0.15/2.12)		(0.22/1.71)
lnres	**0.16**	(omitted)	**0.20**
	(0.39/0.41)		(0.43/0.45)
lncarb	**0.09**	(omitted)	**0.03**
	(0.21/0.40)		(0.1/0.31)
lnoil	**0.29**	**0.14**	**0.16*** **
	(0.19/1.52)	(0.12/1.21)	(0.05/3.14)
elect	**-3.18*** **	(omitted)	**-3.64*** **
	(1.09/-2.90)		(0.53/-6.93)
Constant	**3.37**	**9.7*** **	**3.91**
	(4.61/0.73)	(1.00/9.68)	(3.79/1.03)
N	497	497	497

Legend: * p<.1; ** p<.05; *** p<.01; standard error/t-value in parenthesis. Fixed and random effects models include year dummies, their estimates are not presented here.

---

[3] While investigating both models we ran regressions with lagged right-hand side variables, the results did not considerably influence main parameters and were not considered further.

Since our dependent variable and our continuous independent variables are in logarithmic forms, the interpretation of coefficients is quite clear, with the exception for share of produced gas.

Production appears to be highly statistically significant. Despite the lack of consistency in graphical analysis of production/emissions figures, the regression results showed that production coefficient has a positive sign; our expectations were correct. When production increases with 1%, emissions increase with 0.21%.

Size of the field is also highly statistically significant. In Chapter 4 we were not sure about the sign of original recoverable resources, but expected that it would be the same as the sign of production. The results showed that both, production and size, are positive, which corresponds to our prior expectations. Each percent increase in original recoverable resources gives 0.46% higher emissions.

The results show that oil price is of high statistical significance, which leads to 0.16% increase in emissions when it increases by 1%. This makes us conclude that, according to our model, higher oil price encourages even high cost producers to develop resources, which leads to higher total emissions and this effect dominates the cost effect.

The last highly significant variable is electrification. Interpretation of dummy variable is less straightforward since it is not a continuous variable. This peculiarity was noted for more than 30 years ago by Halvorsen and Palmquist (1980). In order to estimate the percentage effect of the dummy variable on emissions, we need to apply the formula: $100*(\exp(-3.64) - 1) \approx -97.4\%$. This means that, when a dummy changes from 0 to 1, there is 97.4% decrease in emissions. Some might think that electrification means zero emissions, in which case there should be 100% decrease. This is not quite true. Electrification reduces considerably but not necessarily completely emissions caused by electricity production offshore (e.g. burning of gas in turbines); however there still remain emissions due to flaring, well-testing, burning of diesel in engines and some emissions due to burning of gas in turbines.

We ran additional estimation[4] without the electrification dummy, but keeping all the fields. We were interested to see which variables bear the effect of lower emissions due to electrification in that case. The estimation report table can be found in appendix C. Among noticeable results were

---

[4] When we discuss additional estimations for model 1, we compare the results of the Hausman-Taylor regressions.

change in coefficient of share of produced gas from -0.47 to -0.49 and change in original recoverable resources (size) from 0.46 to 0.40.

Share of gas produced is significant at 5%. The coefficient is -0.47. We must remember that coefficient is for the natural logarithm of share of produced gas plus one, and this affects interpretation of the results. When actual share of gas increases from 0 to 0.01 (one percentage point increase), the share of gas plus 1 increases by 1% (from 1.00 to 1.01) and emissions then decrease by 0.47%. If actual share of gas increases from 0.99 to 1, the share of gas plus 1 increases by 0.5% (from 1.99 to 2) and emissions then decline by 0.24 % (0.5%*-0.47%). Thus, when actual share of gas increases by 1 percentage point, emissions are reduced between 0.24% and 0.47%, depending on what the share of produced gas was originally.

In order to assess if this effect was influenced by electrification, since three of four electrified fields are gas fields, we ran a regression without those electrified fields. Results of this regression are presented in appendix C. Main changes in parameters concern share of produced gas, production and original recoverable resources of the field. The size of the field coefficient increases from 0.46 to 0.56 and the level of significance is unchanged. Production coefficient increases as well from 0.21 to 0.24. The share of gas produced decreases from -0.47 to -0.54 and becomes highly statistically significant. From this we conclude that it is not only electrification of big gas fields which gives lower emissions per more gas produced. Gas production releases fewer emissions than oil (including NGL, condensate) due to some other factors.

We stated in chapter 4 that we will look at water and reservoir depth separately to evaluate the effect of each depth variable. However, we ran additional regression with total depth, which is the sum of water depth and reservoir depth. The results of this regression are in the appendix, the total depth coefficient was not statistically significant. In our main model water depth turned out to be significant at 10%, emissions increase by 0.38% with 1% increase in water depth in the field area. Reservoir depth, on the contrary, was not statistically significant. Thus, according to our study, water depth has a significant influence on total emissions but reservoir depth does not. It needs to be further investigated whether there is some technological explanation for this.

We expected carbon price to be negative, it turned out to be statistically insignificant. The discussion of possible reasons for this follows in the section on policy implications.

5.2 Model 2

Our second model investigates what influences emission intensity. In the beginning of this subchapter we would like to take a closer look at the development of emission intensity over time and at different ways to calculate it.

Table 4. Average emission intensity.

Year	Overall average emission intensity	Average emission intensity, adjusted	Average emission intensity per field, by Stata	Observations	Std.deviation	Minimum	Maximum
1997	44	65	150	25	428	0.42	2184
1998	47	72	154	26	422	0.50	2205
1999	49	93	93	27	98	0.09	470
2000	52	76	76	27	51	0.07	273
2001	53	84	84	29	71	0.14	393
2002	50	69	69	28	37	0.12	147
2003	49	74	74	30	40	0.14	177
2004	50	76	76	31	43	0.77	163
2005	52	76	84	31	59	0.16	305
2006	51	83	83	32	53	0.16	206
2007	54	86	86	33	57	0.16	222
2008	56	91	91	35	64	0.27	290
2009	53	93	93	35	69	0.34	300
2010	54	99	108	36	88	0.31	414
2011	58	111	111	37	76	0.40	308
2012	55	137	137	36	125	0.19	675

Table 4 shows average emission intensity for the studied period calculated in three different ways. Overall average emission intensity (column two) is calculated by dividing total emissions for one year by total production in that year. This method of obtaining average emission intensity is used by OGP. Fæhn et al. (2013) calculated emission intensity for Norway for 2011 in the same way and they got 60 tons CO_{2e} per 1000 tons of oil equivalents. We got 58 for that year, quite a close result. If we, however, take a look on the average emission intensity calculated by Stata (column four), we see that it is almost two times higher, 111 tons CO_2 per 1000 tons of oil equivalents. Such dramatic difference can be explained by the calculation method. Stata calculated unweighted average emission intensity from emission intensities per each field, thus fields with very high emission intensity increase average value considerably. Number of observations, standard deviation, minimum and maximum values describe average emission intensity per field by Stata based on all fields in our dataset.

We can see that for 1997 and 1998 maximum average intensity was 2184 and 2205 respectively. Very high values result in average intensity of 150 and above. Norne started production in 1997 and Varg in 1998 and these fields account for those *out of range* numbers. Emissions during the first year of production are not necessarily directly connected to production; they can be caused by prior energy intensive activities. Since very little is usually produced during the first year (e.g. production starts in November-December) intensity values can be "extreme". We calculated adjusted average emission intensity per field (column three), where we corrected for these extreme values in the first year of production: Norne 1997 (2184 tCO_2/1000to.e.), Varg 1998 (2205 tCO_2/1000to.e.), Kristin 2005 (305 tCO_2/1000to.e.) and Gjøa 2010 (414 tCO_2/1000to.e.).

Emission intensity in the decline phase also tends to be high: Frigg 1999 (470 tCO_2/1000to.e.) last year of production, Glitne 2012 (675 tCO_2/1000to.e.) last year of production, Gyda 2012 (413 tCO_2/1000to.e.) in the decline phase; Brage, Oseberg Øst, Veslefrikk have values above 200 tCO_2/1000to.e since 2006. All of the fields are in the decline phase. These fields stand for higher intensity values from 2006. Since many fields enter decline phase by the end of studied period, that is why we see gradual increase in emission intensity over time.

Minimum intensity values belong to Troll I, a big gas field which is electrified from the shore.

Analysis of descriptive statistics allowed us to conclude that fields in initial phase, as well as in the decline phase of production, have higher emission intensity than otherwise; electrification gives very low emission intensity. We proceed to the econometric analysis' results to see if they support our conclusions from the descriptive analysis.

Table 5 presents results of main emission intensity estimation. We base our discussion on Hausman-Taylor regression as it was the most statistically precise one, provided our interest in time-invariant variables.

Table 5. Model with emissions intensity as dependent variable, table of results.

Variable	Random effects	Fixed effects	Hausman-Taylor IV regression
lnsharegas	**-1.03***** (0.31/-3.32)	**-0.39** (0.33/-1.17)	**-0.37*** (0.22/-1.66)
lnshare	**-0.69***** (0.05/-13.18)	**-0.74***** (0.05/-13.99)	**-0.74***** (0.02/-30.08)
lnsize	**-0.07** (0.09/-0.78)	(omitted)	**-0.07** (0.11/-0.64)
lnw	**0.19** (0.16/1.16)	(omitted)	**0.29** (0.22/1.29)
lnres	**0.44** (0.36/1.22)	(omitted)	**0.46** (0.43/1.07)
lncarb	**0.02** (0.22/0.11)	(omitted)	**0.07** (0.11/0.62)
lnoil	**0.14** (0.21/0.68)	**0.01** (0.14/0.07)	**0.09** (0.06/1.46)
elect	**-2.78***** (0.93/-2.98)	(omitted)	**-3.37***** (0.53/-6.41)
Constant	**-1.33** (4.42/-0.30)	**3.35***** (0.83/4.04)	**-2.10** (3.80/-0.55)
N	497	497	497

Legend: * p<.1; ** p<.05; *** p<.01; standard error/t-value in parenthesis. Fixed and random effects models include year dummies, their estimates are not presented here.

As we can see from Table 5, original recoverable resources, water and reservoir depth, oil price and price of carbon turned out to be of no statistical significance. Phase of production and electrification, however, are highly statistically significant.

We expected the coefficient for the size of the field to be negative. We based our expectation on the earlier research which mentioned that smaller fields had higher emission intensity historically (Fæhn et al. 2013). We did not find support for the statement. The coefficient on the size of the field turned out to be not statistically significant which doesn't allow us to discuss the sign of coefficient.

The coefficient for share of production is -0.74. The coefficient shows percentage change when a share of production is originally 1. If a share of production changes with one percentage point from 0.99 to 1, the emission intensity reduces by 0.74%; if it changes with one percentage point from 0.49 to 0.50, the emission intensity reduces by 1.48%; if a share of production changes with one percentage point from 0.09 to 0.10, emission intensity decreases by 7.4%. In the converse situation, emission intensity increases by 7.4% if phase of production reduces from 0.10 to 0.09. Thus, the effect of changes in emission intensity due to changes in phase of production is stronger, the lower the original phase of production is. This interpretation is due to the chosen functional form. Low phase of production characterizes both, initial and decline phases in a field's lifetime. Coefficient result supports our expectation about the sign in chapter 4.

A share of produced gas is significant at 10%, the coefficient is -0.37. In this model we also have to remember that coefficient is for a share of produced gas plus one, which affects interpretation of the results. If an actual share of produced gas changes with 1 percentage point, emission intensity reduces between 0.19% and 0.37%, depending on what the share of produced gas was initially.

As we discussed both, in chapter 4 and earlier in chapter 5, emission intensity tends to be higher the older the field gets; thus when we have a time-variant share of gas produced, it can be influenced by when in a field's lifespan gas extraction takes place. The effect of a share of gas production in the early years can be reinforced by the early stage with lower emissions, while the effect of gas production can be lower if gas is produced by the end of a field's lifetime. In order to see the "pure" gas production effect, we ran additional estimation[5] with a share of gas of original recoverable resources, time-invariant share of gas. Result table for this regression is in the appendix C. Electrification effect is lower in the new regression, the coefficient changes from -3.37 to -2.85. Time invariant share of gas production is significant at 5%, the coefficient is -1.5, while time variant share of gas was significant at 10%, the coefficient -0.37. From this we can conclude that the gas production effect may be higher than what the main model suggests, time of gas extraction influences emission intensity.

---

[5] When we discuss additional estimations for model 2, we compare the results of the Hausman-Taylor regressions.

In order to interpret the effect of electrification, we apply the formula mentioned earlier: 100*(exp(-3.37) –1) ≈ 96.56%. This implies that an electrified field has 96.6% lower emission intensity than a field which is not supplied with electricity from the shore.

As in model 1, we ran a regression without electrified fields. Our primary interest was to see if a share of produced gas coefficient changes. New results, which can be found in the appendix, showed changes in two significant variables, a share of total production and a share of produced gas. The phase of production changes from -0.74 to -0.71, the same level of significance. A share of gas becomes more significant: it was significant at 10 %, now it is significant at 5%, and the coefficient changes from -0.37, to -0.46. This change shows that gas production has lower emission intensity not only due to electrification.

In addition, we ran a model where we kept electrified from the shore fields, but did not include electrification dummy. We were interested to see which variables bear the effect of lower emissions due to electrification in that case. Table of results for this model is also in the appendix C. It is worth mentioning that a share of produced gas coefficient changes from -0.37 to -0.40, while a phase of production coefficient is unchanged and other variables are not statistically significant.

5.3 Policy implications

In March 2014 Norwegian Environment Agency published a report called "Scientific basis for further development of the national and international climate policy - Climate measures for 2020 and plan for further work" (Norwegian Environment Agency 2014). The report specifies that at the moment there is a 7.5 million tons of CO_2e gap between expected emission reductions and the goal in emission reductions to be achieved by Norway by 2020. The report also underlines that considerable part of the emission reductions must be taken domestically.

Most recent publication (April 13, 2014) of the fifth IPCC assessment report, part on mitigation of the climate change (IPCC 2014), stressed again how acute the problem of domestic emission reductions in all the countries is, in order to achieve the 2 degrees goal. In Norway, among other sectors of economy, petroleum activity has big potential for emission reductions.

Even though the study has not delivered any breakthrough in understanding emissions from offshore, it supported some earlier findings and suggestions adding to their validity. We would like to draw attention to the three most valuable conclusions of this work.

Main source of emissions offshore is the burning of fuel in turbines (Norwegian Environment Agency 2014) therefore electrification of oil and gas fields leads to considerable reduction in these emissions. In the case of Norway, supplying fields with electricity from the shore is especially justified because it is produced dominantly by hydropower. Electrification of oil and gas fields has been assessed by the Norwegian Environment Agency and is already included in the emission reduction measure plan by 2020. According to the report, Utsira High Power Hub project will allow to electrify Johan Sverdrup, Edvard Grieg, Ivar Aasen and Gina Krogh fields by 2020 (Norwegian Environment Agency 2014).

A phase of production was significant in the model with emission intensity. Low percentage of top production characterizes both, the starting phase and the final phase of a field’s lifetime. While higher emissions and emission intensity during the first year (years) of field’s existence are acceptable and at the moment unavoidable, it might be worth considering production cessation earlier than what is common now. Finding an appropriate point of time for termination of oil and gas extraction needs further investigation, but the idea is worth being taken into consideration. This suggestion supports the conclusion of the study by Fæhn et al. (2013), but so far has not been accepted politically. Counter argument to this can be that companies pay for their emissions already and this will ideally imply that they have internalized the externality, unless the emission price is too low.

The price of environmental regulation which includes the price of emission tax and the quota price per 1 ton CO_2 equivalents was not significant in both models. One of the possible explanations for this is that it is simply too low to affect the behavior of petroleum producers. When a quota was introduced to the offshore sector in 2008, the existing at that time CO_2 tax was adjusted downwards so that the total environmental burden for the companies would be at approximately the same level. Because of unstable quota prices, which decreased gradually, the total cost of emitting CO_2 became even lower than before 2008 despite the fact that the offshore was regulated by two policy instruments. A low price does not give any incentives for petroleum companies to reduce emissions, hence quite straightforward measure seem to be to either adjust emission tax upwards or to take measures that increase the EU emission allowance prices, or both. However, increasing the cost of emissions will undoubtedly be highly politically unpopular and, taken into consideration the lobbying power from offshore companies, this measure will not be among the first ones to be implemented in the fight against warmer environment.

Another possible explanation for insignificant carbon price can be that it has partly long-term effect, e.g. adoption of new technology, increasing energy efficiency, and it is difficult to capture in this study. Moreover, we investigate the period 1997-2012, all this time the offshore sector was regulated by emission tax and later by both, tax and quota. In order to evaluate the pure effect of environmental regulation, we should capture the period before and after introduction of the emission tax in 1991.

6 Conclusion

In this work we followed emissions of 43 fields on the Norwegian continental shelf from 1997 to 2012. We evaluated how production, share of produced gas, phase of production, size of a field, water and reservoir depth, oil price, emission price and electrification affect emissions and emission intensity on fields.

6.1 Practical contribution

While analyzing results of the study we came up with several relevant conclusions, some of them could be incorporated in emission reduction plan:

- Gas production tends to produce fewer emissions than oil production. This effect is not only due to electrification of primarily gas fields, results of estimation without electrified fields confirmed the effect. Gas fields also seem to have lower emission intensity than oil fields. This is confirmed when we consider share of gas of original recoverable reserves instead of share of gas of annual production.

- Emission intensity tends to be higher when a field is either in initial or decline phase, in other words when share of maximum production is low. Earlier production cessation might be considered as emission reduction measure.

- According to our estimations higher oil price encourages more petroleum production and hence total emissions; this effect seems to dominate the cost effect.

- Water depth in the field area showed to have positive influence on total emissions.

- Our findings couldn’t support that smaller fields have higher emission intensity.

6.2 Limitations of the study

We faced problems with availability of data on emissions, sufficient and detailed database starts from 1997, and this limited our research to only 16 years. Ideally we would have covered all the period of activity on Norwegian Continental Shelf. We could also investigate how emissions and emission intensity vary over a field’s lifespan, but at the moment there are few fields which have already ceased production.

Another limitation of the study is the transformation we had to make with smaller fields tied to bigger fields. It would have given more precise results if emissions and production were reported for each separate field. This was not the case, however, and we had to undertake some modifications.

In addition we had limitations of econometric study mentioned in chapter 4.

6.3 Suggestions for further research

This study did not consider technological characteristics of fields. It is possible to carry on a study where technology variables are included, e.g. combined power cycle solutions, energy installations and energy efficiency parameters.

It is also possible to develop this study into a comparative study of Norwegian and United Kingdom continental shelf.

Another approach is to focus more on environmental policy measures, to obtain data before and after introduction of emission tax offshore to evaluate the effect of regulation.

Possible future research might also be to distinguish between various emission sources offshore and incorporate information about gas use from the Norwegian Petroleum Directorate which dates back to 1970s.

Reference List

Bovenberg, A. L. & Mooij, R. A. d. (1994). Environmental Levies and Distortionary Taxation. *The American Economic Review*, 84 (4): 1085-1089.

BP. (2013). *BP Statistical Review of World Energy June 2013*. Available at: http://www.bp.com/content/dam/bp/pdf/statistical-review/statistical_review_of_world_energy_2013.pdf (accessed: 24.04.2014).

Bruvoll, A. & Dalen, H. M. (2009). Pricing of CO2 emissions in Norway. *Statistics Norway, Documents*, 16. Available at: https://www.ssb.no/a/english/publikasjoner/pdf/doc_200916_en/doc_200916_en.pdf (accessed: 15.02.2014).

Böhringer, C. & Lange, A. (2005). On the Design of Optimal Grandfathering Schemes for Emission Allowances. *European Economic Review*, 49 (8): 2041-2055.

Charpentier, A. D., Bergerson, J. A. & MacLean, H. L. (2009). Understanding the Canadian Oil Sands Industry's Greenhouse Gas Emissions *Environmental Research Letters*, 4 (1).

Climate Agreement. (2008). *Climate Agreement*: Government (Regjeringen). Available at: http://www.regjeringen.no/upload/MD/Vedlegg/Klima/avtale_klimameldingen.pdf (accessed: 15.02.2014).

Cramton, P. & Kerr, S. (2002). Tradeable Carbon Permit Auctions: How and Why to Auction not Grandfather. *Energy Policy*, 30 (4): 333-345.

EU Comission. (2007). *Decision of the EEA Joint Committee No 146/2007 of 26 October 2007*. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:22007D0146:EN:NOT (accessed: 15.02.2014).

Fischer, C., Parry, I. W. H. & Pizer, W. A. (2003). Instrument Choice for Environmental Protection When Technological Innovation is Endogenous. *Journal of Environmental Economics and Management*, 45 (3): 523-545.

Fæhn, T., Hagem, C., Lindholt, L., Mæland, S. & Rosendahl, K. E. (2013). Climate policies in a fossil fuel producing country. Demand versus supply side policies. *Discussion Papers (747), Statistics Norway, Research department*.

Goulder, L. H. (1995). Environmental Taxation and the Double Dividend: A reader's Guide. *International Tax and Public Finance*, 2 (2): 157-183.

Goulder, L. H., Parry, I. W. H. & Burtraw, D. (1997). Revenue-Raising versus Other Approaches to Environmental Protection: The Critical Significance of Preexisting Tax Distortions. *The RAND Journal of Economics*, 28 (4): 708-731.

Goulder, L. H. (2013). Markets for Pollution Allowances: What Are the (New) Lessons? *Journal of Economic Perspectives*, 27 (1): 87-102.

Greaker, M. & Pade, L.-L. (2009). Optimal carbon dioxide abatement and technological change: should emission taxes start high in order to spur R&D? *Climatic Change*, 96 (3): 335-355.

Gujarati, D. N. & Porter, D. C. (2009). *Basic Econometrics*. Fifth Edition ed. International edition: McGraw Hill.

Gujarati, D. N. (2011). *Econometrics by Example*: Palgrave Macmillan. 372 pp.

Halvorsen, R. & Palmquist, R. (1980). The Interpretation of Dummy Variables in Semilogarithmic Equations. *American Economic Review*, 70 474–475.

Hoel, M. (1998). Emission Taxes versus Other Environmental Policies. *The Scandinavian Journal of Economics*, 100 (1): 79-104.

Howe, C. W. (1994). Taxes versus Tradable Discharge Permits: A Review in the Light of the U.S. and European Experience. *Environmental and Resource Economics*, 4 (2): 151-169.

IPCC. (2014). *Climate Change 2014: Mitigation of Climate Change*. The Fifth Assessment Report (AR5) Intergovernmental Panel on Climate Change. Available at: https://www.ipcc.ch/report/ar5/wg3/ (accessed: 05.05.2014).

Karp, L. & Zhao, J. (2009). *Suggestions for the Road to Copenhagen*. CUDARE Working Paper No. 1085: Department of Agricultural & Resource Economics, University of California.

McKibbin, W. J. & Wilcoxen, P. J. (1997). A Better Way to Slow Global Climate Change *Brookings Policy Brief No 17, The Brookings Institution*.

Ministry of Petroleum and Energy. (2007). *Emissions to Air from the Petroleum Sector*. Available at: http://www.regjeringen.no/en/dep/oed/Subject/carbon-capture-and-storage/emissions-to-air-from-the-petroleum-sect.html?id=443519 (accessed: 03.05.2014).

Ministry of Petroleum and Energy. (2014). *Oil and Gas*. Available at: http://www.regjeringen.no/en/dep/oed/Subject/oil-and-gas.html?id=1003 (accessed: 24.04.2014).

Moe, O. B. (2013). Facts and Fiction about Energy (Fakta og Fiksjon om Energi). *Dagens Næringsliv 06.09.2013*, pp. 48-49.

Moe, T. (2010). Norwegian Climate Policies 1990-2010: Principles, Policy Instruments and Political Economy Aspects. *CICERO* (03).

Norwegian Environment Agency. (2014). *Scientific Basis for Further Development of the National and International Climate Policy - Climate Measures for 2020 and Plan for Further Work (Faglig grunnlag for videreutvikling av den nasjonale og internasjonale klimapolitikken - Klimatiltak mot 2020 og plan for videre arbeid)*. Available at: http://www.miljodirektoratet.no/Documents/publikasjoner/M133/M133.pdf (accessed: 29.04.2014).

NPD. (2013). *Facts 2013 the Norwegian Petroleum Sector*: Norwegian Petroleum Directorate, Ministry of Petroleum and Energy. Available at: http://npd.no/en/Publications/Facts/Facts-2013/ (accessed: 03.05.2014).

OGP. (2013). *Environment Performance Indicators – 2012 data*. OGP Data Series: International Association of Oil and Gas Producers. Available at: http://www.ogp.org.uk/publications/environment-committee/environmental-performance-indicators/environment-performance-indicators-2012-data/ (accessed: 29.04.2014).

Osmundsen, P. (2011). Expensive measures with no effect (Dyrt tiltak uten virkning) *Dagens Næringsliv 19.12.2011*, p. 26.

Pizer, W. A. (2002). Combining Price and Quantity Controls to Mitigate Global Climate Change. *Journal of Public Economics*, 85 (3): 409-434.

Pizer, W. A. & Popp, D. (2008). Endogenizing technological change: Matching empirical evidence to modeling needs. *Energy Economics*, 30 (6): 2754-2770.

Roberts, M. J. & Spence, M. (1976). Effluent Charges and Licenses under Uncertainty. *Journal of Public Economics*, 5 (3–4): 193-208.

Romstad, E. (2014). Economic Instruments: the Importance of Incentives, Emission Taxes and Tradable Emission Permits. . *Lecture notes in Environmental Economics, Norwegian University of Life Sciences*.

Rosendahl, K. E. (2004). Cost-effective environmental policy: implications of induced technological change. *Journal of Environmental Economics and Management*, 48 (3): 1099-1121.

Rosendahl, K. E. (2011). Slowdown in oil extraction is a cheap climate cure (Oljebrems er billig klimakutt). *Dagens Næringsliv 16.12.2011*, p. 3.

Rosendahl, K. E. (2013). Policy measures. *Lecture notes in Climate Economics, Norwegian University of Life Sciences*.

Sadoulet, E. & De Janvry, A. (1995). *Quantitative Development Policy Analysis*. Johns Hopkins Univ. Press, Baltimore.

Silberberg, E. & Suen, W. (2001). *The Structure of Economics: A Mathematical Analysis*.

Solhjell, B. V. (2013). Facts Must Have Power (Fakta må ha makta). *Dagens Næringsliv 04.09.2013*, p. 3.

Sorrell, S. & Sijm, J. (2003). Carbon Trading in the Policy Mix. *Oxford Review of Economic Policy*, 19 (3): 420-437.

SSB. (2014). *Emissions of greenhouse gases, 1990-2012, final figures*: Statistics Norway (Statistisk Sentralbyrå). Available at: http://www.ssb.no/en/klimagassn/ (accessed: 24.04.2014).

Varian, H. R. (1992). *Microeconomic Analysis*. 3rd. ed.: W W Norton and Company.

Weitzman, M. L. (1974). Prices vs. Quantities. *The Review of Economic Studies*, 41 (4): 477-491.

Weitzman, M. L. (1978). Optimal Rewards for Economic Regulation. *The American Economic Review*, 68 (4): 683-691.

Woerdman, E., Clò, S. & Arcuri, A. (2008). European Emissions Trading and the Polluter-Pays Principle: Assessing Grandfathering and Over-Allocation. In Faure, M. G. & Peters, M. (eds) *Climate Change and European Emissions Trading: Lessons for Theory and Practice*, pp. 128- 150. Cheltenham, UK: Edward Elgar Publishing.

Wooldridge, J. M. (2002). *Econometric Analysis of Cross Section and Panel Data*: The MIT Press.

Appendix A

1. Overview of the tied fields.

MAIN FIELD NAME	Tied field name
ALVHEIM	Vilje, Volund
BALDER	Jotun
ELDFISK	Embla
GJØA	Vega and Vega Sør
GULLFAKS	Gimle, Tordis Øst,Borg; Visund Sør, Gullfaks Sør
HEIMDAL	Atla, Huldra, Skirne, Vale
KRISTIN	Tyrihans
NORNE	Alve, Marulk, Urd
OSEBERG	Tune
SLEIPNER ØST+ VEST (1997-2002)	Gungne, Sleipner Øst, Sleipner Vest
SLEIPNER ØST (2003-2012)	Gungne, Sigyn
SNORRE	Vigdis
STATFJORD	Sygna, Statfjord Nord, Statfjord Øst
TROLL II	Fram
ULA	Tambar, Olsevar
VALHALL	Hod
ÅSGÅRD	Mikkel, Morvin, Yttergryta

2. Correlation between variables

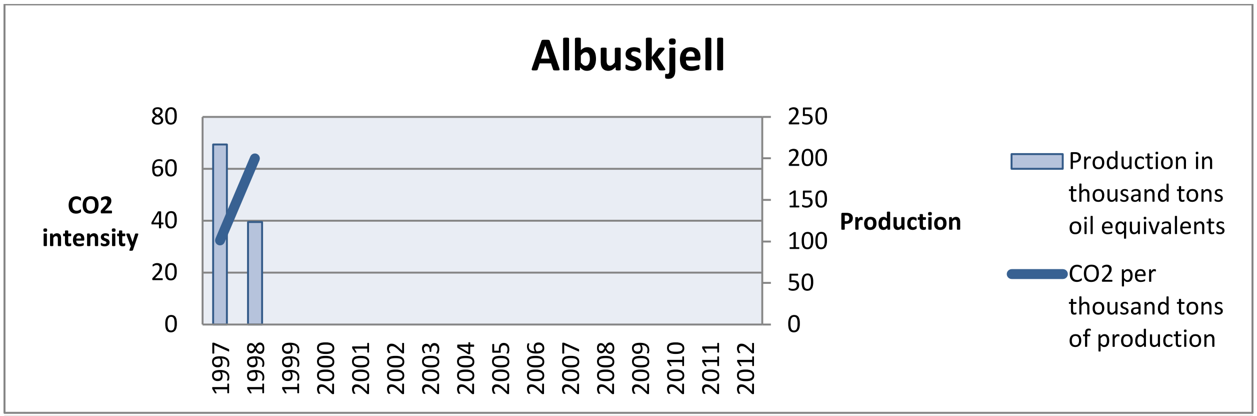
```
             |     emis   emispt     prod sharep~d sharegas    gasor     size    water reserv~r   carbon      oil    elect
-------------+------------------------------------------------------------------------------------------------------------
        emis |   1.0000
      emispt |  -0.0508   1.0000
        prod |   0.5973  -0.2920   1.0000
   shareprod |   0.1475  -0.3771   0.5459   1.0000
    sharegas |  -0.0699  -0.1288   0.3143   0.0491   1.0000
       gasor |  -0.1367  -0.0750   0.2010   0.0147   0.8498   1.0000
        size |   0.3786  -0.1706   0.7465   0.2161   0.3817   0.2900   1.0000
       water |   0.0019  -0.0824   0.3089   0.2447   0.1693   0.2198   0.1540   1.0000
   reservoir |   0.0346   0.0756  -0.1603  -0.0844   0.0019   0.1636  -0.2118  -0.0928   1.0000
      carbon |   0.0517   0.0260   0.1059   0.1417  -0.0250   0.0140   0.0364  -0.0892  -0.0131   1.0000
         oil |  -0.0627  -0.0009  -0.1181  -0.1625   0.0459  -0.0060  -0.0414   0.0937   0.0281  -0.8184   1.0000
       elect |  -0.2148  -0.1209   0.4177   0.1707   0.5231   0.4823   0.6167   0.4629  -0.2468  -0.0734   0.0755   1.0000
```

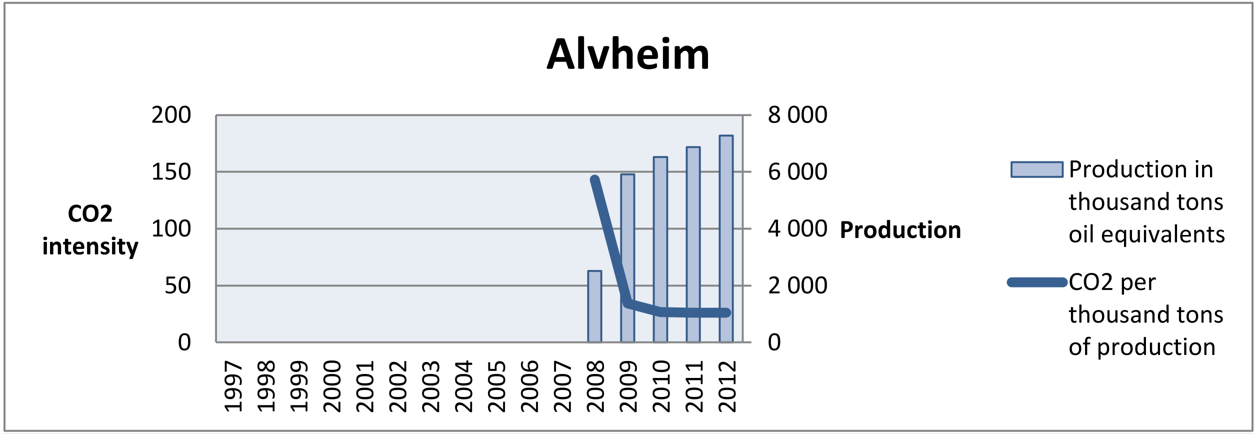
3. Correlation between variables in logarithmic form

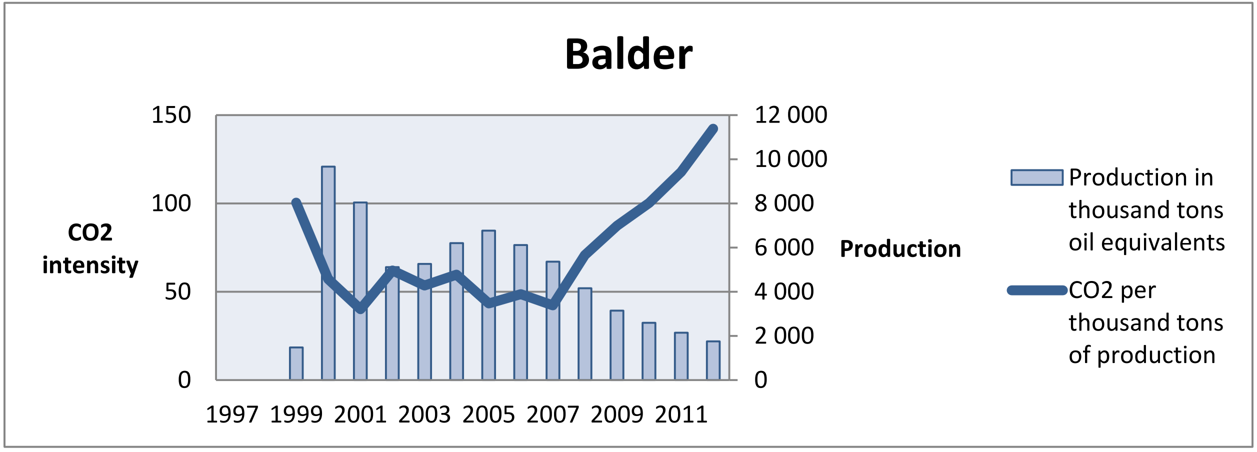
```
             |     lnem   lnempt  lnshare    lnoil   lncarb   lnprod lnshar~s   lnsize      lnw    lnres  lngasor    elect
-------------+------------------------------------------------------------------------------------------------------------
        lnem |   1.0000
      lnempt |   0.4287   1.0000
     lnshare |   0.2671  -0.4801   1.0000
       lnoil |   0.0322   0.0586  -0.0740   1.0000
      lncarb |  -0.0184  -0.0652   0.0950  -0.8318   1.0000
      lnprod |   0.5006  -0.5673   0.7038  -0.0259   0.0450   1.0000
  lnsharegas |  -0.2786  -0.4739  -0.0504   0.0452  -0.0409   0.2052   1.0000
      lnsize |   0.3680  -0.4620   0.2921  -0.0311   0.0310   0.7766   0.2880   1.0000
         lnw |   0.0751  -0.3322   0.2790   0.0882  -0.0825   0.3840   0.0946   0.2764   1.0000
       lnres |   0.0839   0.3763  -0.1405   0.0176  -0.0091  -0.2845   0.0022  -0.2042  -0.2305   1.0000
     lngasor |  -0.2943  -0.3679  -0.0809  -0.0083   0.0088   0.0873   0.8339   0.2466   0.1364   0.1735   1.0000
       elect |  -0.5269  -0.7665   0.1373   0.0672  -0.0800   0.2540   0.4987   0.3485   0.3617  -0.3042   0.4587   1.0000
```

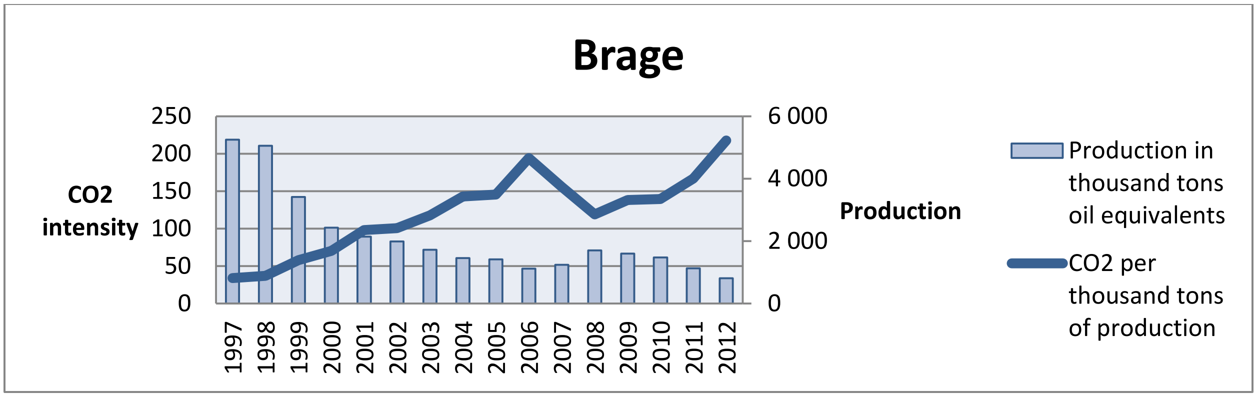
Appendix B

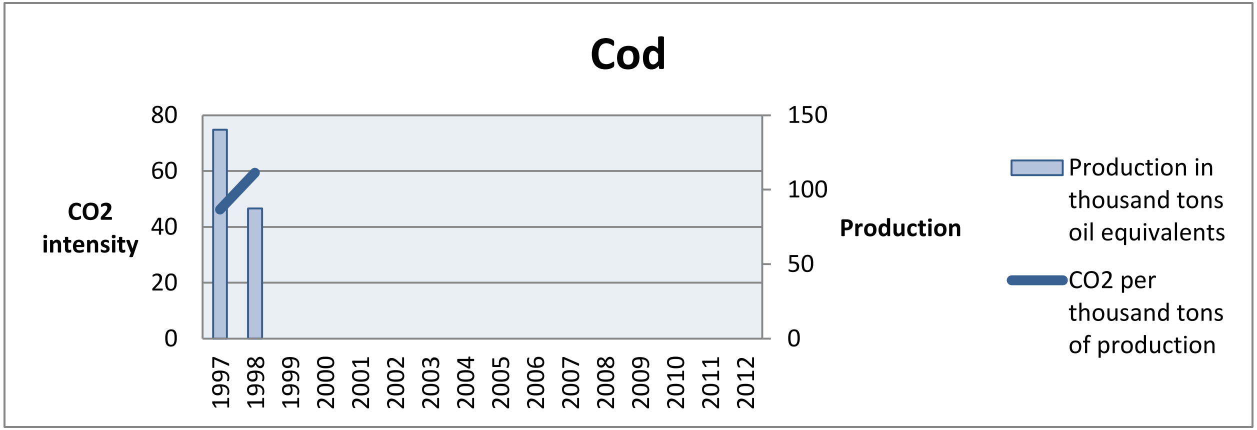
Emission intensity and production. Fields marked with asterix are electrified from the shore.

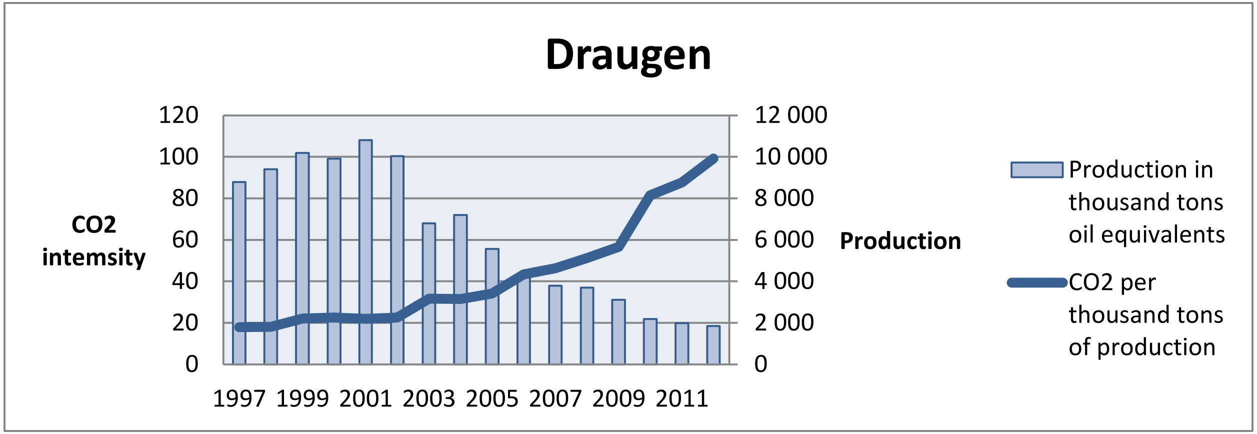


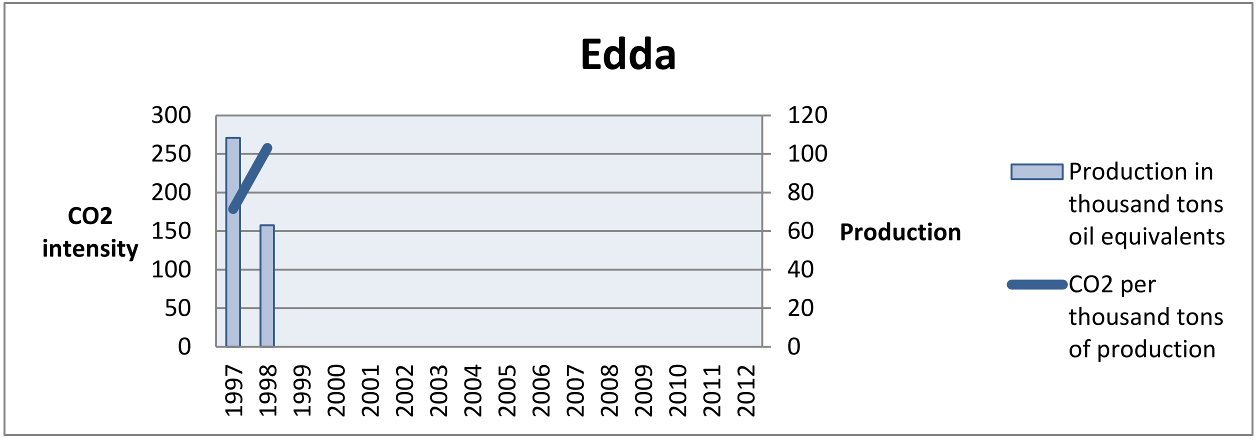


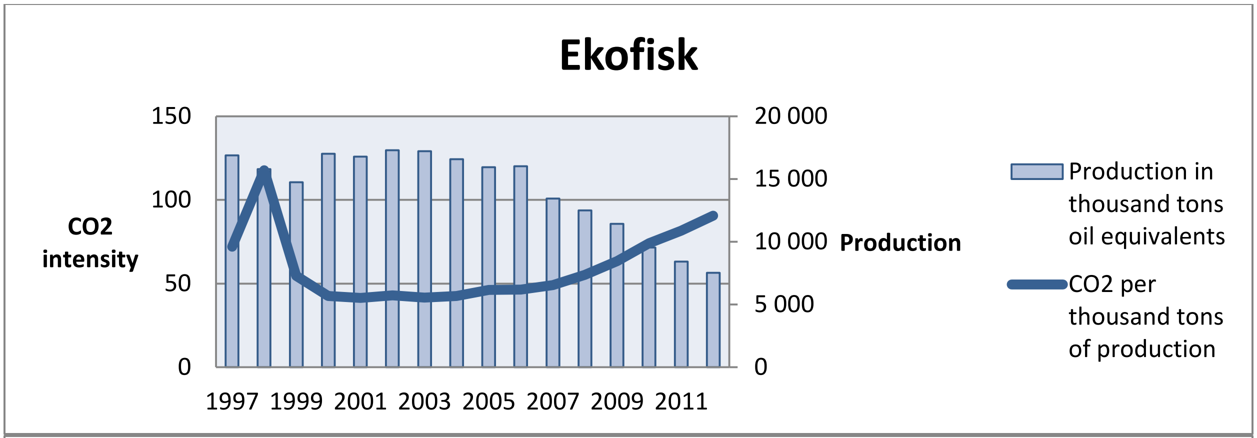


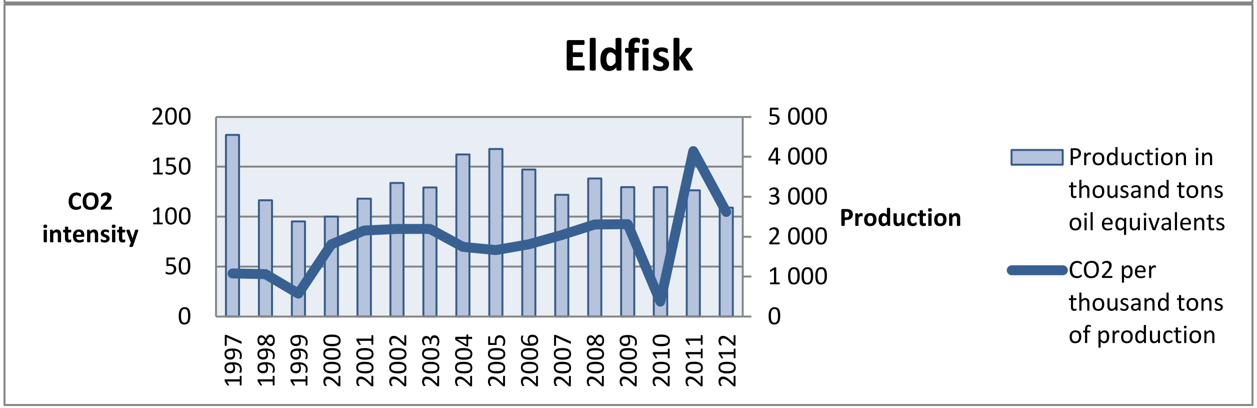

Brage
CO2 intensity
250
200
150
100
50
0
6 000
4 000
2 000
0
Production
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

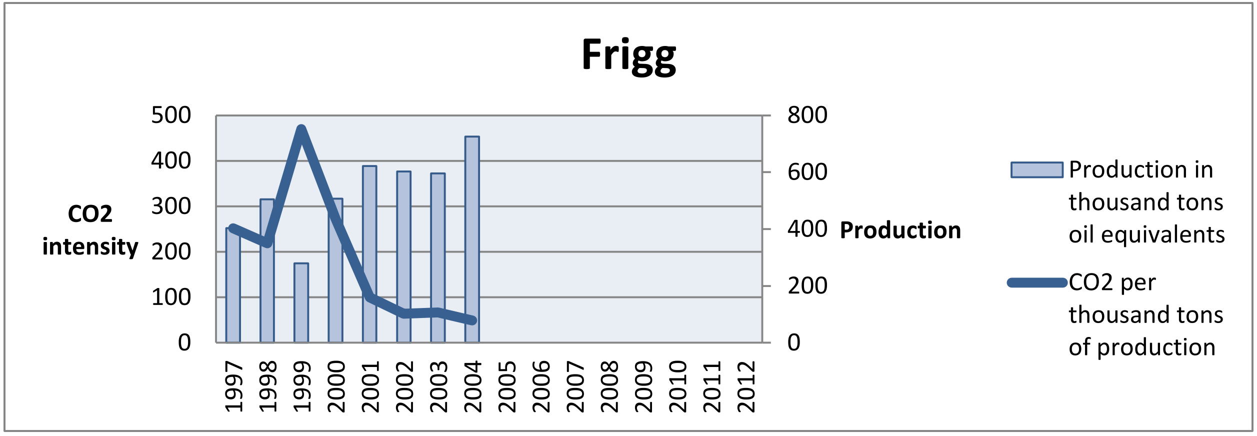

Cod
CO2 intensity
80
60
40
20
0
150
100
50
0
Production
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

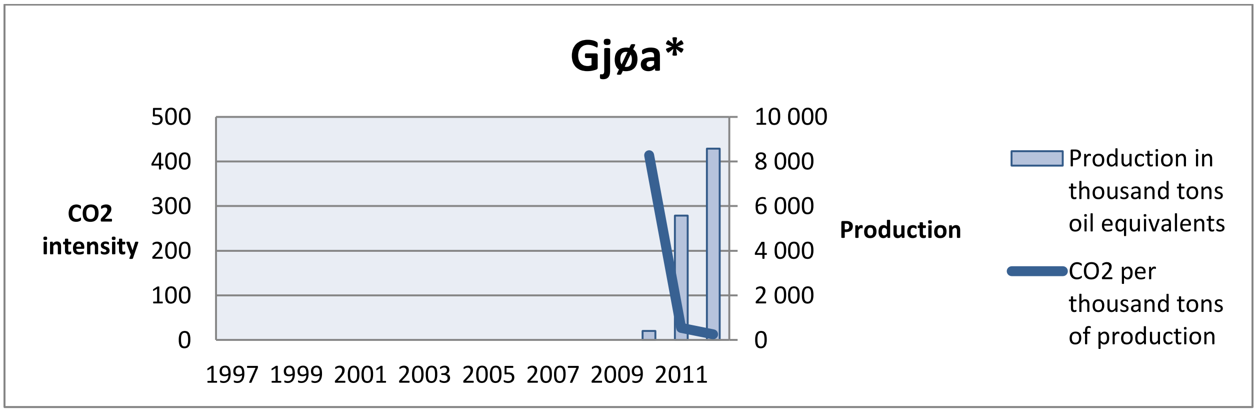

Draugen
CO2 intemsity
120
100
80
60
40
20
0
12 000
10 000
8 000
6 000
4 000
2 000
0
Production
1997 1999 2001 2003 2005 2007 2009 2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production

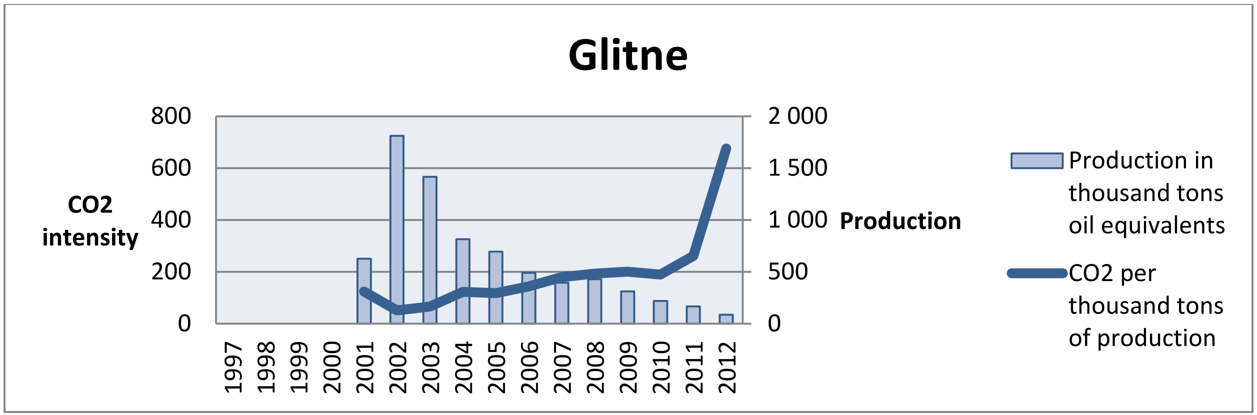

Edda
CO2 intensity
300
250
200
150
100
50
0
120
100
80
60
40
20
0
Production
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

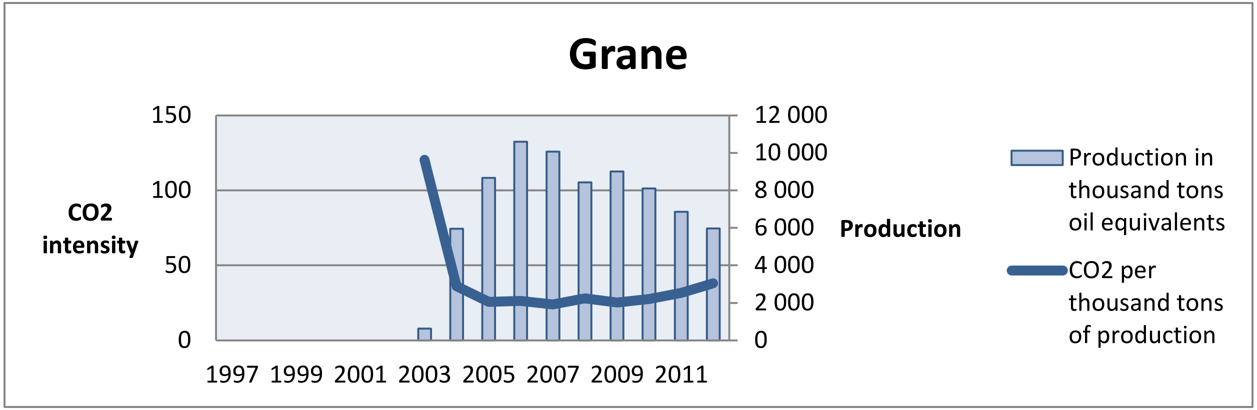

Ekofisk
150
100
50
0
CO2 intensity
20 000
15 000
10 000
5 000
0
Production
1997 1999 2001 2003 2005 2007 2009 2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production

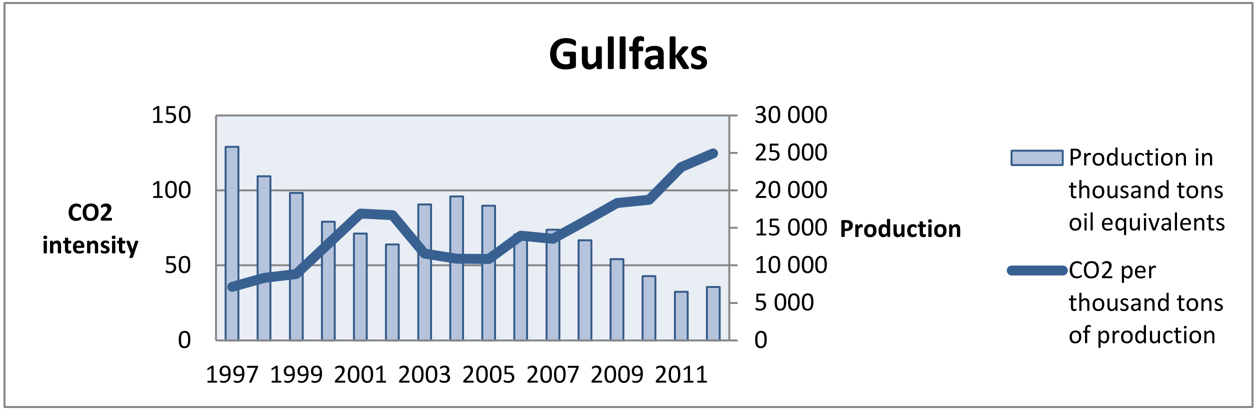

Eldfisk
200
150
100
50
0
CO2 intensity
5 000
4 000
3 000
2 000
1 000
0
Production
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

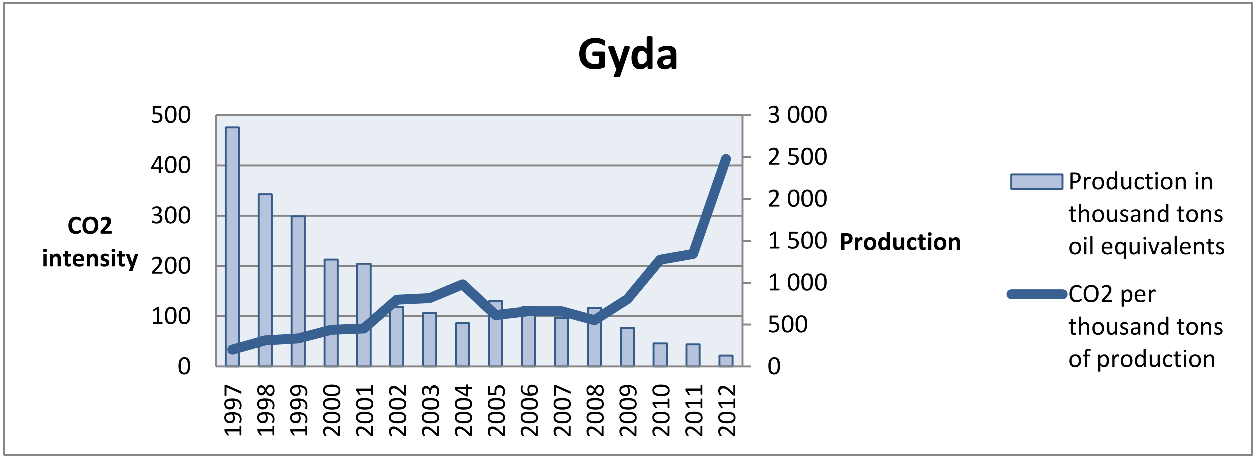

Frigg
500
400
300
200
100
0
CO2 intensity
800
600
400
200
0
Production
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

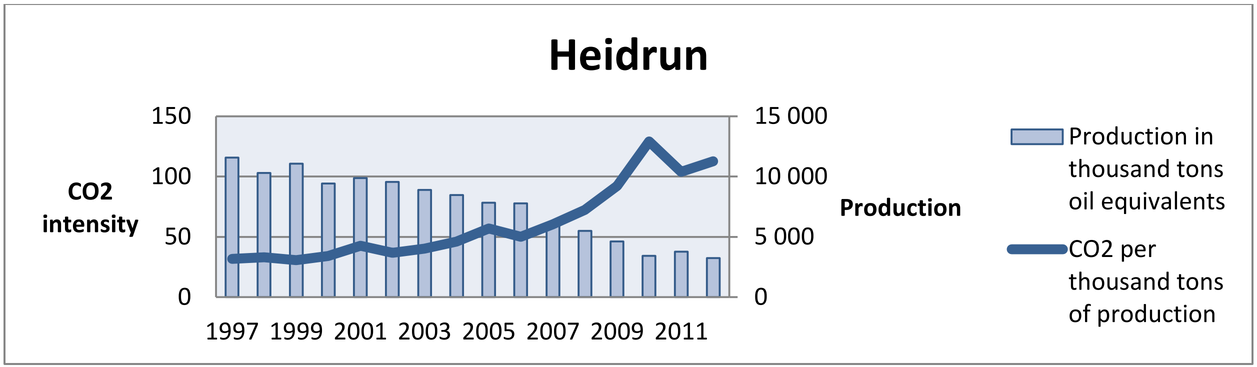

Gjøa*
500
400
300
200
100
0
CO2 intensity
10 000
8 000
6 000
4 000
2 000
0
Production
1997 1999 2001 2003 2005 2007 2009 2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production

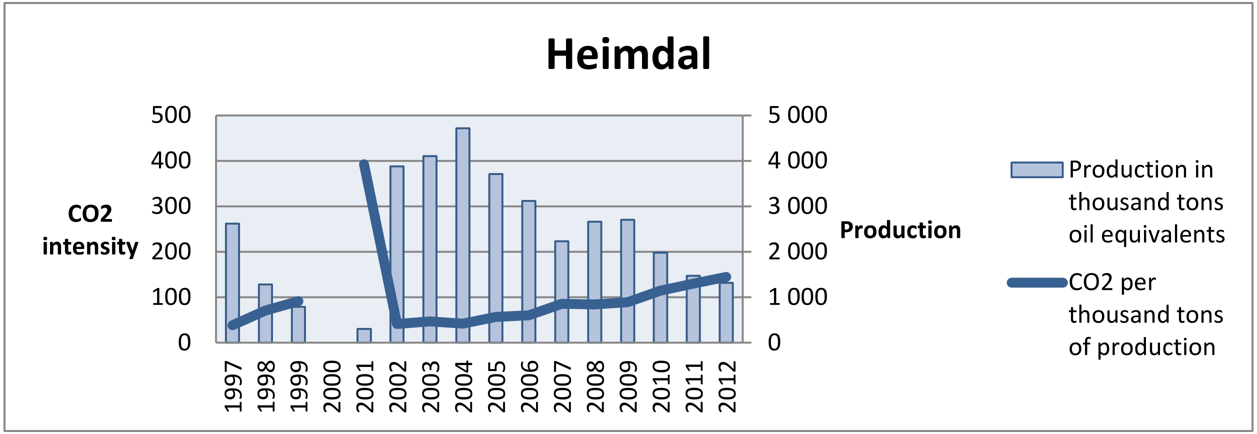

Glitne
CO2 intensity
800
600
400
200
0
2 000
1 500
1 000
500
0
Production
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

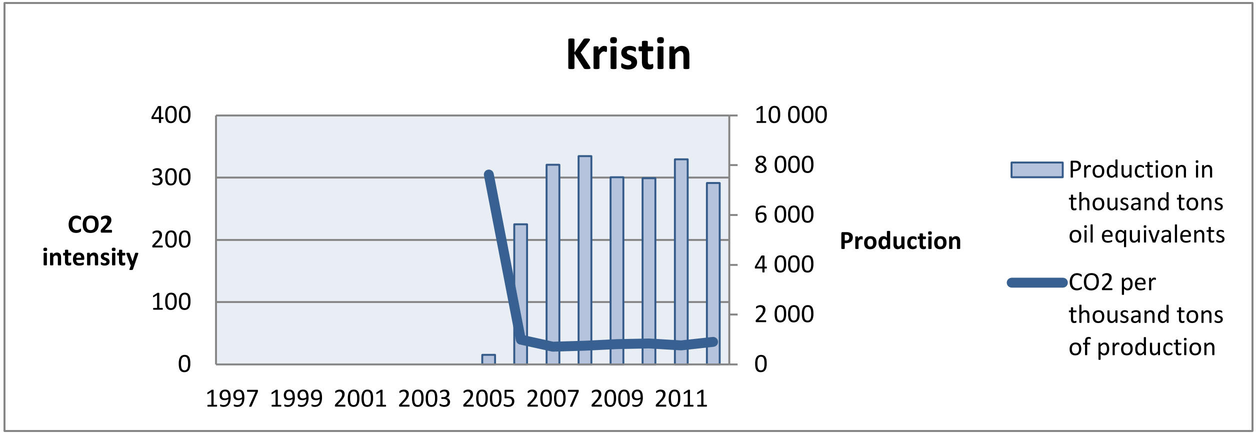

Grane
CO2 intensity
150
100
50
0
12 000
10 000
8 000
6 000
4 000
2 000
0
Production
1997
1999
2001
2003
2005
2007
2009
2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production

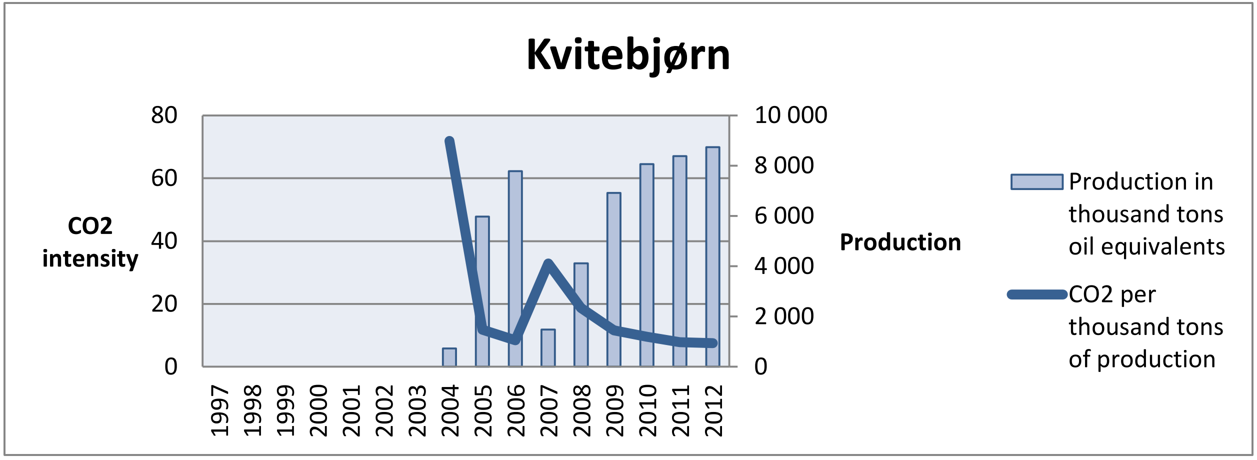

Gullfaks
CO2 intensity
150
100
50
0
30 000
25 000
20 000
15 000
10 000
5 000
0
Production
1997
1999
2001
2003
2005
2007
2009
2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production

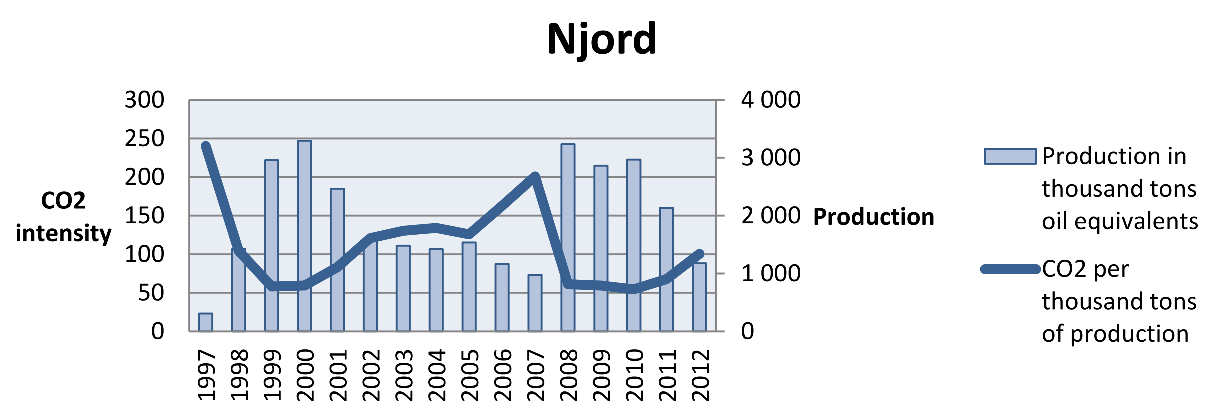

Gyda
CO2 intensity
500
400
300
200
100
0
3 000
2 500
2 000
1 500
1 000
500
0
Production
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

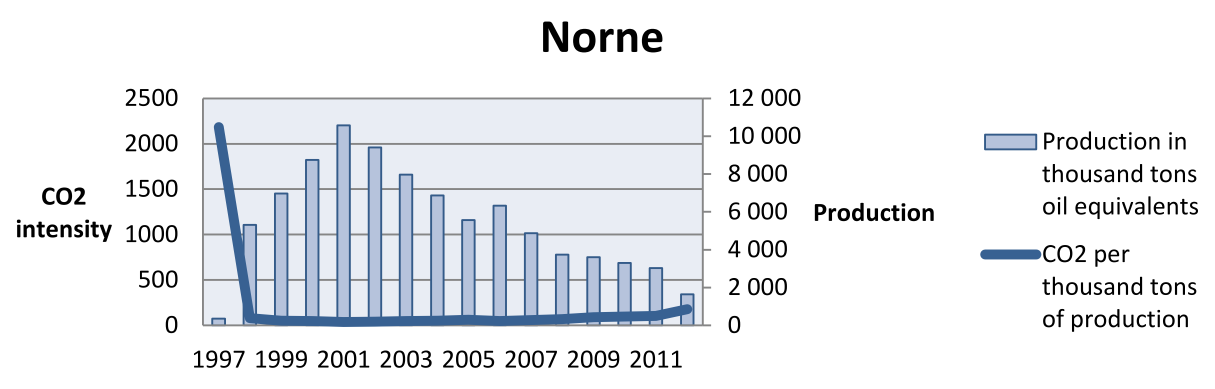

Heidrun
CO2 intensity
150
100
50
0
15 000
10 000
5 000
0
Production
1997 1999 2001 2003 2005 2007 2009 2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production

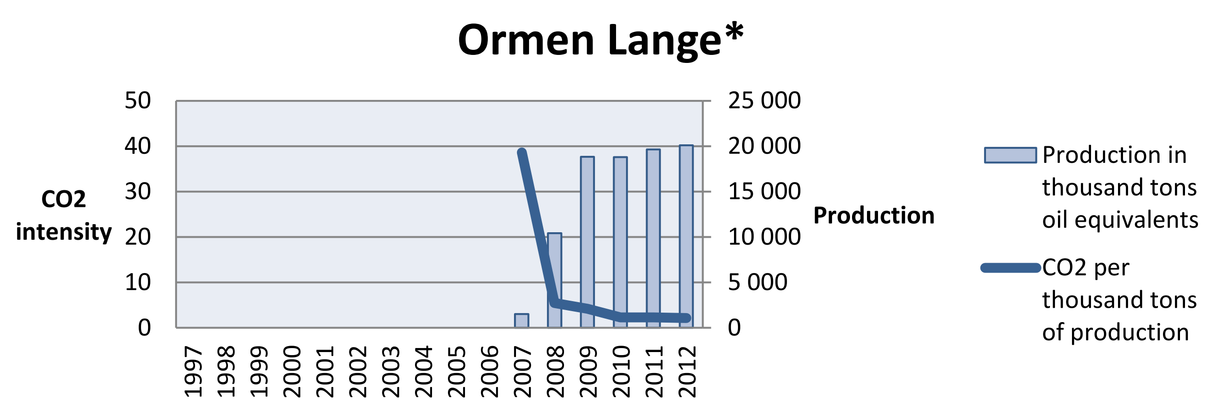

Heimdal
CO2 intensity
500
400
300
200
100
0
5 000
4 000
3 000
2 000
1 000
0
Production
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

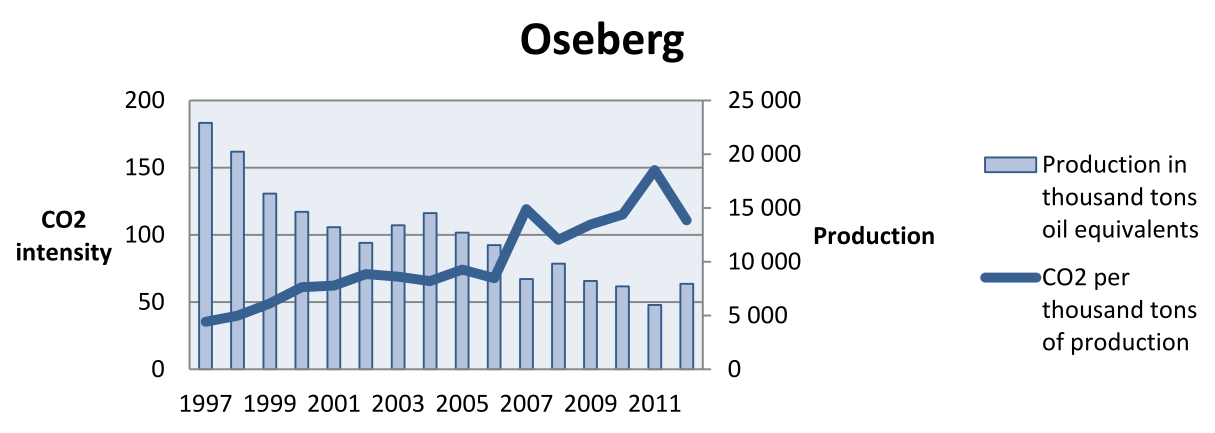

Kristin
CO2 intensity
400
300
200
100
0
10 000
8 000
6 000
4 000
2 000
0
Production
1997 1999 2001 2003 2005 2007 2009 2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production

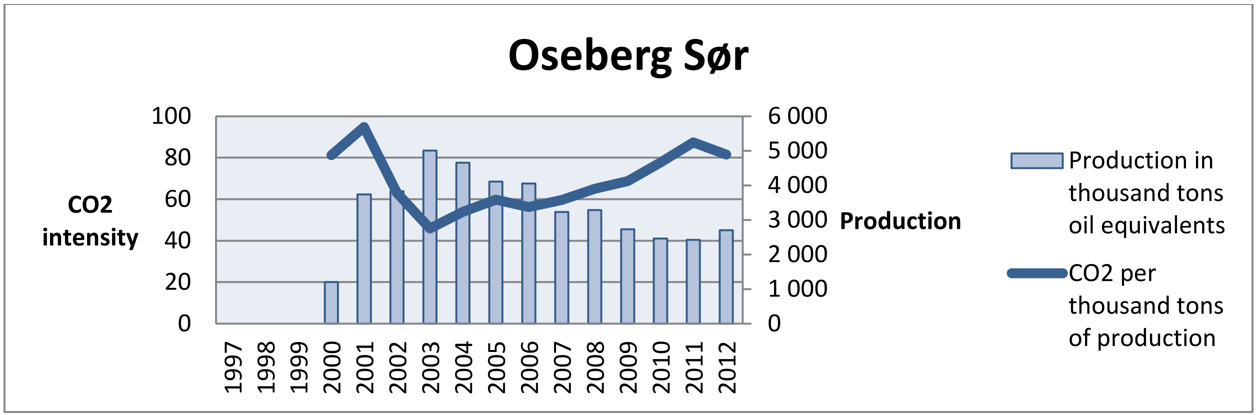

Kvitebjørn
CO2 intensity
80
60
40
20
0
10 000
8 000
6 000
4 000
2 000
0
Production
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

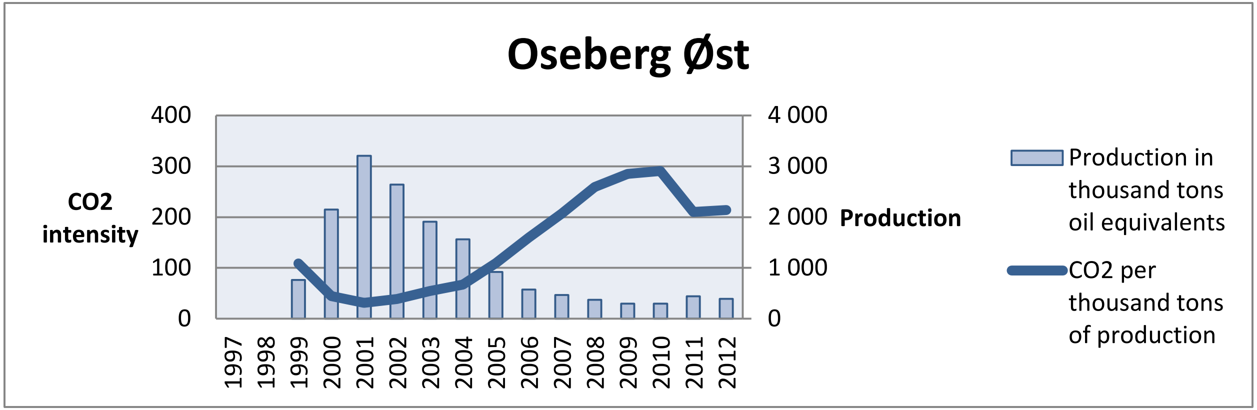

Njord
CO2 intensity
300
250
200
150
100
50
0
4 000
3 000
2 000
1 000
0
Production
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

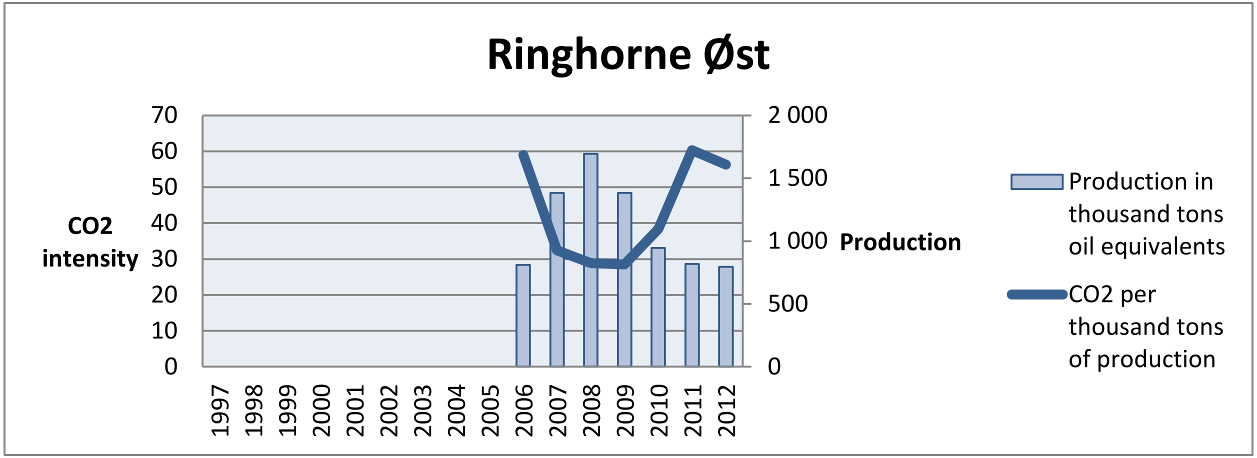

Norne
CO2 intensity
2500
2000
1500
1000
500
0
12 000
10 000
8 000
6 000
4 000
2 000
0
Production
1997
1999
2001
2003
2005
2007
2009
2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production

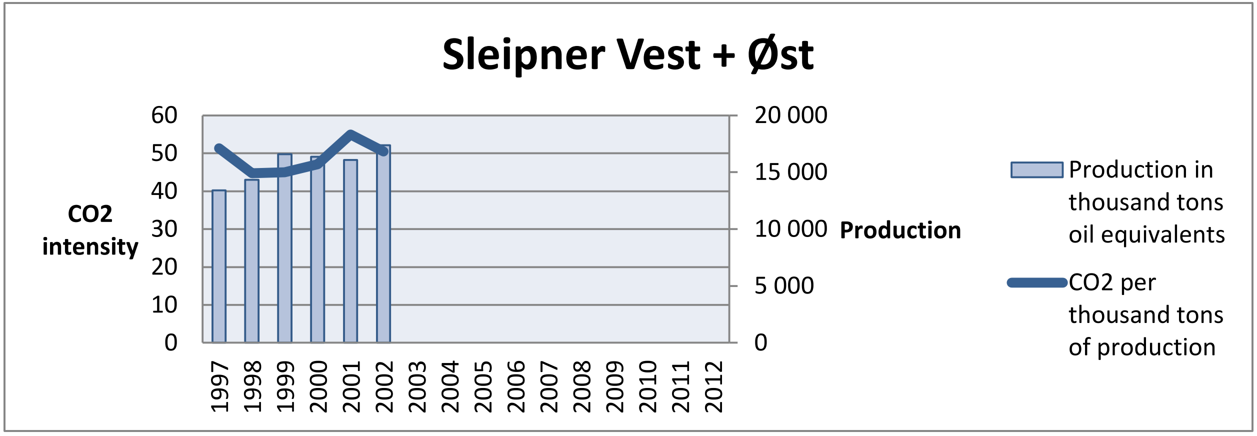

Ormen Lange*
CO2 intensity
50
40
30
20
10
0
25 000
20 000
15 000
10 000
5 000
0
Production
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

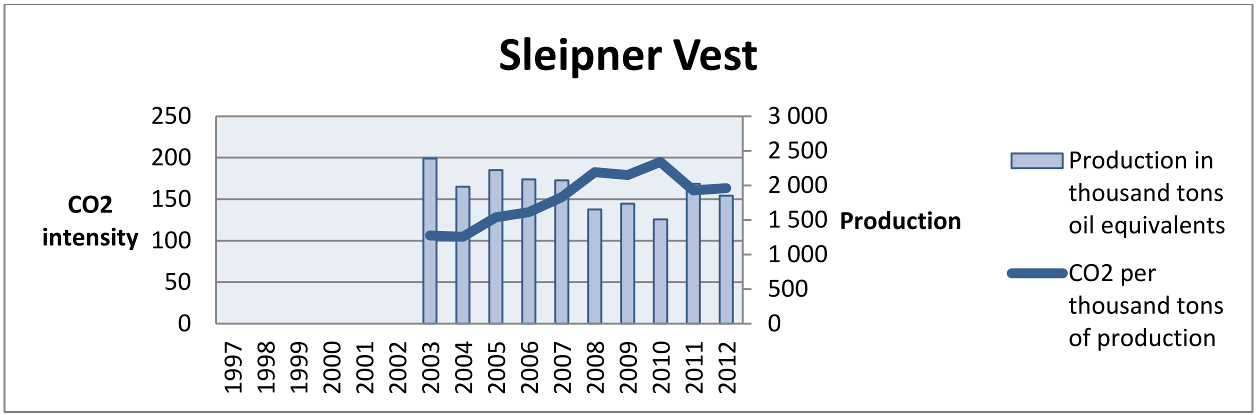

Oseberg
CO2 intensity
200
150
100
50
0
25 000
20 000
15 000
10 000
5 000
0
Production
1997
1999
2001
2003
2005
2007
2009
2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production

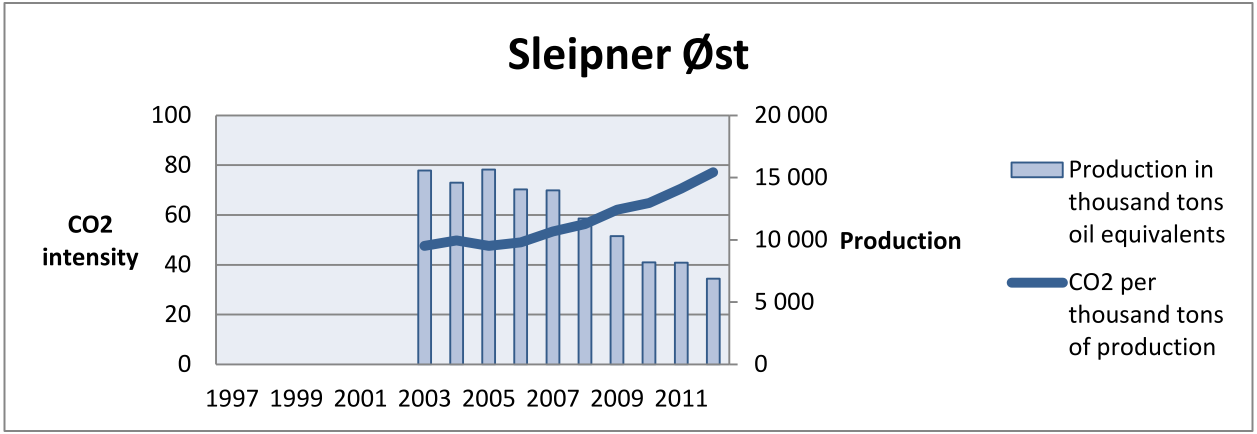

Oseberg Sør
CO2 intensity
100
80
60
40
20
0
6 000
5 000
4 000
3 000
2 000
1 000
0
Production
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

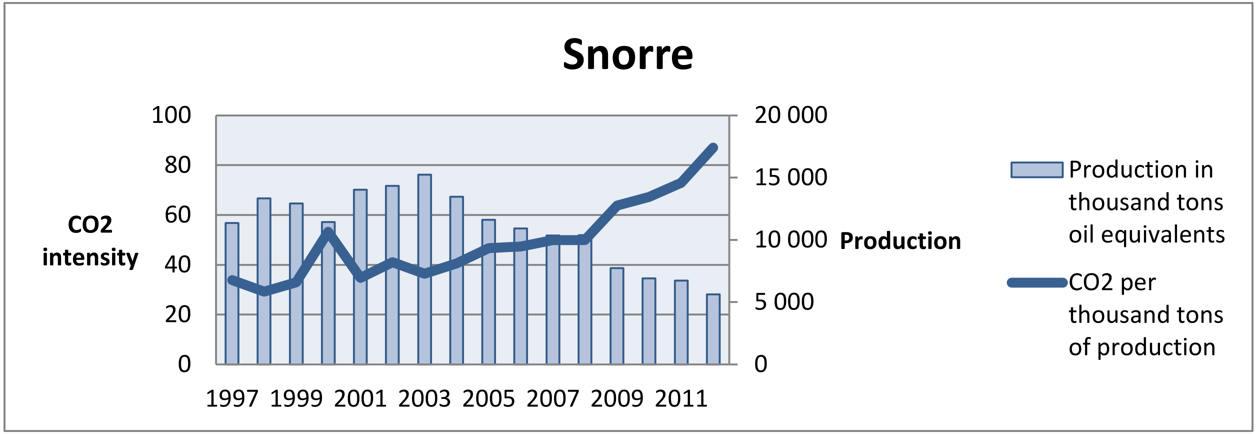

Oseberg Øst
CO2 intensity
400
300
200
100
0
4 000
3 000
2 000
1 000
0
Production
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

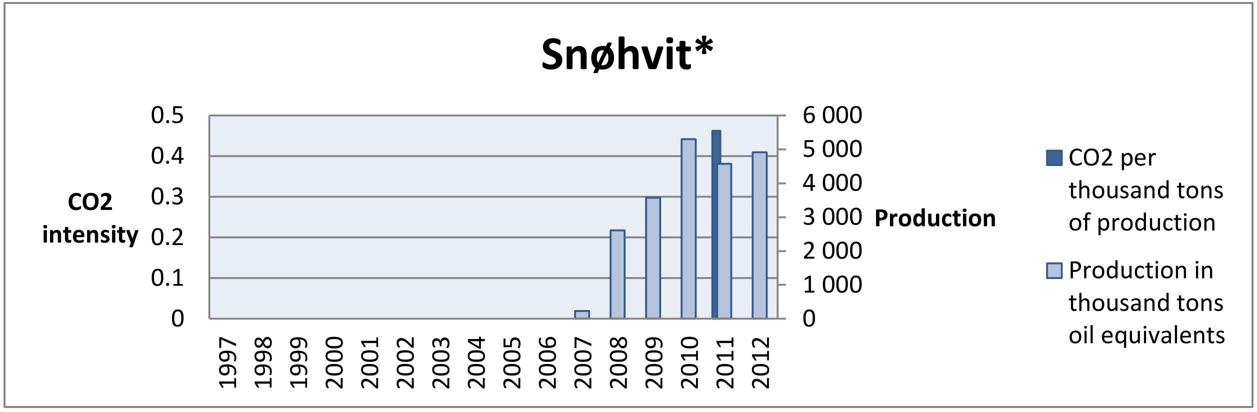

Ringhorne Øst
CO2 intensity
70
60
50
40
30
20
10
0
2 000
1 500
1 000
500
0
Production
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

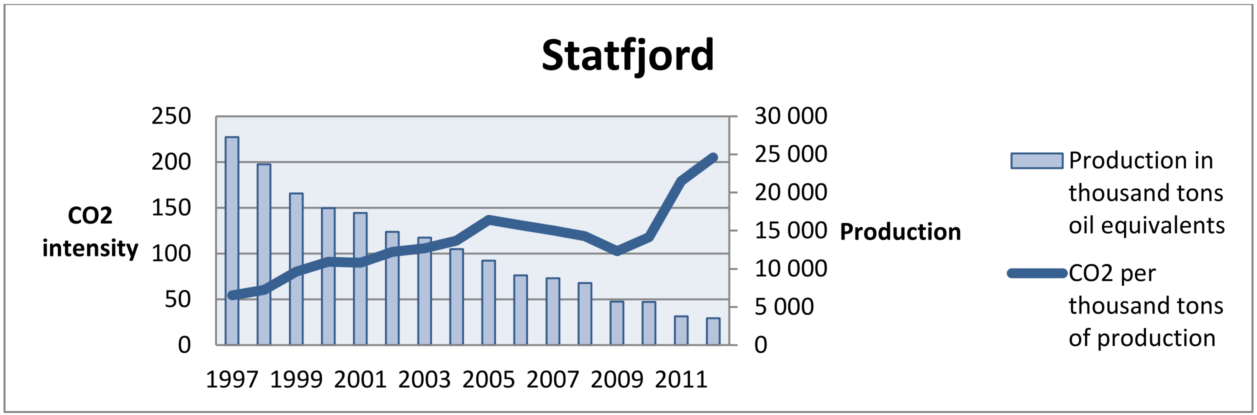

Sleipner Vest + Øst
CO2 intensity
60
50
40
30
20
10
0
20 000
15 000
10 000
5 000
0
Production
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

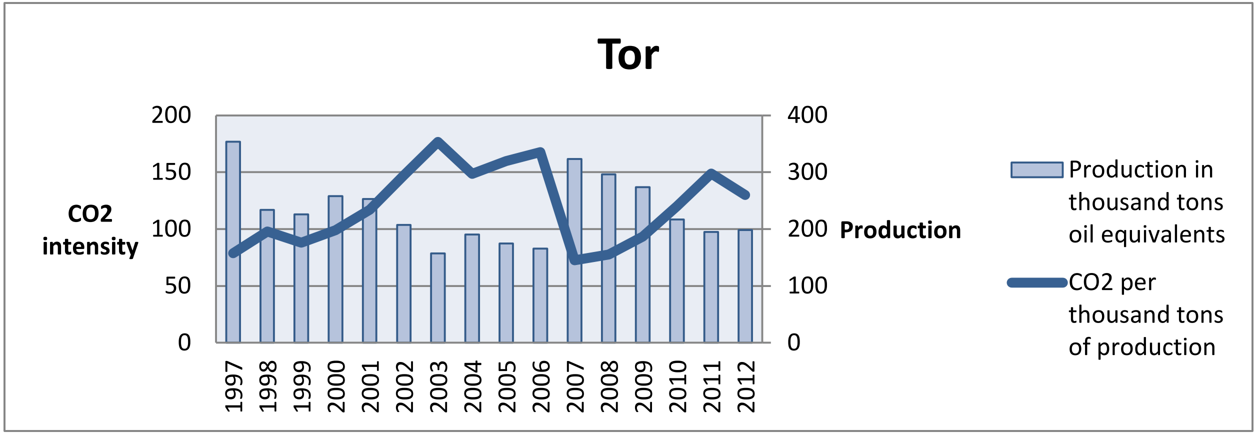

Sleipner Vest
CO2 intensity
250
200
150
100
50
0
3 000
2 500
2 000
1 500
1 000
500
0
Production
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

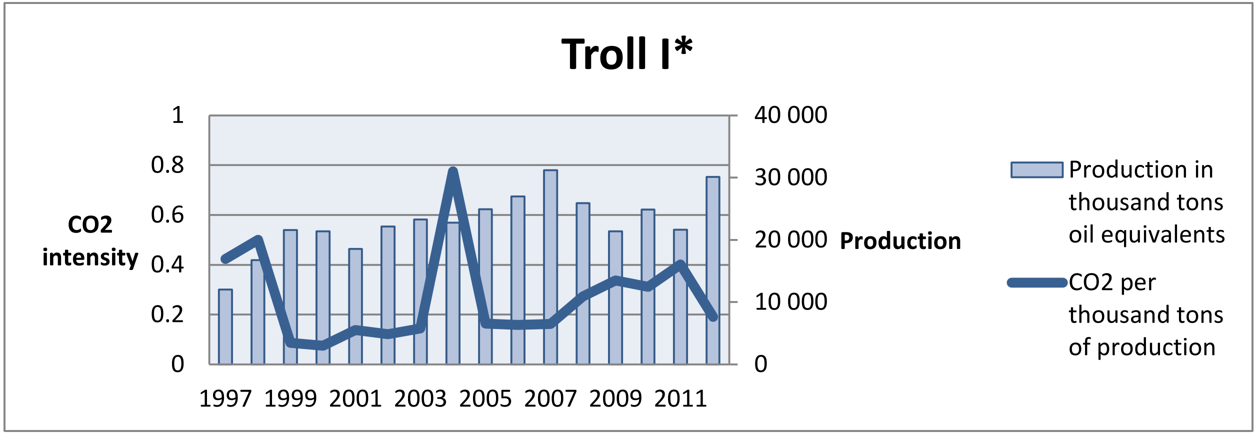

Sleipner Øst
CO2 intensity
100
80
60
40
20
0
20 000
15 000
10 000
5 000
0
Production
1997 1999 2001 2003 2005 2007 2009 2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production

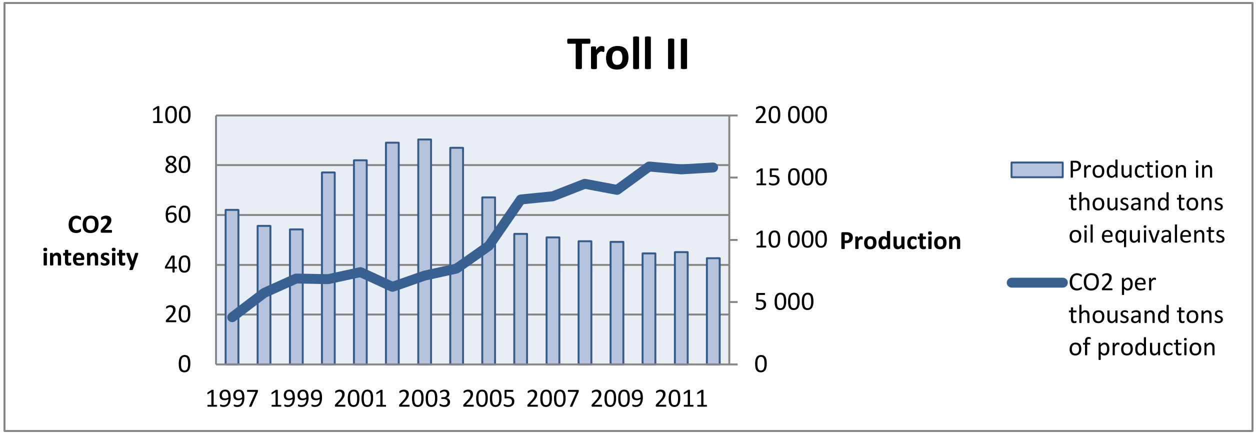

Snorre
CO2 intensity
100
80
60
40
20
0
20 000
15 000
10 000
5 000
0
Production
1997 1999 2001 2003 2005 2007 2009 2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production

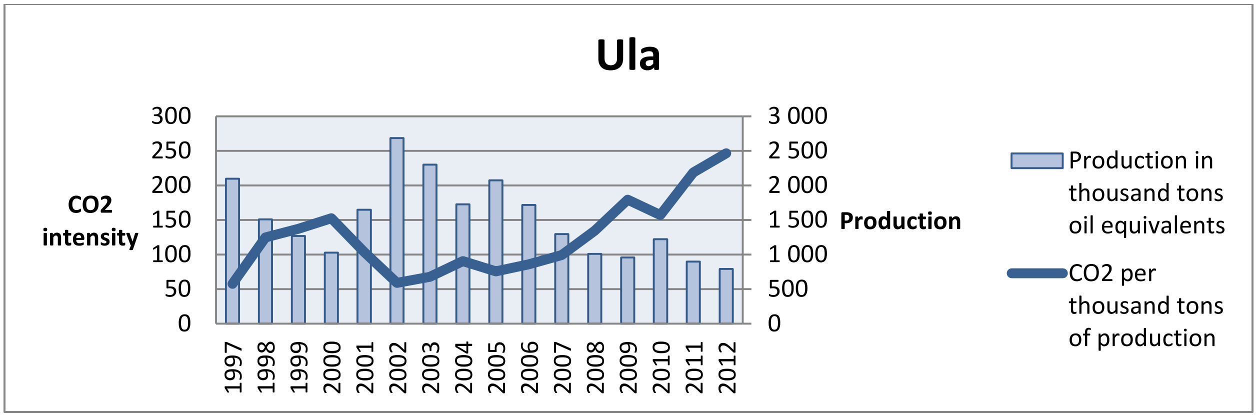

Snøhvit*
CO2 intensity
0.5
0.4
0.3
0.2
0.1
0
6 000
5 000
4 000
3 000
2 000
1 000
0
Production
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
CO2 per thousand tons of production
Production in thousand tons oil equivalents

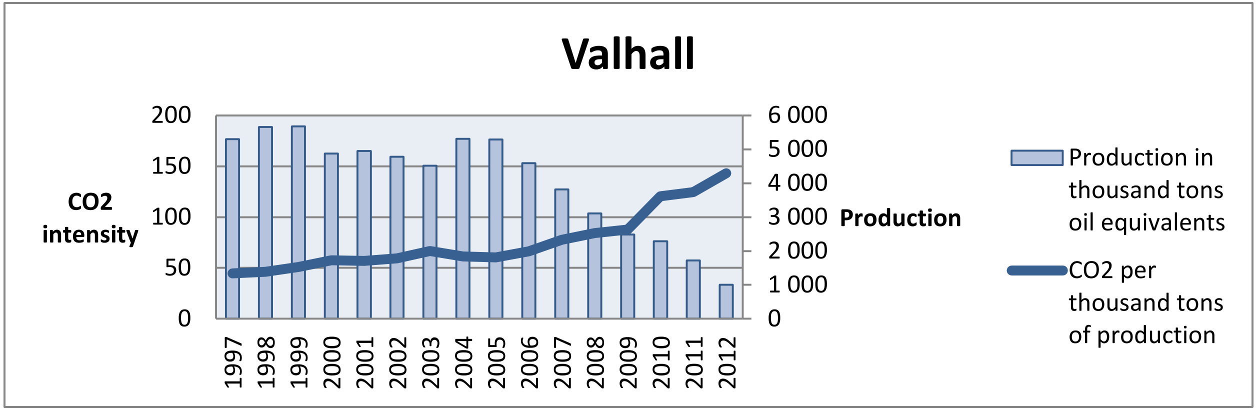

Statfjord
250
200
150
100
50
0
CO2 intensity
30 000
25 000
20 000
15 000
10 000
5 000
0
Production
1997 1999 2001 2003 2005 2007 2009 2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production

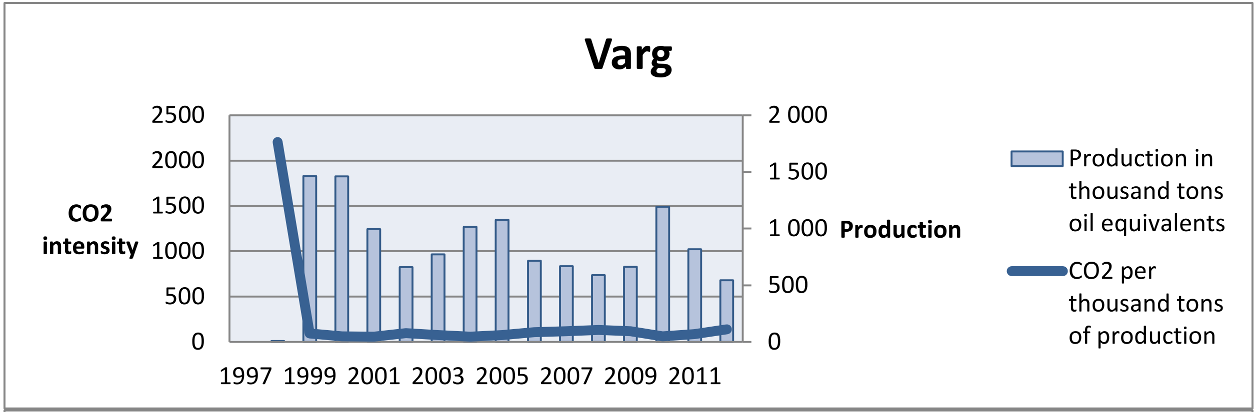

Tor
200
150
100
50
0
CO2 intensity
400
300
200
100
0
Production
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

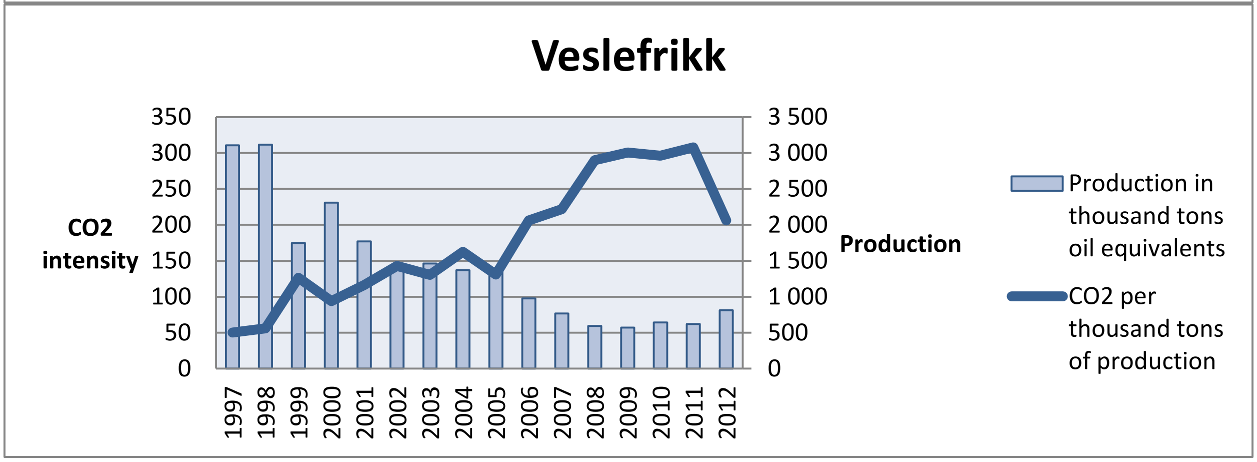

Troll I*
1
0.8
0.6
0.4
0.2
0
CO2 intensity
40 000
30 000
20 000
10 000
0
Production
1997 1999 2001 2003 2005 2007 2009 2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production

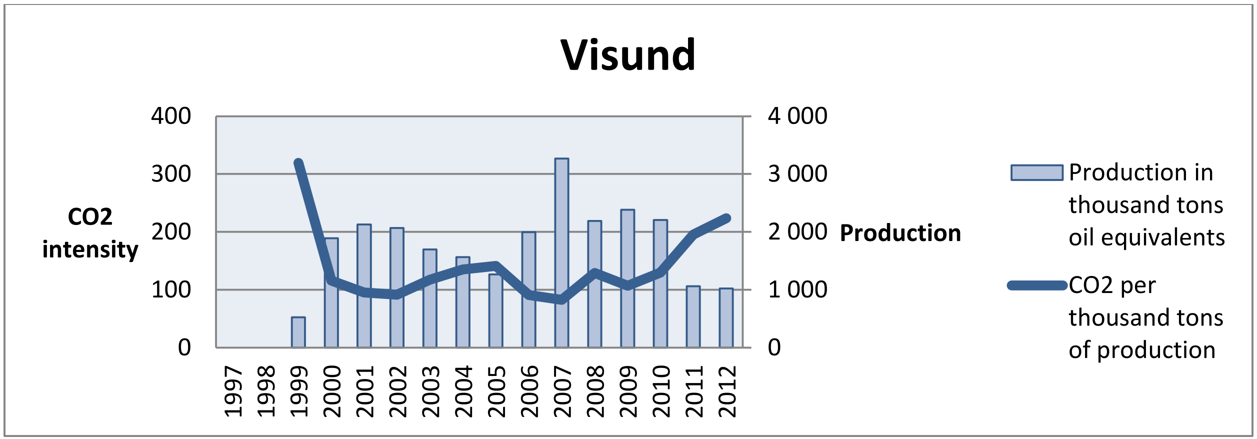

Troll II
100
80
60
40
20
0
CO2 intensity
20 000
15 000
10 000
5 000
0
Production
1997 1999 2001 2003 2005 2007 2009 2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production

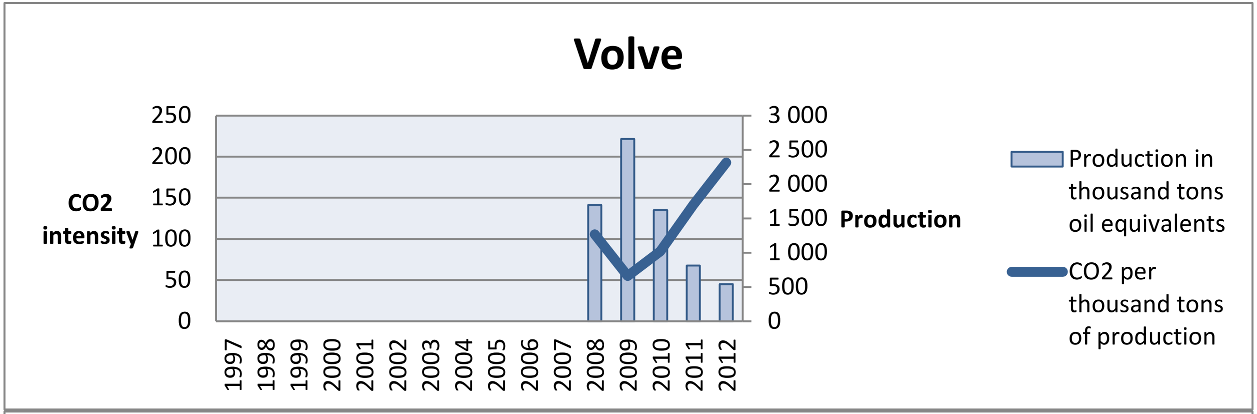

Ula
CO2 intensity
300
250
200
150
100
50
0
3 000
2 500
2 000
1 500
1 000
500
0
Production
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

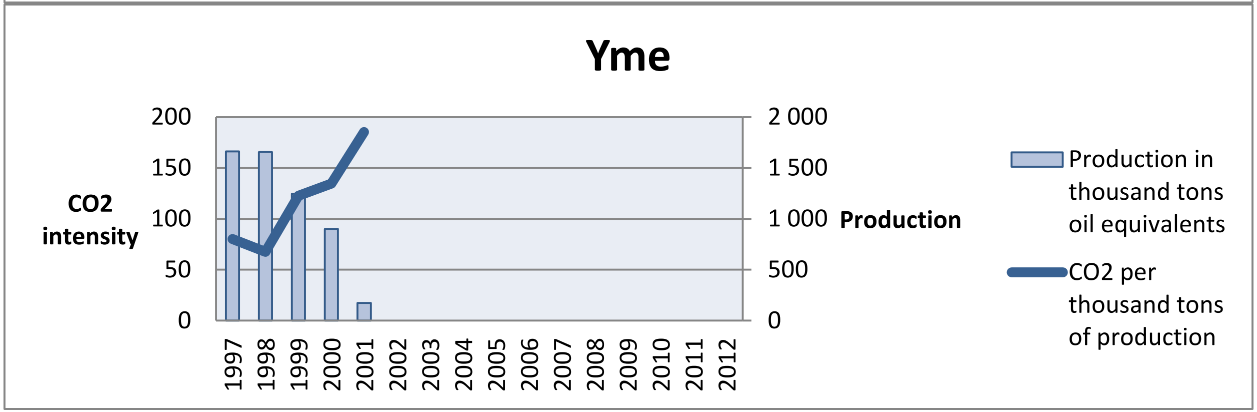

Valhall
CO2 intensity
200
150
100
50
0
6 000
5 000
4 000
3 000
2 000
1 000
0
Production
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production

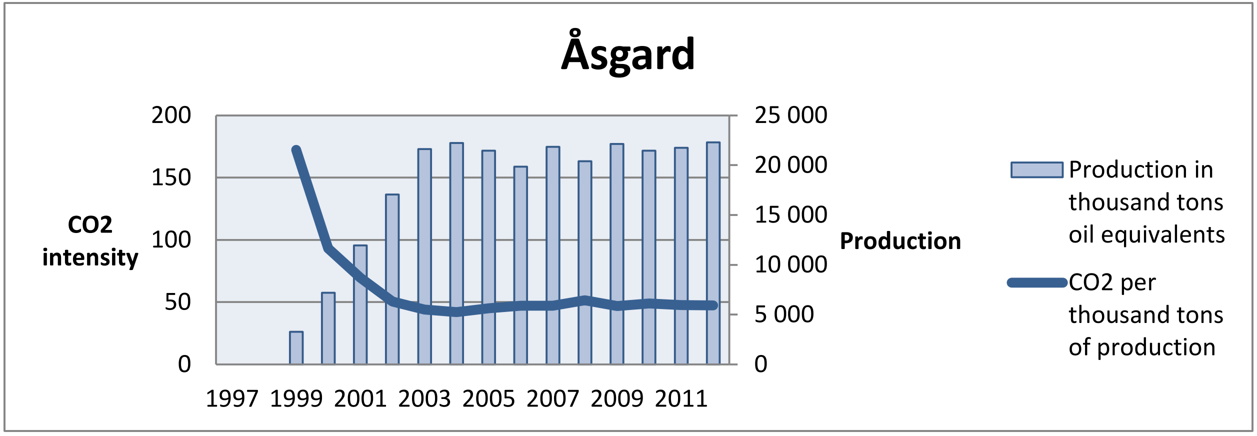

Varg
CO2 intensity
2500
2000
1500
1000
500
0
2 000
1 500
1 000
500
0
Production
1997
1999
2001
2003
2005
2007
2009
2011
Production in thousand tons oil equivalents
CO2 per thousand tons of production


Veslefrikk
CO2 intensity
350
300
250
200
150
100
50
0
3 500
3 000
2 500
2 000
1 500
1 000
500
0
Production
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Production in thousand tons oil equivalents
CO2 per thousand tons of production


Visund


Volve


Yme


Åsgard

Appendix C

1. **Regression with total emissions as dependent variable without electrification dummy but keeping all the fields.**

```
-----------------------------------------------------------
    Variable | re0ef_lnemm     fe0ef_lnemm     lnem0ef_htm    
-------------+---------------------------------------------
      lnprod |  .2299484***    .20780744***     .2092529***  
  lnsharegas | -.8843187***   -.46902934      -.48552643**  
         lnw | -.28357038      (omitted)       -.1880568      
       lnres |  .52615601      (omitted)         .592274      
      lnsize |  .37427709**    (omitted)       .39811737**  
      lncarb |  .11831451      (omitted)       .03481153      
       lnoil |  .27333526      .14110905       .16298172***
             |
        year |
       1998  |  .11154525      .07045032                  
       1999  | -.01295879     -.02814265                  
       2000  | -.03772852     -.01169007                  
       2001  |   .0241029      .02154859                  
       2002  |    .041157      .03135665                  
       2003  |  .03453338      .02475051                  
       2004  |  .09425123       .1049539                  
       2005  |  .00222919      .04174549                  
       2006  | -.04295227      .01703858                  
       2007  | -.01233528      .03040646                  
       2008  |  .01430442      .07722175*                 
       2009  |   .0925708*     .08596385*                 
       2010  |   .0013555      .01025795                  
       2011  |  (omitted)      .03950561                  
       2012  |  (omitted)      (omitted)                  
             |
       _cons |   3.455844      9.6966084***    3.6001117      
-------------+---------------------------------------------
           N |        497            497             497      
-----------------------------------------------------------
                          legend: * p<.1; ** p<.05; *** p<.01
```

2. Regression with total emissions as dependent variable without electrified fields.

```
-------------+------------------------------------------------
    Variable |  re0e_lnemm      fe0e_lnemm      lnem0e_htm
-------------+------------------------------------------------
      lnprod |  .26074275***     .2328137***    .23849525***
  lnsharegas | -.63345529***   -.47978668      -.53823056***
         lnw |  .13207785       (omitted)       .17229674
       lnres | -.21734416       (omitted)      -.18749601
      lnsize |  .54239069***    (omitted)       .56245667***
      lncarb |  .02824849       (omitted)      -.02361854
       lnoil |  .26100577       .19379505       .15415915***
             |
        year |
       1998  |  .10580578       .07812184
       1999  |  .04886594       .02442174
       2000  |  .00864686       .01762717
       2001  |  .04716702       .04025666
       2002  |  .05990651       .05183528
       2003  |  .04836767       .03819695
       2004  |  .05302137       .05564137
       2005  |  .01291293       .02857507
       2006  | -.03184333       -.0056393
       2007  | -.02634064      -.00835585
       2008  |  .01143507       .03603406
       2009  |  .05965331       .05392459
       2010  | -.03665044      -.03431636
       2011  |  (omitted)       .00946052
       2012  |  (omitted)       (omitted)
             |
       _cons |  7.0811079**     9.3529938***    7.6844979***
-------------+------------------------------------------------
           N |        471             471             471
-------------+------------------------------------------------
                           legend: * p<.1; ** p<.05; *** p<.01
```

3. Regression with total emissions, total depth instead of separate water depth and reservoir depth

Variable	re_lnemtd	fe_lnemtd	lnem_htmtd
lnprod	.26086329***	.20780744***	.21340388***
lnsharegas	-.87926931***	-.46902934	-.48088895**
lntotald	.21092859	(omitted)	.2216812
lnsize	.44809248***	(omitted)	.50700588***
lncarb	.07172689	(omitted)	.02920428
lnoil	.29087169	.14110905	.16590897***
elect	-2.8510825***	(omitted)	-3.2844617***
year			
1998	.12777719	.07045032	
1999	.01111999	-.02814265	
2000	-.04236715	-.01169007	
2001	.0256343	.02154859	
2002	.04110709	.03135665	
2003	.03840695	.02475051	
2004	.09270108	.1049539	
2005	-.00169866	.04174549	
2006	-.04923144	.01703858	
2007	-.01194549	.03040646	
2008	.01335936	.07722175*	
2009	.09012899*	.08596385*	
2010	.01182866	.01025795	
2011	(omitted)	.03950561	
2012	(omitted)	(omitted)	
_cons	4.3638286	9.6966084***	5.3510936
N	497	497	497

legend: * p<.1; ** p<.05; *** p<.01

4. Regression with emission intensity with share of gas of original recoverable resources.

```
----------------------------------------------------------
    Variable | reor_lnempt     feor_lnempt     lnemptor_ht
-------------+--------------------------------------------
     lnshare | -.71884824***   -.74894722***   -.74779852***
      lncarb |  .08961959       (omitted)       .08530659
       lnoil |   .1154984      -.01575967       .07339599
     lngasor | -1.5824795***    (omitted)      -1.5111769**
      lnsize | -.05249552       (omitted)       -.0429141
         lnw |  .22802543       (omitted)       .27007413
       lnres |   .6739012*      (omitted)       .79536123*
       elect | -2.5675152**     (omitted)      -2.8475233***
             |
        year |
       1998  |  .05420619         .007927
       1999  |  -.0172451      -.06321319
       2000  | -.03326173      -.03255393
       2001  |  .02352205       .00408058
       2002  | -.02261195      -.04987734
       2003  | -.05221236      -.08266041
       2004  |  .02968392       .02613737
       2005  | -.02473242       .00764393
       2006  | -.06488307      -.00958386
       2007  | -.02646203       .00969944
       2008  |  .02024098       .08206863
       2009  |  .03286756       .03099036
       2010  | -.01543759      -.01177677
       2011  |  (omitted)       .03326779
       2012  |  (omitted)       (omitted)
             |
       _cons |  -3.569917       3.4245099***   -4.5359467
-------------+--------------------------------------------
           N |        497             497             497
----------------------------------------------------------
                         legend: * p<.1; ** p<.05; *** p<.01
```

5. Regression with emission intensity excluding electrified fields.

```
--------------------------------------------------------------
    Variable |  re0e_lnempt     fe0e_lnempt     lnempt0e_ht
-------------+------------------------------------------------
     lnshare | -.66774512***    -.7128638***   -.71243484***
      lncarb | -.06714184       (omitted)        .00769166
       lnoil |  .10884184       .07044764        .07704799
  lnsharegas | -.83501322***   -.41117171       -.45952306**
      lnsize |  .03781398       (omitted)        .03918665
         lnw |   .0343691       (omitted)        .11227327
       lnres |  .10906628       (omitted)        .12730842
             |
        year |
       1998  |  .06162802       .03074669
       1999  |   .0147271      -.01488829
       2000  | -.03962058       -.0269685
       2001  |  .01335991       .01130222
       2002  | -.03726965      -.03880328
       2003  | -.06567704      -.07634804
       2004  | -.02839729      -.03274415
       2005  | -.01740704      -.01876439
       2006  | -.04569618      -.04707196
       2007  | -.04054963      -.04358374
       2008  |   .0350213       .02890559
       2009  |  .01066358       .00034727
       2010  | -.05325812      -.06221942
       2011  |  (omitted)      -.00169894
       2012  |  (omitted)       (omitted)
             |
       _cons |   2.290049       3.2386711***    1.3630365
-------------+------------------------------------------------
           N |        471             471             471
--------------------------------------------------------------
                                legend: * p<.1; ** p<.05; *** p<.01
```

6. Regression with emission intensity without electrification dummy but keeping all the fields.

Variable	re_lnempte	fe_lnempte	lnempt_hte
lnshare	-.72128319***	-.74115293***	-.74464446***
lnsharegas	-.89645682***	-.38893726	-.40270492*
lncarb	.06899158	(omitted)	.07524552
lnoil	.11353479	.00933111	.08636403
lnw	-.33120867	(omitted)	-.24283728
lnres	.72202421	(omitted)	.82767834
lnsize	-.12311433	(omitted)	-.12600067
year			
1998	.05436069	.01860765	
1999	-.05488339	-.0687841	
2000	-.07574071	-.05211823	
2001	-.00349561	-.00460774	
2002	-.04935294	-.05704101	
2003	-.07863054	-.08825781	
2004	.01430261	.01958101	
2005	-.02714705	-.00077707	
2006	-.05861998	-.01860044	
2007	-.0251354	.00303072	
2008	.0348553	.07637203	
2009	.04421393	.03495634	
2010	-.01099332	-.00891294	
2011	(omitted)	.03028111	
2012	(omitted)	(omitted)	
_cons	-1.1301972	3.3542377***	-2.4147081
N	497	497	497

legend: * p<.1; ** p<.05; *** p<.01

Norwegian University
of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no