Carbon Leakage: The Case of Norway

An empirical paper examining how Norwegian CO_2 trade patterns respond to bilateral cost levels

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Foreword

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Executive Summary

Unilateral climate policies between countries challenge international climate efficiency. While many countries are implementing increasingly strict environmental regulations, other regions rather prioritize pure growth strategies. If the regulatory asymmetries grow too large, emission-intense production may simply shift from regulated countries to laxer regions, a phenomenon known as carbon leakage. When CO_2 emissions simply are outsourced, the cost-efficiency of implemented regulations fall. Examining to what degree mitigated CO_2 "leaks" from highly industrialized countries is therefore a matter of significance.

This thesis takes an empirical approach to examine the extent of carbon leakage from Norway, as a highly industrialized country. By using country-sector panel data on Norway's bilateral CO_2 trade with 35 foreign countries in eight industrial sectors, this paper uses fixed effects models to simulate how CO_2 trade flows respond to relative cost changes. Using derived CO_2 trade elasticities in a national CO_2 accounting framework, an industrial carbon leakage rate of roughly 50 % is estimated, although subject to considerable uncertainty. Lastly, a brief policy discussion on how to mitigate Norwegian carbon leakage is offered.

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1 Introduction

Unilateral climate policies between countries challenge international climate efficiency. While many industrialized countries are becoming increasingly regulated and strive to internalize domestic CO_2 emissions, less-developed countries often have weaker economic incentives to mitigate emissions and rather prioritize pure growth strategies. If regulatory asymmetries grow too large, industrial production in highly regulated regions may loose its international competitiveness. Without wide-ranging global policies, the risk that emission-intensive production simply shifts from regulated to laxer countries is therefore noteworthy. Either, this could be domestic companies outsourcing their production facilities, or it can be foreign competitors scaling up production themselves. Such cost-induced shifts to laxer regions is often referred to as carbon leakage, whereas abated CO_2 emissions in regulated countries "leaks" out to other countries. Norway, as a highly industrialized country that participates in EU's cap and trade system and has implemented its own increasingly strict regulatory strategy, is at risk of such leakage.

The research question this thesis aims to answer is whether carbon leakage occurs in Norwegian industry. The hypothesis is that when Norwegian industrial operating costs increase, a larger share of our CO_2 emissions originate from foreign countries. The overall empirical target is therefore to estimate the industrial carbon leakage rate from Norway, meaning the share of domestically abated CO_2 emissions that return through international trade. By using country-sector panel data on Norway's bilateral CO_2 trade with 35 foreign countries in eight emission-intensive sectors, as well as country-sector data on tax-inclusive energy prices, fixed effects models are used to estimate how Norway's CO_2 trade flows respond to domestic and foreign cost changes. Specifically, the domestic and foreign price elasticities of Norwegian CO_2 imports and exports are estimated, in addition to a sample selection domestic price elasticity to CO_2 from domestic production. A national CO_2 accounting framework is thereafter used to estimate the final carbon leakage rate.

In terms of thesis structure, there will first be an elaboration of Norway's climate policies and a comparison with foreign policy levels, in order to illustrate Norway's vulnerability to carbon leakage. Secondly, the theoretical funding of carbon leakage will be elaborated, presenting four different economic drivers of carbon leakage. A brief review of some academical paper and their empirical findings will also be provided. Moreover, my data will be explained and presented in descriptive statistics, followed by an explanation of the empirical model. Empirical results will be presented and utilized in a theoretical framework to estimate Norway's industrial carbon leakage rate. Lastly, a brief policy discussion on how to mitigate Norwegian carbon leakage will will be provided.

2 Background

2.1 The Global Challenge

As our planet is heating up, the global focus to restructure activity is sharpened. United Nations has highlighted the urgent need to take immediate action in reducing global greenhouse gases, and this topic currently sits high on many political agendas (FN-sambandet, 2022a). This aim is partly systematized and realized through the Paris Agreement, a legally binding agreement built on proportionate, national target levels and deadlines for abatement. The overall goal of the Paris Agreement is to avoid a global temperature increase of more than 2 degrees Celsius within the next decade, and all participating countries shall evaluate and update their targets every fifth year (FN-sambandet, 2020). Hope exists that the Paris Agreement will push countries into mitigating their greenhouse gas emissions remarkably. Most countries have ratified the agreement.

Simultaneously, UN has visioned eradicating extreme poverty by 2030. This is a goal highly reliant on implementing powerful growth strategies in developing countries in the coming decades (FN-sambandet, 2022b). Approximately 10 % of the global population lives in extreme poverty, meaning that they consume for under the equivalent of slightly under two dollars (1.90) a day. Combined with effectual distribution and societal development, economic growth is viewed as one of the key factors in beating poverty. Stimulating growth in poor countries is therefore crucial.

However, large-scale CO_2 abatement could dampen growth significantly in many parts of the world. Factors such as resource bases, technological development, energy-mixes and access to financing determine how efficiently countries can reduce their CO_2 emissions. For instance, a developing country highly reliant on fossil fuels with restricted access to capital may naturally struggle more to mitigate its emissions. In addition, countries' unrealized potential within non-green production will determine their alternative cost of abatement - a factor that definitely also affects countries' willingness to abate. Countries with high reserves of fossil fuels or competitive advantages in emission-intensive industries may wish to extract and utilize these resources before going green. Many countries therefore invest less resources into greenhouse gas mitigation and rather prioritize pure growth strategies as of today (The World Bank, 2021).

Returning to UN's poverty and climate goals, this dynamic goal system requires climate targets to be achieved at the lowest possible cost globally. Optimizing a global green shift with respect to costs is however not a straightforward mission, as it calls for highly unified, international action plans. In spite of the Paris Agreement, the world lacks a globally unified strategy today[1].

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[1] The Paris Agreement systematizes both global focus and efforts to mitigate emissions. However, as its main objective is to ensure that global temperatures do not increase more than two degrees Celsius, and it does not impose penalties if targets are not met, it has been criticized for incentivizing countries to "free-ride" and rather benefit from other countries' mitigation (Nordhaus, 2019).

2.2 The Endeavour of Norway

2.2.1 Internal Strategy and Policies

As a highly industrialized country, Norway has quite some responsibility in achieving its climate targets. Prominently, since having ratified the Paris agreement in 2016, Norway is aiming to reduce own emissions to 50-55 percent of 1990-levels by 2030. Further, a lower legal bound of abatement is set to 40 percent in coordination with the EU, thus realizing a contractual target that must be met (Klima- og miljødepartementet, 2021b).

Firstly, in high co-ordinance and cooperation with the European Union, Norway participates in the European quota system for emissions: EU ETS (Miljødirektoratet, 2019). The system controls production levels of heavy-emission industries in the EU by requiring companies to purchase carbon permits prior to actually producing. Norwegian industries such as offshore petroleum, gas plants, steel, iron, aluminum, cement, fertilizers and aviation are incorporated in the quota system, all being energy-intensive industries (Cicero, 2019). The systems' purposes are respectively to set a roof on heavy-emission production in the EU (incl. Norway) as well as shrinking this roof steadily by cutting the number of quotas.

From the system's implementation in 2005 until 2018, carbon permit prices have been fairly constant, laying between zero to 25 euros per ton of CO_2. However, energy-intensive industries have for long received full or partial compensation of permit purchases to maintain international competitiveness to foreign producers (European Comission, 2021a). The compensation has been justified by that lost competitiveness may drive production shifts to regions with laxer policies. For some industries, phasing out compensation is however already initiated, and the union aims to eventually cut all free allowances. Regardless, in terms of permit price development, permit prices per ton of CO_2 emitted have accelerated considerably as quotas have been cut in an effort to intensify CO_2 abatement, reaching almost 100 euros in early February 2022 (Trading Economics, 2022). While averaging around 80 euros so far in 2022, prices are expected to increase further when the number of permits are set to decrease by 2.4 % annually from 2021 (European Comission, 2021c). As both free allowances are set to phase out and the number of quotes set to be cut steadily in the years to come, heavy industrial production may gradually loose its international competitiveness on European soil due to higher operating costs.

Secondly, Norway has implemented an own set of taxes on heavy-emission production. In contrast to quotas, fees and taxes do not induce a roof on production, but in a similar matter, they directly disincentive production by upping the costs in affected industries. In Norway, such fees and taxes are firstly imposed on industrial sectors not incorporated in the EU ETS, such as mineral oils, agriculture, gasoline, natural gas and liquid petroleum gases (LPG's). However, the Norwegian government also aims at targeting selected sectors already operating under ETS quotas (offshore petroleum and aviation) with own, national fees to strengthen their incentives to downscale and/or innovate themselves to lower carbon intensity (Regjeringen, 2021).

Domestic Norwegian CO_2 taxes are amongst the world's highest on average, laying only behind Lichtenstein, Switzerland and Sweden (The World Bank, 2021). In 2022, Norway's average environmental tax level is nearly 60 euros per ton of CO_2 omitted, but a proposal of 200 euros by 2030 has been issued by the government in non-ETS sectors (Finansdepartementet, 2022). Further, non-tax policies such as legal regulations and support schemes are already complementing the taxation strategy. The Norwegian government has estimated that roughly 80 % of Norwegian CO_2 emissions is either taxed and/or covered by the EU ETS, which shows the overall scale of Norway's overall abatement efforts (Klima- og miljødepartementet, 2021b).

Looking abroad, only 31 countries have implemented CO_2 taxes today (The World Bank, 2021). Essentially, this means that about 84 % of the countries in the world does not tax greenhouse gas emissions in any extent. Particularly, there exist almost no CO_2 taxation in Asia, Latin-America and Africa, with the exception of a few countries with relatively mild taxation rates (Argentina, Chile, Columbia, Japan, Kazakhstan, South-Korea, Mexico, Singapore and South Africa). Here, the few CO_2 taxes that actually are implemented average around only five euros per ton of CO_2, with South-Korea having the maximum of 15 euros. Viewing this altogether with Norway's powerful CO_2 abatement plan, both through the EU ETS and domestic taxation, it seems clear that Norway is set to lead the way as a pioneering nation in greenhouse gas abatement.

2.2.2 External Strategy and its Limitations

Norway also contributes internationally to augment strategies provide finance that help developing countries meet their own targets. On top of mediating and advising internationally, Norway invests massively in international green funds, such as The Green Climate Fund (GCF) and The Global Environment Fund (GEF) (Klima- og miljødepartementet, 2021a). The overall external objective is to nudge developing countries into cleaner production technologies and sustainable management of natural resources. However, since Norway is a small country, its effect on aggregate foreign emissions remains quite limited.

2.3 The Challenge of Norway

While industrialized countries like Norway is tightening regulation to rapidly transition into low-emission societies, other regions remain more passive and rather prioritize pure economic growth strategies, particularly in the short-term. With the current level of announced climate measures, the already existing asymmetry in policies is set to grow in the coming decades. For heavy-emission industries, the asymmetry may eventually result in production shifts from regulated regions to regions with laxer climate policies, a phenomenon often referred to as carbon leakage (European Comission, 2022). Norway, with its participation in EU ETS and its own strict environmental taxation strategy, may be at risk of such leakage.

3 Carbon Leakage

This section will explain concept of and economic drivers behind carbon leakage.

3.1 Definition

In its simplest form, the carbon leakage from a country (i) is the foreign increase in emissions directly driven by abatement policy or cost changes in the country of origin (i) (European Comission, 2022). It therefore occurs when emission-intense production in country (i) is shifted to another country single-handedly as a response to any operational change in country (i). Therefore, a foreign country simply scaling up its emission-intensive production parallelly with abatement in country (i) does not necessary classify as carbon leakage, because the foreign up-scaling can be driven by other factors than the abatement in country (i). Resultingly, when carbon leakage actually occurs, the excess foreign production is often aimed at the market experiencing regulations or cost-changes. The production shift can either happen by domestic companies shifting their industrial production abroad, or by foreign companies scaling up their own production to fill the supply gap occurring in the regulated country (i).

Carbon leakage is often measured in leakage rates. The carbon leakage rate from a country (i) tells us the percentage rate of domestically abated CO_2 emissions that are restored by increased emissions abroad. If a domestic CO_2 tax is implemented in country (i) and initiates a CO_2 abatement of 2000 tons, but 1500 tons is revived in foreign countries, the leakage rate from country (i) would be 75 %. Mathematically, the carbon leakage rate from country (i) to the rest of the world (J) following an implemented tax (t) in country (i) can be projected as

$$LR_i(t_i) = -\frac{\Delta Y_J(t_i)}{\Delta Y_i(t_i)} \tag{1}$$

The carbon leakage rate from country (i) equals the change in total foreign emissions as a share of the change in domestic emissions, driven by the tax change in country (i). One can observe that a negative domestic change in emissions, offset by an increase in foreign countries, generates a positive carbon leakage rate. Contradictory, if foreign countries also reduce their emissions, the carbon leakage rate comes back negative. The size of the leakage rate is exclusively defined by the size ratio of emission changes in country (i) and the rest of the world.

3.2 Drivers of Carbon Leakage

Economic policies are the foremost driver of carbon leakage. Environmental taxation, fees and cap-and-trade systems that change the cost base of industrial companies may weaken their international competitive edge and eventually force them to shut down or outsource production to laxer regions (Ward et al., 2015). Such systems can either be placed directly on CO_2 emissions in end-products, or they can be policies affecting input factors, such as a tax on the use of electricity.

In the short term, economic policies may trigger carbon leakage by regulated companies loosing international market shares to unregulated competitors. If rapidly incentivized or even legally obligated to reduce production, affected companies' initial market shares might quite immediately be snapped up by foreign companies. The International Energy Agency (2008) argue in their carbon leakage report that energy-intensive industries are at higher risk of such short-term leakage, since CO_2 emissions from energy use and fuel combustion most frequently are regulated. Energy-intensive industries are simply industries that rely highly on energy inputs in production, usually manufacturing industries. Also, the degree of product differentiation between competing products may also affect how easily market shares can be replaced by foreign companies in the short-term (Næss-Schmidt et al., 2019). Firstly, companies able to distinguish their products from international competitors may quietly increase its price, pass the burden onto consumers and maintain most of its market shares. Secondly, it becomes harder for competitors to quickly overtake production if the regulated products are unique and require specially designed production technologies or rare input factors. With this, uniform, energy-intensive industrial products like metals, chemicals and cement are often deemed at high risk of short-term leakage (Bye and Rosendahl, 2012).

In the longer run, economic policies may cause carbon leakage through investment shifts that forces regulated companies to either shut down or to relocate production abroad (Ward et al., 2015). As a tax on either end-product or input factors reduces the profit margins of affected companies, expected return for investors fall. With this, companies' access to new capital may gradually shrink when regulations are implemented, prohibiting them from making necessary investments to maintain a competitive edge against their unregulated competitors. Eventually, they may have to close shop or relocate to regions where regulations are laxer and expected capital returns are higher. Here, energy-intensity and degree of product differentiation should also be principal indicators of carbon leakage risk, but also the selection of cleaner production technologies available in the industry. If companies quickly can invest in and adapt to cleaner technologies when a regulation is implemented, they may dodge the bullet by transitioning away from regulation before their capital access becomes insufficient. Here, companies initial profit margins may also be an important factor, as companies with higher margins may survive for longer while transitioning to cleaner technologies. Næss-Schmidt et al (2019) highlight emission-intense industries such as metals and paper as vulnerable to long-term leakage from regulation.

In addition to short- and long-term leakage induced by economic policies, carbon leakage may arise from structural, asymmetrical cost shocks between different countries as well. If a region experiences a structural energy supply shock, energy prices typically rise and lower the competitive edge of energy-intense companies in these countries. In the short-term, affected companies may lose market shares in similarity with the short-term policy effect elaborated above. For example, McKinsey highlights in an article that upward gas price pressure has increased some European energy-intensive industries' production costs by nearly 50 % this year already, and the authors argue that affected companies must innovate strongly to maintain international competitiveness (Crispeels et al., 2022). As for asymmetrical shocks, longer-term relocation decisions will depend on the markets' perceived durability of the shock. Short-term price volatility may easily be offset by expectations of lower prices in the near future, but structural trend changes may produce market expectations of further increases, potentially creating capital flight from energy-intensive companies in affected regions.

From a game-theoretic perspective, a third potential driver of carbon leakage may be strategic actions by foreign countries. If a regulation is implemented in a region of the world, other countries may wish to respond to either amplify or reduce the asymmetry that initially has been established from the regulation itself. If the responding country has most of its international competitors in the newly regulated region, it may amplify the asymmetry by subsidizing its domestic producers, in attempt to more quickly let them absorb the market shares of the regulated competitors. In that sense, the implemented regulation will have stronger repercussions than if the foreign country does not respond at all. On the other hand, if foreign countries respond symmetrically to the implemented policy to reduce the asymmetry, the leakage will be lower or zero. Ward et al. (2015) argue that technological development derived from regulations in some countries may spill over to other countries, so that their CO_2 emissions decrease as well. In that sense, the leakage rate becomes negative.

The fourth driver of carbon leakage is global fuel price effects. If regulations in a region incentivize companies to innovate and lower their factor use of fossil fuels, world demand for fossil fuels falls. All else equal, this may cause global fuel prices to fall and incentivize companies in laxer regions to use relatively more fossil fuels in their production (Bye and Rosendahl, 2012). Consequently, the production clean-up in the regulated region is countered or even zeroed out from dirtier production mixes in foreign countries. Notably, regulated companies does not have to loose market share for leakage through global fuel price effects to occur, since its the change in foreign companies' factor mixes that increases their CO_2 emissions. Gas is often traded regionally, while oil is traded globally to practically one price, so this driver applies mostly to oil-intensive industrial sectors such as chemicals and petrochemicals. Overall, this driver is however mostly relevant for large economies like USA and China, because their demand to a much larger extent can alter world prices than a smaller country like Norway.

4 Empirical Literature

Estimating carbon leakage rates is far from an easy task. However, since it stands high on the agenda of policy-makers, many studies have examined carbon leakage empirically to examine its extent. This section will cover some of the findings.

4.1 Nordic Papers

Misch and Wingender (2021) from the International Monetary Fund predict an industrial leakage rate from Norway of 42 %, meaning that 42 % of Norway's abated emissions will be replaced in foreign countries. They use country-sector panel data on 38 countries, 21 industrial sectors and 10 years to estimate how countries' CO_2 trade with the rest of the world responds to domestic, sectoral energy price changes. Their energy prices are tax-inclusive, so they to a certain extent captures regulatory changes as well. Empirically, the authors use a log-log fixed effects model to estimate domestic price elasticities of CO_2 embodied in imports, exports, production and consumption, measuring the percentage change in CO_2 emissions arising from a percentage domestic price increase[2]. They find significant negative elasticities for CO_2 exports, production and consumption (-0.321, -0.523 and -0.198 respectively), but no significant effect on CO_2 imports. Their elasticities are however sample selection averages for the 38 countries and 21 sectors, so the degree of nuance is arguably a little low. The authors point out that this naturally may cause considerable uncertainty in pinpointing sector- or country-specific leakage rates.

Regardless, Misch and Wingender build a national CO_2 accounting framework suggesting that the leakage rate from a country must equal its change in net CO_2 exports divided by its change in CO_2 levels from domestic production. With their estimated average elasticities, they plot in country-specific values of aggregate CO_2 from imports, exports and domestic production in each country. As highlighted, they find a Norwegian leakage rate of 42.2 %, laying considerably above the sample average of 25 %. Conclusively, they argue that smaller countries may have higher leakage rates because they often are more open to trade and reliant on imports, producing more acute import increases in high-cost periods where domestic production falls.

Næss-Schmidt et al (Næss-Schmidt et al., 2019) from Copenhagen Economics predict in a report that carbon leakage rates from energy-intensive industries in Nordic countries may be as high as 84 percent, if the Nordic countries unilaterally exceed the abatement efforts decided the Paris Agreement. Their report initially examines which Nordic sectors are at highest *risk* of carbon leakage, but they also simulate carbon leakage rates in a general equilibrium model using data from the GTAP-database, a trade database including bilateral trade patterns, consumption and production data, as well as factor input mixes. Their predicted rate of 84 % is however in a simulated scenario where the Nordic countries unilaterally impose stricter policies to meet IEA's

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[2] For instance, the domestic price elasticity of CO_2 embodied in imports measures the % change in CO_2 imports stemming from a one % increase in domestic prices.

"sustainable development scenario" of not exceeding a temperature rise of 2 degrees, whereas the rest of the world remain at today's policy- and emission-levels.

The main goal of their analysis is however to classify which Nordic industries are at highest *risk* of carbon leakage, by examining three key indicators: cost implications of regulations, international competitive pressure and capital-intensity. For cost implications of regulations, they measure industries' total energy expenditures per value added, ranging industries in how energy-intensive they are. In similarity with the IEA (2008), Næss-Schmidt et al argue that energy-intensive industries are at higher risk of leakage either through direct CO_2 taxation or indirectly through taxation on fossil fuels. They only use this indicator as a filter to determine which sectors may be exposed to carbon leakage risk, using a cutoff value of minimum 10 % energy expenses per value added. Secondly, they measure the degree of leakage risk from international competitive pressure by viewing international transportation costs and trade barriers for different industries. The intuition is that industries protected of international competitors by either high transportation costs and/or political trade barriers such as tariffs will be at lower risk of leakage if taxation is implemented, since they to a higher degree will be able to increase their prices. Thirdly, Næss-Schmidt et al argue that the capital-intensive industries have reduced short-term leakage risk due to large capital investments using time to depreciate when taxes are implemented, resulting in a long transition period with lowering profit margins before industrial companies eventually relocate or shut down. When evaluating the three indicators altogether they conclude that Nordic mineral, chemical, refined petroleum product, machinery, paper product and textile production are at *high* risk of short-term carbon leakage. The authors further point out that some sub-sectors in the metal, food and paper industries obtain more long-term risk due to higher capital-intensity and thereby longer burnout time. Their risk evaluation is in high co-ordinance with EU's carbon leakage risk list (European Comission, 2019).

The Danish Economic Council of Environmental Economics (2019) examine carbon leakage from Denmark and estimate an average carbon leakage rate of $45 - 53$ %. They also use the GTAP-database, and they use 2019-data to simulate how a Danish national CO_2 tax increase of 100 DK per tonne of CO_2 omitted in Danish production affect foreign emissions, if foreign policies remain unchanged. Importantly, they find that leakage rates are predicted between 65 - 75 % for agriculture, energy-intensive manufacturing sectors and electricity and heating. This conforms well to the predicted Nordic leakage rate of 84 % in energy-intensive sectors by Næss-Shcmidt et al (2019). The authors highlights that EU ETS may be a strong driver for these sectors' high carbon leakage rates, possibly because the cap-and-trade system already had begin to intensify in transitioning to its next phase beginning in 2021 (The European Environment Agency, 2022). For non energy-intensive manufacturing sectors, they actually predict a negative leakage rate of - 15 %, meaning that foreign countries reduce their CO_2 emissions by 15 % of Danish abatement following the 100 DK CO_2 tax. This could be due to subsequent technological spillovers, as highlighted in Ward et al (2015).

4.2 International Papers

Aichele and Felbermayr (2015) analyze if the Kyoto protocol has induced carbon leakage from ratifying countries. Entering force in 2005, the protocol was designed to commit industrialized countries to shrinking their greenhouse gas emissions (UNFCCC, 2022). 192 countries have ratified the agreement. As the protocol is based on individual and highly differentiated targets, Aichele and Felbermayr hypothesizes that carbon leakage would arise from highly committed countries to developing countries and non-ratifiers of the agreement.

With sectoral panel data on CO_2 embodied in bilateral trade for 40 countries, 12 industries and 12 years (1995-2007), they use a difference-in-difference approach to estimate the protocol's treatment effect on CO_2 embodied in imports. In their two control groups, all country pairs have the same Kyoto status – either ratified or not. Their two treatment groups consist of all country pairs where either the initial importer or initial exporter ratified the agreement, but their trading partner did not. Importantly, they find that CO_2 imports increased by 8 % from noncommitting countries if the initial importer ratified the protocol. Evidently, this corresponds to the short-term market share effect of regulation elaborated in chapter 3. Aichele and Felbermayr also find that the CO_2 intensity of imported goods increased 3 % more for the treatment group of initial importers ratifying the protocol than the control groups. To back up this result, they also find that the CO_2 intensity of exports from ratifying net exporters decreases. This conforms to the fossil fuel price effect elaborated in chapter 3, whereas the clean-up in regulated countries are offset by dirtier factor mixes in unregulated countries. Allover, they find that the CO_2 import effects of ratifying the protocol are largest in the metal, mineral, paper, machinery and transport equipment sectors. Despite not estimating leakage rates itself, the authors conclude from their findings that the Kyoto protocol indeed has generated some degree of carbon leakage from ratifying countries.

Fowlie et al (2016) analyze carbon leakage induced from California's cap-and-trade system. Aiming to lower greenhouse gas emissions % percent below 1993-levels by 2030, California's cap-and-trade system is a multi-sectoral system that has shrunk its number of allowances since its implementation in 2013, yielding higher operating costs for heavy-emission industries. Fowlie et al hypothesized that this system has induced leakage to laxer countries from U.S. industries highly dominated by Californian production.

To estimate leakage risk empirically, they use panel data on foreign countries' trade flows with the US and energy prices for 98 energy-intensive-industries. In similarity with Misch and Wingender (2021), they use energy prices as a proxy variable for taxation. Hereby, they also assume that companies respond equally to trend changes in energy prices as they would to changes in economic policies. Fowlie et al do however not account for CO_2 embodied in trade, but rather use shipment values in US$ to examine changes in production and trading patterns following changes in relative, bilateral cost levels. They predict that the median industry lowers domestic production by five %, exports by six % and increases imports by four %, following a tax increase of 10 US$ per ton of CO_2. They also find that elasticities increase with the energy-intensity in industries, whereas industries like cement, lime and industrial gas are estimated to decrease exports and increase imports by roughly 20 and 11 %, respectively. While combining aggregate production, export and import values with the derived mean elasticities, they conclude that "market transfer rates", meaning the share of down-scaled domestic production transferred to foreign countries following domestic tax changes, has an upper bound of 20 % for most industries. Unless foreign countries' CO_2 intensity are higher that of the United States, this corresponds to lower leakage rates than the previous papers[3].

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[3] There often is much variation between estimated leakage rates in empirical papers, assumably because results are sensitive to sector and country specifications.

5 Data

This section will explain the data and how it has been processed to fit the analysis.

5.1 Raw Data

5.1.1 Norway's CO_2 Trade Volumes

Firstly, panel data from the Organisation for Economic Co-operation and Development on bilateral Norwegian CO_2 imports and CO_2 exports are used, extracted from their "TECO2: Carbon Dioxide Embodied in International Trade" database (OECD, 2021). Their data is both country- and sector-specific, as it contains sectoral, bilateral CO_2 trade volumes between 78 countries, categorized into 58 industries in the ISIC-4 framework. For this analysis, Norway's bilateral CO_2 imports and exports with all 77 remaining countries are extracted for eight industrial sectors in the period 1995-2015. Measured in millions of tons of CO_2, Norway's imported and exported emissions will be the outcome variable in the coming empirical analysis.

OECD calculates sectoral CO_2 trade flows by factoring in country-sector-specific data on fuel combustion from the International Energy Agency in their already existing input-output data (Wiebe and Yamano, 2016). Resultingly, their CO_2 data captures emissions generated through every chain of the production process, and quite suitably, their data sources emissions to where it has been emitted along the production chain. For instance, if Norway imports a car from Germany that has wheels from Poland, screws from Indonesia and an electric system from Japan, emissions along the production chain is sourced to Poland, Indonesia and Japan. The data therefore provides a highly nuanced system of the 77 countries' CO_2 trade with Norway.

Additionally, sectoral production measured in millions of CO_2 tons are extracted for all countries. Despite not being a main outcome variable itself, produced emissions will be utilized to estimate domestic production elasticities, used in a national emissions accounting framework to estimate leakage rates. This will be further elaborated in the empirical chapter.

5.1.2 Sectoral Energy Prices

Secondly, a data-set containing weighted, sectoral tax-inclusive energy prices for 14 industrial sectors and 48 countries in the period 1995-2015 is utilized. This is constructed by Sato et al (2020), a renowned energy economist at the London School of Economics. The data combines data on inflation-adjusted national fuel prices and sector-wise energy factor mixes from the International Energy Agency to produce yearly, sectoral price indexes for all 48 countries. The fixed index is calculated as the weighed geometric mean of energy prices per ton of oil equivalent, in constant 2010 USD. A ton of oil equivalent (TOE) is the quantity of energy from any energy source that generates the same energy level as a ton of oil, allowing for energy prices to be directly compared (Petroleumstilsynet, 2022). The fixed price index is calculated by

$$FEPI_{i,z,t} = \sum_{j}^{J} w_{i,z}^{j} * log(P_{i,t}^{j}) \tag{2}$$

For each different energy type (j), the fixed index weighs its share in the factor mix in sector (z) in country (i) and multiplies it with logged energy prices per TOE in country (i) during year (t). When summarizing this for all different energy types (J), a country-sector-year-specific weighed geometric average of energy types is produced. Notice that the price index keeps energy shares constant during the whole 20 year period, and it uses shares from 2010 as the anchor year. It therefore neglects any changes in energy factor mixes within sectors over time. Since companies' chosen energy mix definitely should be affected by energy prices, and energy prices on a national level to a certain extent should be affected by companies' chosen energy mixes, keeping shares constant should eliminate potential endogeneity issues. All variation in the fixed index should hereby come from real change in actual energy prices or energy taxes itself. Norwegian and foreign energy prices will be used as the explanatory variables in the empirical analysis.

5.1.3 Control Variables

Four different control variables will be included in the analysis. In simple terms, a control variable can be defined as a variable that is held constant to ensure it does not affect the outcome variable of interest in an analysis(Stock and Watson, 2020). In regression models, control variables are primarily included to ensure that their effect on the outcome variable is not assigned to the dependent variable itself.

Firstly, country-specific wage data has been extracted from OECD and the International Labour Organization (ILO), and it contain yearly average wages in each country measured in USD (The International Labour Organisation, 2022)(OECD, 2022d). With this, Norway's relative wage in each year (t) to each foreign country (i) will be constructed. Importantly, using average wages is not optimal as countries with uneven income distributions may have highly right-skewed averages, but any structural changes in Norway's relative wages should assumably still be captured. Average wages was also the wage measure with the most credible sources and most publicly available data. Nevertheless, the reasoning behind keeping Norway's relative wage levels constant is that relative wage changes may drive production shifts itself. From a Norwegian cost perspective, the incentives to outsource production increases when foreign wages fall (Norway's relative wages increase), because labor costs will be relatively lower (Bottini et al., 2008). Wage levels may additionally correlate with energy prices in some extent. For instance, Keane and Prasad (1996) conduct an empirical analysis and pinpoint in a wide-spread negative effect of oil price shocks on wages in USA. Keeping Norway's relative wages constant therefore seem altogether logical.

Secondly, country-specific data on countries' net foreign direct investment inflows has been extracted from the World Bank (2022b). The FDI net inflow of a country measures the difference between aggregate foreign direct investment and aggregate foreign disinvestments in the country, so the variable measures if most foreign capital is flowing in or out of the country, on a yearly basis. The variable is measured in US$ and take a positive value if yearly investments are higher than yearly disinvestments, and negative if otherwise. The reason to keeping net capital movements constant is to ensure that capital-driven production shocks in foreign countries are not assigned to the energy price estimates. For instance, Kutan and Vuksic (2007) pinpoint a positive relationship between inward FDI and exports, through heightened supply capacities. If capital movements also correlate with energy prices, for instance if global foreign direct investments falls in periods of high oil prices, price estimates may be biased. Controlling for aggregate capital movements therefore appears reasonable.

Thirdly, countries' net imports of energy (% of energy use) has been extracted from the World Bank (2022a). This is a variable measuring net energy imports, meaning total energy use minus domestic energy production, as a share of total energy use. The parameter ranges from [-∞, 100 %], because countries can export more than their domestic use of energy (negative value) but not import more than their use (positive value up til 100 %). Since countries heavily reliant on energy imports may be more exposed to global supply disturbances, controlling for net energy imports seems plausible. For instance, Yepez-Garcia and Dana (2012) argue in a report for The World Bank that net energy-importing countries obtain more price and supply risk due to weaker ability to diversify their energy portfolio, particularly in times of high oil prices. Even though most of this dynamic should be captured in higher energy prices itself, the higher risk level may also have a negative impact on industrial investments in net importing countries, possibly creating even stronger production responses in times of higher energy prices. Countries' reliance on energy imports will therefore be held constant during the analysis.

Lastly, data on countries' primary energy supplies has been extracted from OECD (2022a). The primary energy supply of a country equals its domestic energy production plus energy imports, minus its energy exports, energy stored in international bunkers and eventual energy stock changes. The variable is measured yearly in million tons of oil equivalents, and it serves as a suiting measure of how much energy countries have available on a yearly basis. Naturally, most energy supply variation should be captured through the energy prices itself, but since oil and coal (partly) is traded to global prices (Bye and Rosendahl, 2012), there might be national energy supply disturbances that are not fully reflected in the price indexes. This is particularly relevant for smaller countries that do not have the ability to affect world fuel prices with their energy supplies. To ensure energy supply-driven changes in trading patterns are not fully assigned to the energy price indexes, foreign countries' primary energy supplies will therefore be controlled for.

5.2 Data Processing

There has been a considerable amount of work in restructuring, merging and processing raw data to finalize data ready for econometric analysis. Firstly, all sector-specific datasets from OECD on both CO_2 imports and exports (and production) had to be restructured in Excel to match the row-column structure of the price data from Sato. Both data sources followed the international classification structure of SITC-4, but there were however a few mismatches between Sato and OECD regarding the number of SITC-digits that some sectors were stated in. Hence, merging sectoral data was quite challenging for some of the sectors.

Firstly, energy price data was too general to match OECD data directly in the sector ”chemicals and petrochemicals” (OECD, 2022c). The OECD data on CO_2 trade in this sector was split into two different subcategories: “coke and refined petroleum products” and “chemical and chemical products”. Fortunately, as the OECD data only contain absolute values of Norwegian CO_2 imports and exports, this data mismatch was quite manageable to overcome by adding the absolute volumes together. For each observation of the two sub-sectors, their observations in each country (i) in each year (t) was added together, which generates yearly, country-specific observations of ”chemicals and petrochemicals”.

A data mismatch that was quite challenging was that the OECD data in one sector, basic metals, was too general to match the energy price data. While CO_2 trade from OECD was summarized under “basic metals”, the price data from this sector was split into “iron and steel” and “non-ferrous metals”. The two sub-sectors constitute ”basic metals” in the SITC-4 framework. Resultingly, the data from OECD was initially unfit to directly merge with the price data, and the two sub-sectors had to be merged to be mergeable with OECD data. Unlike absolute volumes of CO_2 imports and exports, sub-sectoral price data cannot be merged simply by adding prices together, as this simply would produce a price sum of the two sub-sectors. Instead, by using highly detailed production data from OECD, EUStat and UNIDO, I was able to create a yearly, weighed price estimate for each country in the sector ”basic metals” by weighing the two sub-sectors' energy prices by their production shares (EUROSTAT, 2022)(UNIDO, 2022)(OECD, 2022b). Mathematically, the weighed price index in basic metals (Z) at year (t) for country (i), as a function of the two subsectors ($z_1 \quad z_2$), was calculated as

$$FEPI_{i,Z,t} = \pi_{z_1} * FEPI_{i,z_1,t} + (1 - \pi_{z_1}) * FEPI_{i,z_2,t} \tag{3}$$

Here, each of the two sub-sectors' price indexes was weighed with their production share (π) of ”basic metals” for each country (i) in each year (t). With this, price data of the sector “basic metals” has been replicated for all countries and all years, thus making it mergeable with CO_2 data from OECD. The production data was however partly restricted for some countries, as there were some missing observations on sub-sector shares. A single null between two data observations was treated as the mean of the former and following year, and coherent nulls of up to three years was treated as gliding means between up to three former and following years. Naturally, there come some limitations to assuming that the two sub-sectors' shares equal the mean between previous and latter shares, but since sector shares should correlate highly between years, this seemed like the best approach to approximate missing data [4]. Countries with a considerable share of missing data will be omitted from the analysis.

5.3 Finalized Data

After restructuring and merging the data together, a panel data-set obtaining data on bilateral, sector-specific CO_2 trade levels with Norway, energy prices, wages, net foreign direct investments, degree of energy import-reliance and primary energy supplies has been finalized for 36 countries (incl. Norway) and eight industrial sectors from 1995-2015. The eight sectors are respectively basic metals, chemical and petrochemicals, construction, machinery, mining and quarrying, non-metallic minerals, transport equipment and textiles and leather, all being energy-intensive industries having either all or a considerable share of its sub-sectors listed in both Næss-Schmidt et al (2019) and EU's updated list for sectors at risk of carbon leakage (European Comission, 2019). The countries consist of all European countries (excl. Latvia, Lithuania, Luxembourg, Cyprus and Gibraltar), in addition to China, Russia, Mexico, Indonesia, South Africa, South Korea, Kazakhstan, Japan, Canada, Australia and Brazil. 18 of the foreign countries are in the category of Norway's 20 largest industrial trading partners measured in CO_2 emissions, only lacking India (18th) and Taiwan (20th) (OECD, 2021). The remaining 17 trading partners also trade significantly with Norway. Lastly, the panel data-set is nearly balanced, except that Turkey, Russia, Bulgaria and Indonesia lack either wage data and/or fixed energy price indexes in a few years. They will still be included in the analysis.

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[4] This may naturally cause some impreciseness, but assuming that the production share of "iron and steel" of "basic metals" in year (t) equals the average between year (t-1) and year (t+1) appears as the most reasonable solution to approximating missing data points. From the already existing data, countries' shares seem to be fairly constant over time, so it seems rather unlikely that there should be high volatility in the missing data points.

6 Descriptive Statistics

This section will present descriptive statistics on Norway's CO_2 trade and explanatory variables, using statistical tables and historical graphs. A summary statistics table is provided below.

Table 1: Summary statistics

Variable	N	Mean	Median	SD	Unit
CO_2 imports	6216	0.043	0.004	0.145	Mill. ton. CO_2
CO_2 exports	6216	0.045	0.002	0.234	Mill. ton. CO_2
p_{NO}	6216	517.793	530.044	125.295	US$ per TOE
p_{FO}	5604	592.455	544.071	285.979	US$ per TOE
$\mathrm{RelWage}_{NO}$	5808	4.445	1.277	9.036	$\mathrm{Wage}_{NO}/Wage_{FO}$
$\mathrm{FDIFlows}_{FO}$	6216	32.073	9.801	65.437	US$, billions
$\mathrm{EnergyNet}_{FO}$	6144	5.873	44.732	128.568	Net energy imports (% of use)
$\mathrm{MillToes}_{FO}$	6216	226.707	74.780	472.308	TOEs, millions

The number of observations, mean values, median values and standard deviations are tabulated for dependant variables, regressors and control variables. The reason that the number of observations are not equal for all variables is that some countries has limited data on energy prices, wages and net energy imports. Sectoral, Norwegian energy prices appears to have 6216 observations, but this is because they are merged onto each sector (z) for each year (t) in each foreign country (i) to fit the panel data structure. In reality, there is naturally only one Norwegian energy price index per sector (z) per year (t).

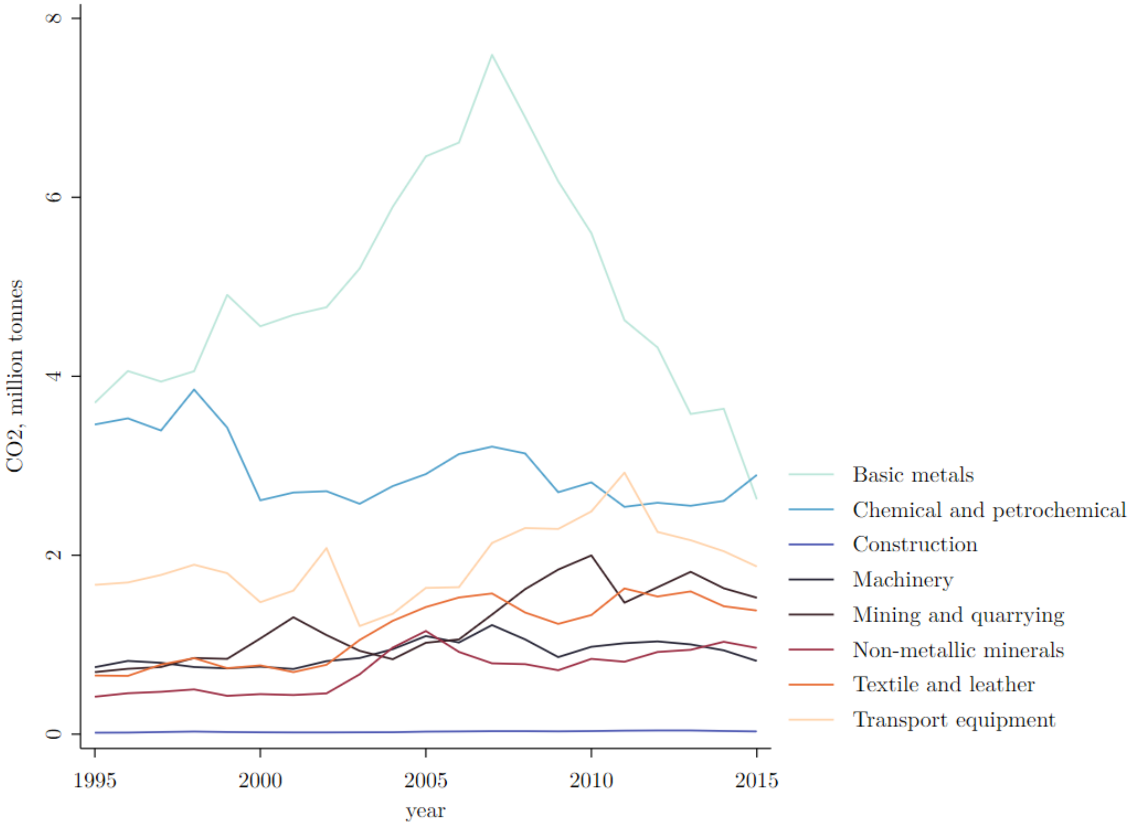
For Norwegian CO_2 imports and exports, the mean and median values show the average (and median) bilateral trade observation, measured in millions of tons of CO_2. Both variables seem to obtain much variation, when looking at standard deviations relatively to mean and median values. For sectoral energy prices, Norway's energy prices (P_{NO}) obtain lower mean and median values than average foreign energy prices (P_{FO}) in the 35 foreign countries. The standard deviation is however much larger for foreign prices. Norway's relative wage ($Relwage_{NO}$) seems to have an interestingly high mean value. This seem to be driven particularly by some early years of remarkably low wages in Kazakhstan, Bulgaria, Indonesia and China. For net FDI inflows in the 35 foreign countries ($FDIFlows_{FO}$), both the average and median observation is positive, implying that most countries' seem to attract more foreign investments than foreign disinvestments. The standard deviation is however considerable. Regarding net energy imports ($EnergyNet_{FO}$), both the mean and median value is positive, and this means that the average foreign country is a net importer of energy. The standard deviation is large due to large net exporters (negative value) like Russia, Canada and Kazakhstan. Total energy supply ($MillToes_{FO}$) is naturally positive.

Table 2: Sectoral Statistics on Norway's CO_2 trade

Variable	Sector	Mean	Sum	St.dev
CO_2 Imports				
	Basic metals	4.95	103.91	1.28
	Chemical and petrochemical	2.96	62.14	0.39
	Construction	0.03	0.60	0.01
	Machinery	0.91	19.01	0.14
	Mining and quarrying	1.24	26.09	0.41
	Non-metallic minerals	0.72	15.13	0.24
	Textile and leather	1.16	24.26	0.36
	Transport equipment	1.92	40.33	0.41
	All sectors		291.56	
CO_2 Exports				
	Basic metals	1.65	34.69	0.30
	Chemical and petrochemical	2.85	59.94	0.35
	Construction	0.01	0.18	0.00
	Machinery	0.11	2.23	0.04
	Mining and quarrying	8.60	180.64	1.06
	Non-metallic minerals	0.14	2.88	0.03
	Textile and leather	0.02	0.32	0.01
	Transport equipment	0.13	2.68	0.04
	All sectors		283.55	

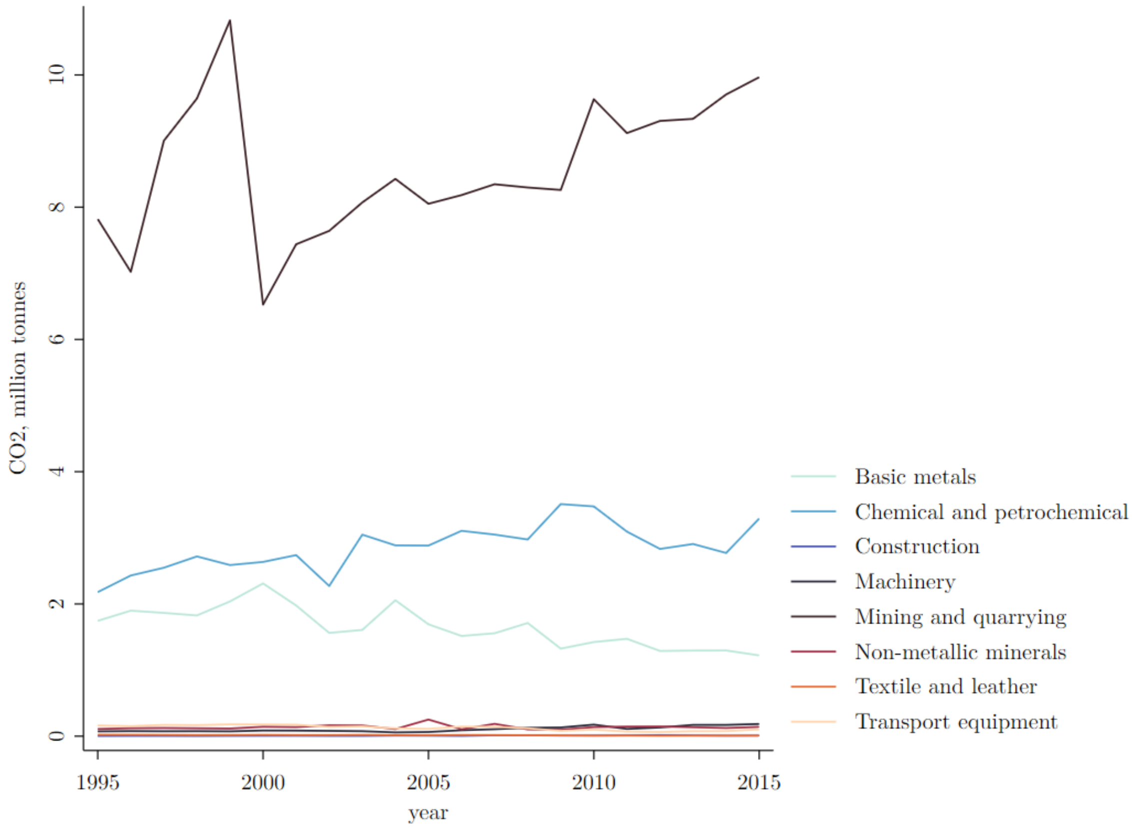
Above, sectoral, aggregate CO_2 trade data is tabulated. Yearly mean values, the aggregate sum throughout the whole 20 year period and yearly standard deviations are tabulated sector-wise for Norway's total CO_2 imports and exports with the world, in million tons. Norway has been a net CO_2 importer in seven of the eight sectors throughout the period, but a clear net exporter in the mining and quarrying sector. Other than this, Norway also obtain considerable exported CO_2 emissions in the chemical and basic metal sectors, despite being a net CO_2 importer here. For construction, both imported and exported CO_2 emissions are very low, and for the remaining sectors, CO_2 exports are low, but CO_2 imports considerable. Aggregating the imports and exports throughout the whole period, Norway has been a net importer of CO_2 emissions.

Figure 1: Norwegian CO_2 imports



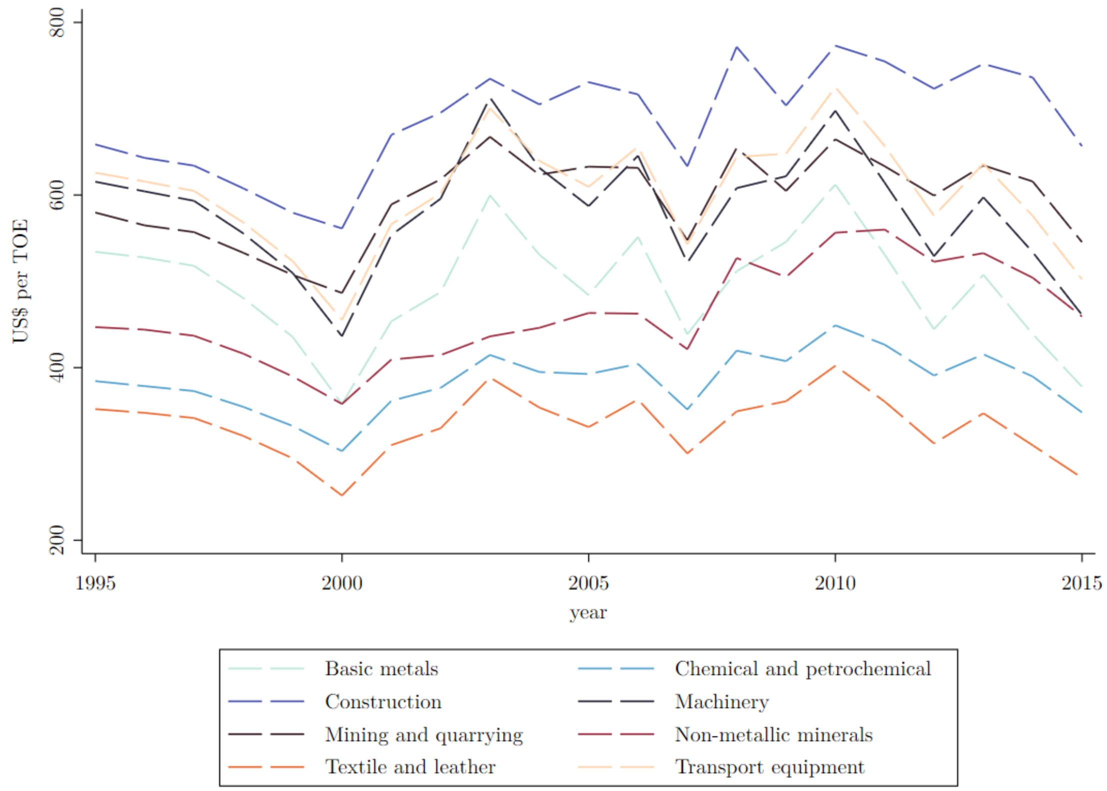
Norway's sectoral CO_2 imports from the world are tabulated above. At first glimpse, one can observe that basic metals and chemicals/petrochemicals are the two most foregoing sectors in terms of Norway's imported CO_2 emissions. Interestingly, one can also observe that for basic metals, imported emissions rose steadily until 2007-2008, where they have been falling sharply since. The financial crisis may be a potential explanation, where banks systematically crashed, lost lending capacity and cut back on investments. Resultingly, trading partners' metal export supply and Norway's import demand may have been simultaneously reduced, giving the decline in imported CO_2 emissions. It may however also be a result of technological development in trading partners as many of them ratified the Kyoto protocol in 2005. Further, all remaining sectors except construction also seem to be sectors where Norway import considerable CO_2 emissions. Imported CO_2 emissions in transport equipment, textiles, mining and quarrying, machinery and non-metallic minerals seem to have increased carefully, but steadily, throughout the period. However, from 2014, they seem to initiate a drop, possibly due to reduced Norwegian import demand following the oil price crash in 2014.

Figure 2: Norwegian CO_2 exports



Norway's sectoral CO_2 exports to the world are tabulated above. Not surprisingly, the mining and quarrying sector stands out as the area where Norway exports by far the most CO_2 emissions. Exported emissions rose sharply until 1998, before falling even more sharply for roughly two years. Much of this rapid movement may have been oil-driven, because the oil price soared before beginning a rapid fall in 1997 (Mabro, 1998). CO_2 exports in the sector have increased steadily since 2000. One can also observe that chemicals/petrochemicals and basic metals also are important contributors to Norway's exported industrial CO_2 emissions. Norway's aluminium and petroleum coke sectors assumably contributes a lot to this. Further, unlike for imported emissions, the remaining sectors are almost a standstill, despite a small period of mineral exports around 2005. We can observe from this that most of Norway's exported emissions stem from extracting and processing energy and industrial materials, whereas general manufacturing exports are extremely low.

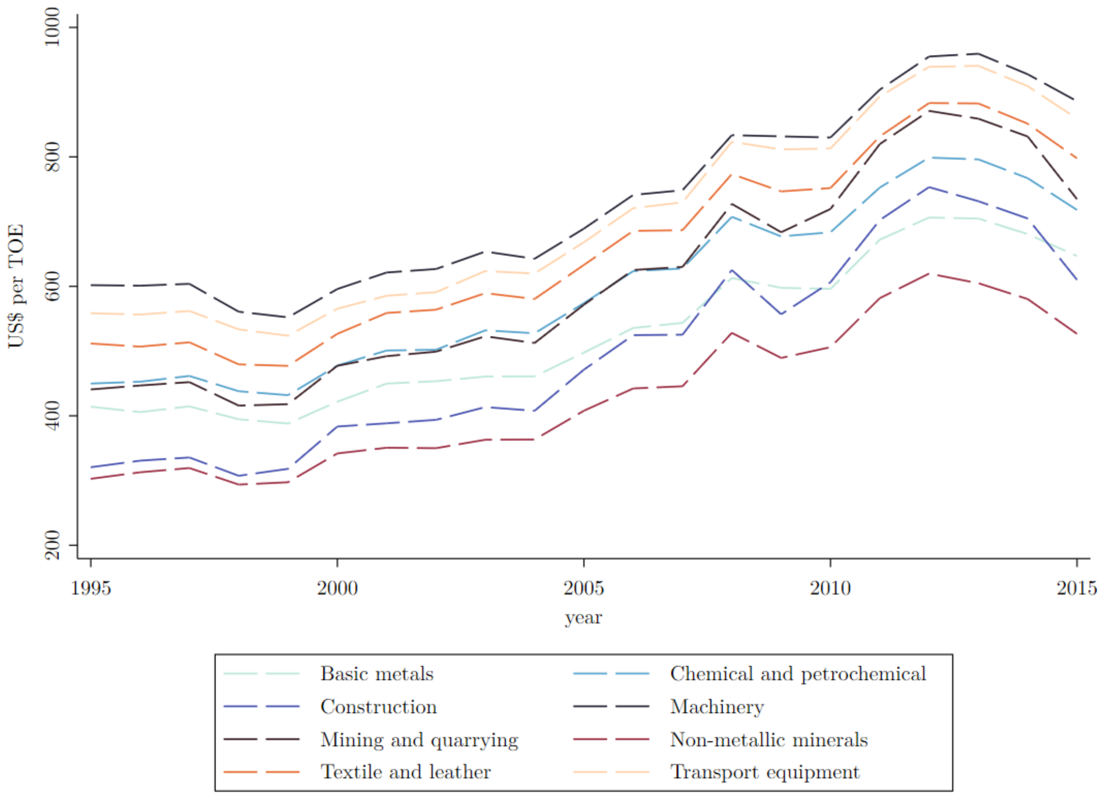
Figure 3: Norwegian energy prices, US$ per TOE



Real sectoral energy prices measured in US$ per tonne of oil equivalents for Norway are graphed above. The energy prices are strongly correlated, both because they are constructed by the same underlying fuels and because they are engulfed by the same Norwegian fees. Overall, construction, mining and quarrying, transport equipment and machinery lay evenly over the four remaining sector per TOE. Chemicals and textiles stands out as sectors with relatively low prices throughout the whole period.

In terms of price development, one can observe a broad and accelerating fall until year 2000. This fall may be partly driven by the low oil price plunge elaborated above, but assumably most by fixed-contract electricity prices that had declined steadily over multiple years, until late 2000 (Statistisk Sentralbyrå, 2001). From here, a sharp increase is observed particularly in the high-price sectors. Despite some volatility and disruption from the financial crisis in 2008, prices appear to have increased quite steadily over time. A new fall is initiated in 2014, probably due to the 2014 oil price plunge.

Figure 4: Average foreign energy prices, US$ per TOE



Average, real sectoral energy prices measured in US$ per tonne of oil equivalents are graphed above for 35 foreign countries in the sample selection. There is however huge variation between countries' energy prices. For example, the observed minimum value is 78 US$ per TOE in Kazakhstan's' basic metals sector in 2006, and the maximum value is 1992 US$ per TOE in Japan's transport equipment sector in 2014[5]. There appear to be some sectoral cost asymmetries between Norway and the average foreign country, especially for the construction and textile sectors. Machinery and transport equipment stand out as the sectors with highest energy prices.

In terms of price development, a fall in real prices can be observed until 2000, in similarity with Norway. The fall is however milder than for Norway, potentially due to milder decreases in electricity prices on average. Since 2000, foreign energy prices have increased steadily, with the exception of a fall in the 2008 financial crisis and a preliminary fall in the 2014 oil price plunge. One can also observe that the average increase in real energy prices throughout the whole period appear to be higher in foreign countries than for Norway.

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[5] Due to the high differences in energy prices between foreign countries, comparing the average directly with Norway's prices should be done cautiously.

7 Empirical Model

This section will concretize the overall empirical objective, present the empirical model and its underlying econometric founding.

7.1 The Empirical Objective

The overall empirical objective is to estimate how Norway's CO_2 trade responds to changes in both domestic and foreign tax-inclusive energy prices. Methodically, this will be done by estimating domestic and foreign price elasticities of Norway's CO_2 imports and exports, meaning the percentage change in CO_2 exports and imports that arises from a percentage increase in domestic and foreign energy prices. In light of the leakage dynamics elaborated in chapter 3, a positive domestic and negative foreign price elasticity is hypothesized for Norway's CO_2 imports. Oppositely, a negative domestic and positive foreign price elasticity is hypothesized for Norway's CO_2 exports. Moreover, a general domestic price elasticity of CO_2 from domestic production will be estimated for the sample selection, for supplementary use in a national CO_2 accounting framework for deriving the actual carbon leakage rate. This will be elaborated in chapter 8.

7.2 The Empirical Model

Fixed effects regression models will be used to analyze how tax-inclusive prices affect Norway's CO_2 trade. The two following CO_2 trade regression models will be estimated

$$ln(M_{i,z,t}) = \alpha + \beta_0 * ln(p_{NO_{z,t}}) + \beta_1 * ln(p_{FO_{i,z,t}}) + (x_{i,z,t})' * \delta_x + \lambda_i + \lambda_z + \sigma_t + \epsilon_{i,z,t} \qquad (4)$$

$$ln(X_{i,z,t}) = \alpha + \beta_0 * ln(p_{NO_{z,t}}) + \beta_1 * ln(p_{FO_{i,z,t}}) + (x_{i,z,t})' * \delta_x + \lambda_i + \lambda_z + \sigma_t + \epsilon_{i,z,t} \qquad (5)$$

Equation (4) represents Norway's CO_2 imports and equation (5) represents Norway's CO_2 exports. $M_{i,z,t}$ measures the imported CO_2 emissions in Norway in sector (z) from country (i) in year (t), while $X_{i,z,t}$ measures the exported CO_2 emissions from Norway in sector (z) to country (i) during year (t). CO_2 is measured in million tons. Moreover, the two regressors are Norwegian and foreign energy price indexes (P_{FO} and P_{NO}), measured in US$ per tonne of oil equivalents. $P_{NO_{z,t}}$ is the Norwegian sectoral energy price index in sector (z) during year (t), while $P_{FO_{i,z,t}}$ is the sectoral energy price index in sector (z) in foreign country (i) during year (t) [6]. Both CO_2 levels and energy prices will be log-transformed, so β_0 and β_1 will be the estimated domestic and foreign price elasticities, respectively. However, since Norway's CO_2 imports and exports obtain some zero-observations, each observation will be assigned a small constant (0.001) so that they are defined on the logarithmic scale[7].

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[6] Notice that $P_{NO_{z,t}}$ is not indexed with foreign country (i), as Norwegian energy prices does not vary with trading partners.

[7] This is an econometrical technique to ensure that all observations is defined in the logarithmic scale, whereas the econometrical consequence in theory should only be a changed constant term (Burbidge et al., 1988)

$(x_{i,z,t})'$ is a vector of control variables. As elaborated in chapter 5, Norway's wage gap to country (i) and the net inward FDI flow, energy reliance and absolute energy supply of country (i) will be controlled for. Norway's wage-gap to foreign countries will be taken as the log-difference between Norwegian and foreign wages, inspired by (Sato and Dechezleprêtre, 2015) that have used this approach in a bilateral trade analysis. Countries' net FDI inflows is denoted in billions of US$, total energy supply is denoted in millions of tons of oil equivalents and energy reliance is, as previously elaborated, denoted as a percentage of energy consumption ranging from $[-\infty, 100]$. δ_x captures the effect each separate control variable.

The lambdas (λ_i and λ_z) capture country- and sector-fixed effects, meaning all time-invariant characteristics that affect the CO_2 outcome variables, on both a national and sectoral level. Sigma (σ_t) captures unit-equal, yearly effects of time-varying events on CO_2 levels, allowing the model to control for global shocks. Lastly, epsilon ($\epsilon_{i,z,t}$) is a stochastic residual term capturing all variation in CO_2 levels that are not explained by the included variables, on a national, sectoral and time-varying level.

Secondly, in addition to the two Norway-specific, bilateral CO_2 trade models, a domestic CO_2 production model will be estimated for the whole sample selection, including Norway. Unfortunately, a Norway-specific CO_2 production elasticity cannot be estimated due to lack of degrees of freedom. The following model will therefore be estimated with all countries in the sample selection

$$ln(Y_{i,z,t}) = \alpha + \beta_0 * ln(p_{i,z,t}) + (x_{i,z,t})' * \delta_x + \lambda_i + \lambda_z + \sigma_t + \epsilon_{i,z,t} \tag{6}$$

$Y_{i,z,t}$ measures CO_2 emissions from domestic production from sector (z) in country (i) during year (t). The price variable, $p_{i,z,t}$, is here the domestic energy price in sector (z) in country (i) during year (t). Otherwise, the model is completely equal to the two Norway-specific trade models, in regards control variables, country- and sector-fixed effects and time dummies. This model will also log-transform both the dependent variable and regressors.

7.3 The Fixed Effects Regression Model

The three regression models are fixed effects regression models. Such models are widely used with panel data as they control for unobserved, time-invariant heterogeneity between observational units (Wooldridge, 2009). For instance, countries geographically closer to Norway may engage more easily in trade with Norway due to lower transaction costs and stronger diplomatic ties. By including sector- and country-specific dummies, the utilized models filter out all constant factors that affect the CO_2 outcome variables, on both a sector- and country-level. The model therefore allows for correlation between any unobserved, time-invariant factors and the regressors, as all constant characteristics is filtered out. The filtration is done by subtracting the within panel average from each panels' observations estimation, thus filtering out constant heterogeneity between panels (Stock and Watson, 2020). Using the import equation as an exemplification, the following model will be estimated first

$$ln(\bar{M_{i,z}}) = \bar{\alpha} + \beta_0 * ln(\bar{p_{NO_z}}) + \beta_1 * ln(\bar{p_{FO_{i,z}}}) + (\bar{x_{i,z}})' * \delta_x + \bar{\lambda}_i + \bar{\lambda}_z + \bar{\sigma} + \bar{\epsilon_{i,z}} \tag{7}$$

This is the entity-mean model, and it estimates averages for each panel throughout the whole period. For instance, we have that

$$ln(\bar{M_{i,z}}) = \frac{\sum_t ln(M_{i,z,t})}{T}$$

This is the mean, yearly CO_2 import volume in sector (z) from foreign country (i). The same calculation is done for all the other variables in the model. Further, the actual regression model will be estimated by subtracting the mean equation (7) from each actual observation, so that

$$\begin{aligned} ln(M_{i,z,t}) - ln(\bar{M_{i,z}}) = (\alpha - \bar{\alpha}) + \beta_0 * \Big(ln(p_{NO_{z,t}}) - ln(\bar{p_{NO_z}})\Big) + \beta_1 * \Big(ln(p_{FO_{i,z,t}}) - ln(\bar{p_{FO_{i,z}}})\Big) \\ + \Big((x_{i,z,t} - \bar{x_{i,z}})\Big)' * \delta_x + \Big(\lambda_i - \bar{\lambda}_i\Big) + \Big(\lambda_z - \bar{\lambda}_z\Big) + \Big(\sigma_t - \bar{\sigma}\Big) + \Big(\epsilon_{i,z,t} - \bar{\epsilon_{i,z}}\Big) \end{aligned}$$

For each variable, the within panel average is subtracted from all panels' observations, and this is called the "within transformation" (Stock and Watson, 2020). Notice that the country- and sector-fixed effects (λ_i and λ_z) and unit-equal constant term (α) zero out, because they do not vary over time. Consequentially, only the variation within each panel is exploited to estimate the regression model, meaning each variables' deviations from the panel average throughout the period, for each panel (Verbeek, 2004).

Alternatively, a random effects model could have been used. Compared to fixed effects, they exploit both within and between variation in the data, meaning that they would also account for the relative development in the CO_2 outcome variables and regressors between panels (Verbeek, 2004). To be able to exploit the between variation, such models do not filter out constant characteristics, but rather include them in a stochastic residual term and assume they are stochastic characteristics, or random effects. Consistency among elasticities therefore build on a strong, identifying assumption that regressors do not co-vary with the constant characteristics in the error term (Angrist and Pischke, 2009). In my empirical framework, it likely exists constant characteristics that affect CO_2 trade with Norway and correlate with countries' sectoral energy prices. Geographical distance to Norway, for instance, should affect countries' trade with Norway through transportation costs and diplomatic closeness, and it may correlate with foreign energy prices through regional energy production terms and supply capacities. Thus, filtering out constant heterogeneity seems necessary, and all three models will therefore be estimated using fixed effects[8].

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[8] Initially, it would seem appropriate to run models with lagged Norwegian and foreign prices, to account for rigidity in production shits. However, when running models with lagged prices up til three years, explanatory power and statistical interference fell considerably. Real-time prices will therefore be used.

8 Empirical Results

This chapter will present the empirical results. Firstly, regression results from the Norwegian CO_2 import and export models will be presented, following the sample selection CO_2 production model. Secondly, a national CO_2 accounting framework will utilize estimated elasticites to estimate the carbon leakage rate from Norway in the eight industrial sectors.

8.1 CO_2 Trade Elasticities

This subsection presents the domestic and foreign price elasticities of Norwegian CO_2 imports and exports. The four control variables have been added step-wise in each model to show their statistical interference properties. All regressions are run with sector- and country-fixed effects, year-dummies and country-sector robust standard errors to account for potential heteroskedascity. T-values are reported in parentheses.

Table 3: Norwegian CO_2 imports

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	ln(M$_{NO}$)	ln(M$_{NO}$)	ln(M$_{NO}$)	ln(M$_{NO}$)	ln(M$_{NO}$)	ln(M$_{NO}$)	ln(M$_{NO}$)
ln(p$_{NO}$)	0.543***		0.550***	0.540***	0.537***	0.546***	0.557***
	(2.68)		(2.70)	(2.65)	(2.63)	(2.69)	(2.80)
ln(p$_{FO}$)		0.00666	-0.0179	0.0136	0.0210	-0.00576	-0.0425
		(0.08)	(-0.21)	(0.15)	(0.23)	(-0.06)	(-0.47)
Wagegap$_{NO}$				-0.0715	-0.0727	-0.0784	0.0674
				(-0.86)	(-0.88)	(-0.94)	(0.94)
FDIFlows$_{FO}$					0.000514*	0.000526*	0.000290
					(1.92)	(1.96)	(1.13)
EnergyNet$_{FO}$						0.00196	0.00157
						(1.26)	(1.01)
MillToes$_{FO}$							0.00126***
							(5.27)
Time Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	5241	5241	5241	5241	5241	5241	5241
r2_w	0.0366	0.0333	0.0366	0.0375	0.0400	0.0422	0.0684

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Looking to the Norwegian energy price index, a positive relationship with Norwegian CO_2 imports is estimated in all equations. In model (1), without foreign prices nor control variables, a percentage increase in domestic energy prices is predicted to increase Norwegian CO_2 imports by 0.543 percent. The coefficient increases marginally when foreign prices are included in model (3), which in turn may mean that Norwegian and foreign prices obtain a (weak) positive relationship, but affect Norwegian CO_2 imports in different directions. Quite surprisingly, the models' explanatory power does not increase when including foreign prices. When adding all four control variables, the domestic price elasticity eventually settles at 0.557, illustrating that the estimate remains numerically stable through all different specifications. The domestic price elasticity of CO_2 imports is statistically significant at the one percent level in all specifications, meaning that the estimate with a high certainty is not a result of random variation in the data.

The positive relationship between domestic prices and CO_2 imports was expected. Following the intuition from chapter 3, a Norwegian domestic cost increase lowers the competitiveness of Norwegian industrial producers. Short-term loss of market shares to international competitors therefore ensures that a higher share of CO_2 from industrial products originate from abroad. This can be driven through increased import volumes, but it may also be due to more emission-intense factor mixes in the foreign exporters' production. The estimate conforms partly to the estimate by Fowlie et al (2016) that some energy-intensive industries increase their absolute imports by 11 % following a domestic CO2 tax increase of 10 USD/per tonne.

Moreover, model (2) predicts that a percentage increase in foreign energy prices increases Norwegian CO_2 imports by roughly 0.0067 percent. However, the elasticity becomes negative in the fully specified model (7), but its estimate remain statistically insignificant throughout all models. The estimate also changes sign three times when adding controls, implying foreign energy prices indeed correlate with the control variables. Evidently, a negative elasticity was expected, since lower foreign energy prices improve foreign industrial competitiveness and promote exports, but its insignificance prohibits both a direction and numerical value being statistically pinpointed.

Regarding control variables, Norway's wage gap to foreign countries remains statistically insignificant throughout all specifications. Relative, sectoral wage data could potentially have explained bilateral CO_2 flows more systematically. Net inflows of foreign direct investment in foreign countries is estimated to have a positive effect on countries' CO_2 exports to Norway. In model (6), a one billion dollar increase in FDI net inflows in foreign country (i) is predicted to increase its CO_2 exports to Norway by 0.00056 * 100 = 0.0056 %, which fits the finding of Kutan and Vuksic (2007 that inward FDI investments increases supply capacities and hereby exports. Countries' degree of energy imports remains insignificant, but their absolute energy supply is estimated affect their CO_2 exports to Norway positively, as a supply increase of one million tons of oil equivalents is predicted to increase their CO_2 exports to Norway by 0.0126 %. Net FDI inflows loses significance when absolute supply is included.

Table 4: Norwegian CO_2 exports

	(1) ln(X_{NO})	(2) ln(X_{NO})	(3) ln(X_{NO})	(4) ln(X_{NO})	(5) ln(X_{NO})	(6) ln(X_{NO})	(7) ln(X_{NO})
ln(p_{NO})	0.460^{*}		0.483^{*}	0.456^{*}	0.457^{*}	0.465^{*}	0.471^{*}
	(1.70)		(1.76)	(1.66)	(1.66)	(1.68)	(1.73)
ln(p_{FO})		-0.0339	-0.0555	0.0332	0.0327	0.00820	-0.0150
		(-0.29)	(-0.47)	(0.27)	(0.27)	(0.07)	(-0.13)
Wagegap_{NO}				-0.201^{**}	-0.201^{**}	-0.206^{**}	-0.114
				(-2.29)	(-2.29)	(-2.32)	(-1.28)
FDIFlows_{FO}					-0.0000313	-0.0000204	-0.000170
					(-0.15)	(-0.10)	(-0.86)
EnergyNet_{FO}						0.00179	0.00155
						(1.05)	(0.91)
MillToes_{FO}							0.000794^{**}
							(2.19)
Time Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	5241	5241	5241	5241	5241	5241	5241
r2_w	0.0523	0.0510	0.0525	0.0568	0.0568	0.0579	0.0642

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

To quite a surprise, Norwegian energy prices are estimated to have a positive effect on Norwegian CO_2 exports. The estimate remains numerically stable and statistically significant at the one % level through all specifications. In the fully specified model, a percentage increase in Norwegian energy prices is estimated to increase Norwegian industrial CO_2 exports by 0.471 %.

Following the intuition from chapter 3, the positive relationship between domestic prices and CO_2 exports was not expected. When Norwegian energy prices increase, the direct factor cost increase was expected to reduce Norwegian CO_2 exports through lost international competitiveness. In addition, higher prices of non-energy input factors produced domestically should also drive competitiveness down, if the suppliers use energy in production themselves (Kpodar et al., 2019). At first glimpse, a positive effect on CO_2 exports therefore does not appear economically coherent [9].

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[9] However, one should for now notice that the CO_2 export elasticity to domestic prices is numerically *lower* than the CO_2 import elasticity, therefore predicting a reduction in Norway's net CO_2 exports when domestic costs increase.

One potential explanation of the positive elasticity of could be that the mining and quarrying sector is included in the analysis. If an increase in domestic energy prices is driven through surges in the world market prices of oil and gas, Norwegian exports in this sector become more profitable and should increase hereafter. If this sector has a stronger relationship between prices and CO_2 exports than the seven other sectors, this could potentially dominate the elasticity to change its sign. However, and quite importantly, the fixed energy price index (FEPI) corresponding to the mining and quarrying sector is mostly carried by electricity prices, so such a dynamic may be quite limited in explaining the positive estimate (Sato, 2020). To test this potential explanation, a test regression was run without the mining and quarrying sector to examine how the CO_2 export elasticity would change. Interestingly, the coefficient remained positive, statistically significant and numerically quite identical, which means that the oil explanation fails to explain the positive estimate.

Another potential explanation of the positive domestic price elasticity of CO_2 exports may be that the least efficient producers get squeezed out of the export market. For domestic industrial producers with the initially lowest profit margins, a price increase may exceed their threshold value of operating, particularly if prices continue to increase over time. The remaining companies, the initially most efficient ones, may from here overtake the lost companies' international market shares. Economies of scale may further increase their efficiency. Additionally, remaining companies may produce relatively more of their most profitable industrial products to keep profits positive in the high-cost period (Kpodar et al., 2019). Resultingly, the overall competitiveness and productivity in Norway's industrial export sector could raise, and if the remaining companies manage to acquire extra international market shares, aggregate exports will increase. This explanation, however, contradicts the reasoning behind short-term competitiveness loss elaborated in chapter 3, unless foreign prices increase in a similar matter as Norwegian.

A third explanation of the positive elasticity may be that Norwegian exports are partly lagged from production, and domestic prices run in cycles. If energy prices run in cycles, they follow a steady swinging pattern where higher prices are expected after periods of low prices, and vice versa. Looking at the descriptive statistics in chapter 6, Norwegian energy prices appear to a certain degree to have been running in cycles, after 2000. In that sense, it may that domestic industrial production increases in low-price periods, but its exports actually are realized in the subsequent period of the price cycle, where prices increase again. If so, this could potentially contribute to explaining why CO_2 exports is estimated to increase in periods of higher energy prices. Pinpointing this would however necessitate a rather different analysis.

Moreover, foreign energy prices still remain statistically insignificant through all specifications, as in the CO_2 import equation. One would expect a positive foreign price elasticity of CO_2 exports, as a foreign cost increase should increase foreign countries' demand for Norwegian and other countries' exports, in line with the intuition in chapter 3. Norway's relative wage levels has a significant, negative effect on Norway's CO_2 exports, predicting that a one percentage relative increase in Norway's average wage to a foreign country (i) shall decrease its CO_2 imports from Norway by 0.201 %. Foreign net FDI inflows and net imports of energy (% of total use) remain insignificant through all specifications, but foreign, absolute energy supply has a significant, positive effect on CO_2 imports from Norway. An increase of one million tons of oil equivalents in foreign country (i) is predicted to increase its Norwegian CO_2 imports by 0.00794 %.

8.2 General CO_2 Production Elasticities

Unlike price elasticities of Norway's CO_2 imports and exports, estimating a Norway-specific CO_2 production elasticity is not obtainable, due to a lack of degrees of freedom. Therefore, inspired by the empirical framework of Misch and Wingender (2021), the average CO_2 production elasticity in the eight industrial sectors has been estimated for the whole sample selection. Net FDI inflows, net energy imports (% of use) and absolute energy supply are controlled for. Observations that were omitted due to lacking wage data will be included, upping total observations to 5732.

Table 5: Sample selection CO_2 production

	(1) ln(Y_i)	(2) ln(Y_i)	(3) ln(Y_i)	(4) ln(Y_i)
ln(p_i)	-0.175*	-0.173*	-0.170*	-0.156*
	(-1.86)	(-1.84)	(-1.80)	(-1.67)
FDIFlows$_i$		0.000310	0.000318	0.000145
		(1.56)	(1.60)	(0.79)
EnergyNet$_i$			0.000504	0.000477
			(0.72)	(0.69)
MillToes$_i$				0.000911***
				(7.02)
Time Effects	Yes	Yes	Yes	Yes
Fixed Effects	Yes	Yes	Yes	Yes
N	5732	5732	5732	5732
r2_w	0.0448	0.0459	0.0465	0.0653

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

For the sample selection, a negative relationship between CO_2 from domestic production and domestic energy prices is estimated. The elasticity gradually lowers numerically when adding controls, implying that an upward bias may have been present in model (1). In the fully specified model, a percentage increase in domestic energy prices is estimated to decrease CO_2

from domestic production by 0.156 %. The estimate is statistically significant at the one % level. That domestic production is predicted to fall (and corresponding CO_2 emissions) when domestic costs increase was expected. Following economic theory, since marginal costs increase per industrial unit, the optimal production level declines unless the full price increase is passed onto consumers. The estimate also conforms the negative production elasticity estimated by Misch and Wingender (2021), although numerically weaker. Net FDI inflows and energy reliance remain insignificant, but energy supply is estimated to have a significant positive effect CO_2 from domestic production, as an increase in 100 million tons of oil equivalent is predicted to increase production-related CO_2 emissions by 0.0009 * 100 = 0.009 %.

8.3 Elasticity Wrap-Up

To quite a surprise, the Norwegian price elasticity of both CO_2 imports and CO_2 exports was positive and significant. Some potential explanations for the positive export elasticity was offered, but it still remain a highly unexpected result. Nevertheless, the estimated import elasticity is numerically larger than the export elasticity, with a positive difference of $0.557 - 0.471 = 0.086$. Evidently, this suggests that the estimated percentage change in Norwegian net CO_2 exports following a one percentage domestic cost increase is -0.086 %. Following the intuition from chapter 3, this still points to a *net* loss of competitiveness following a domestic operational cost increase. This may hint at a positive carbon leakage rate.

Also in opposition to the elasticity hypothesis, the foreign price elasticity to Norway's CO_2 imports and exports was far from significant in all specifications. In the same way that Norwegian energy prices affect Norwegian competitiveness, they were expected to systematically affect Norway's CO_2 trade through changed foreign competitiveness. Nevertheless, the insignificance may have arised due to a too small sample selection, for instance if yearly observations are too wide-ranging to capture the actual co-variation between foreign countries energy prices' and their CO_2 trade with Norway. Using monthly or quarterly data with a larger set of sectors or countries could pinpoint this more thoroughly.

Lastly, one should notice that for the negative production elasticity to domestic prices to be representative of Norway, it has to be that Norwegian export shares increase in high-cost periods. This is because the export elasticity is positive, and the domestic production elasticity is negative. Higher export shares corresponds to the previously elaborated theory that higher energy prices may streamline the export market through a squeeze-out of the least efficient companies (Kpodar et al., 2019). If simultaneously, domestic producers producing for domestic consumption experience the same clean-up effect, but domestic demand does not increase in the same matter that external demand does, an increased share of domestic production will naturally be exported. Viewed in isolation, this theory does not however correspond to the carbon leakage dynamics elaborated in chapter 3, unless foreign prices also increase.

8.4 The Carbon Leakage Rate

This section will use the estimated domestic price elasticities of Norway's CO_2 imports and exports, as well as the sample selection price of domestic CO_2 production, in a national CO_2 accounting framework to estimate the Norwegian carbon leakage rate from the eight industrial sectors. As previously elaborated, the carbon leakage rate stemming from a policy change (t) in Norway (i) to all other countries (J) equals the change of emissions in Norway (i) divided by the total change of emissions abroad, given by

$$LR_i(t_i) = -\frac{\frac{\partial Y_J}{\partial t_i}\Delta t_i}{\frac{\partial Y_i}{\partial t_i}\Delta t_i} \tag{8}$$

Further, following the methodology of Misch and Wingender (2021), a national accounting framework for the total CO_2 emissions of Norway (i) can be given by

$$Y_i + M_i = X_i + C_i \tag{9}$$

CO_2 embodied in domestic production (Y_i) and imports (M_i) must equal CO_2 embodied in exports (X_i) and final consumption (C_i). Similarly, total CO_2 emissions in all foreign countries (J) must equal

$$Y_J + M_J = X_J + C_J \tag{10}$$

The CO_2 abatement effect of an increased environmental tax (t) in Norway (i) must be

$$\frac{\partial Y_i}{\partial t_i}\Delta t_i + \frac{\partial M_i}{\partial t_i}\Delta t_i = \frac{\partial X_i}{\partial t_i}\Delta t_i + \frac{\partial C_i}{\partial t_i}\Delta t_i \tag{11}$$

For each parameter in the national CO_2 account, the tax effect equals their differential w.r.t. the tax change. The differential equals the parameter change w.r.t a tax change, multiplied by the tax change itself. The Norwegian tax increase (t) may also have an effect on foreign countries. The foreign response to the Norwegian tax, following equation (10), should be

$$\frac{\partial Y_J}{\partial t_i}\Delta t_i + \frac{\partial M_J}{\partial t_i}\Delta t_i = \frac{\partial X_J}{\partial t_i}\Delta t_i + \frac{\partial C_J}{\partial t_i}\Delta t_i \tag{12}$$

Norway is a small country measured in international industrial market shares. Therefore, under the assumption that the foreign consumption response to a Norwegian tax change is zero, equation (12) can be re-arranged to

$$\frac{\partial Y_J}{\partial t_i}\Delta t_i = \frac{\partial X_J}{\partial t_i}\Delta t_i - \frac{\partial M_J}{\partial t_i}\Delta t_i \tag{13}$$

The foreign CO_2 response to the Norwegian tax increase shall therefore equal the change in its net CO_2 exports to Norway. Returning to the leakage equation, substituting this result into equation (8) yields

$$LR_i(t_i) = -\frac{\frac{\partial X_J}{\partial t_i}\Delta t_i - \frac{\partial M_J}{\partial t_i}\Delta t_i}{\frac{\partial Y_i}{\partial t_i}\Delta t_i} \tag{14}$$

The carbon leakage rate from Norway shall equal the negative change foreign in countries' net CO_2 exports to Norway as a share of Norway's abated CO_2 emissions, by reason of the Norwegian tax change. From the leakage fraction, one can observe that a negative change in Norwegian CO_2 emissions combined with a positive change in countries' net CO_2 exports to Norway yields a positive leakage rate. Moreover, since bilateral relationships are inverse, in the sense that exports from foreign countries (J) to Norway (i) equals Norway's imports from foreign countries (J) and vice versa, equation (14) can be rearranged to

$$LR_i(t_i) = -\frac{\frac{\partial M_i}{\partial t_i}\Delta t_i - \frac{\partial X_i}{\partial t_i}\Delta t_i}{\frac{\partial Y_i}{\partial t_i}\Delta t_i} \tag{15}$$

Here, foreign countries' export and import responses are substituted with Norway's import and export responses, respectively. This in turn equals

$$LR_i(t_i) = \frac{\frac{\partial X_i}{\partial t_i}\Delta t_i - \frac{\partial M_i}{\partial t_i}\Delta t_i}{\frac{\partial Y_i}{\partial t_i}\Delta t_i} \tag{16}$$

The carbon leakage rate from Norway shall equal the change in Norway's net CO_2 exports as a share of domestically abated emissions. A decrease in Norway's net CO_2 exports combined with a domestic CO_2 reduction yields a positive leakage rate. Having estimated Norway-specific CO_2 import and export elasticities and a general sample selection CO_2 production elasticity to domestic tax-inclusive energy prices, the above equation can arguably be projected by

$$LR_i(t_i) = \frac{\beta_i^X * \widetilde{X_{i,J}} - \beta_i^M * \widetilde{M_{i,J}}}{\beta_i^Y * \widetilde{Y}_i} \tag{17}$$

Where β_i^X, β_i^M and β_i^Y are the estimated CO_2 import, export and production elasticities estimated in the fully specified models[10]. $\widetilde{X_{i,J}}$, $\widetilde{M_{i,J}}$ and $\widetilde{Y}_i$ represent the aggregate CO_2 levels embodied in Norwegian exports, imports and domestic production in the eight industrial sectors during the 20 year period. Plotting in aggregate CO_2 levels and corresponding elasticities, the estimated industrial carbon leakage rate from Norway becomes

$$LR_i(t_i) = \frac{0.471 * 283.554 - 0.557 * 291.443}{-0.156 * 368.238} = 50.12\% \tag{18}$$

The estimated carbon leakage rate from Norway in the eight emission-intensive sectors is 50.12 %. The finding conforms to the Norwegian leakage rate found by Misch Wingender (2021) of 42 % and partly to the simulated Nordic leakage rates by Næss-Schmidt et al (2019). Mathematically, the estimate implies that roughly half of all abated CO_2 emissions in Norway will be replaced in foreign countries and pumped back to Norway through trade. This estimate appears quite high at first glimpse, but it is important to underline that this is the estimated leakage rate only for heavy, energy-intensive industries in Norway.

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[10] Meaning the regression models with all control variables.

8.4.1 Econometrial Limitations

Importantly, by using tax-inclusive energy prices as a proxy variable for real policy changes, underlying measurement error may cause biased price elasticities, lowering the statistical basis to interpret the leakage rate as representative of policy changes (Verbeek, 2004). Measurement error can in this framework be defined as the numerical difference between the proxied variable and the proxy variable. Viewing the import model for intuition, the true model would in fact be

$$ln(M_{i,z,t}) = \alpha + \beta_0 * ln(t_{NO_{z,t}}) + \beta_1 * ln(t_{FO_{i,z,t}}) + (x_{i,z,t})' * \delta_x + \lambda_i + \lambda_z + \sigma_t + \epsilon_{i,z,t} \tag{19}$$

Where $t_{NO_{z,t}}$ and $t_{FO_{i,z,t}}$ represent the true environmental policy levels in Norway and foreign country (i). The measurement error from using energy prices will be

$$p_{NO_{z,t}} = t_{NO_{z,t}} + u_{NO_{z,t}} \tag{20}$$

$$p_{FO_{i,z,t}} = t_{FO_{i,z,t}} + u_{FO_{i,z,t}} \tag{21}$$

Under the assumptions that the measurement errors ($u_{NO_{z,t}}$ and $u_{FO_{i,z,t}}$) has a mean of zero and do not correlate with ($M_{i,z,t}$), $t_{NO_{z,t}}$ or $t_{FO_{i,z,t}}$, the estimated model will actually obtain a stochastic error term of

$$(\epsilon_{i,z,t} - \beta_0 * u_{NO_{z,t}} - \beta_1 * u_{FO_{i,z,t}}) \tag{22}$$

Resultingly, the domestic and foreign price coefficients (β_0 and β_1) are not independent of the models' stochastic error term. The same applies to the export and production equation as well. Some degree of endogeneity bias is therefore likely present, if the derived elasticities are to be interpreted representative of policy changes (Verbeek, 2004). Since there are two variables with potential measurement error, pinpointing the net direction of the bias is not statistically straightforward, but its size will depend on the measurement error itself and estimated coefficient magnitudes. However, energy prices should be more volatile than regulations, and an energy price elevation may more quickly be offset by expectations of lower prices in the near future, if energy prices follow a cyclical movement over time. Intuitively, this would correspond to a downward bias on the three elasticities.

Secondly, bias from omitted variables may still exist. While measurement error produces bias from the *true* regulation elasticities of Norway's CO_2 imports and exports, omitted variables generate biased elasticities *within* the proxy models itself. If there exists a systematic correlation between energy prices and any of the CO_2 outcome variables' stochastic residual term, we have that

$$E[P_{NOz,t}|\epsilon_{i,z,t}] \neq 0 \qquad or \qquad E[P_{FOi,z,t}|\epsilon_{i,z,t}] \neq 0 \tag{23}$$

Following the expression above, time-variant, omitted factors that both affect CO_2 outcomes and correlate with sectoral energy prices will give a non-zero correlation between the regressors and epsilon (Stock and Watson, 2020). Since such factors are unobservable, a share of these factors' effect on CO_2 flows will been assigned to the price coefficients, yielding either upward or downward bias. For instance, one could imagine that countries obtaining more extreme weather are likely to export less due to disadvantaged production terms, as well as that they may obtain low electricity prices through high precipitation. Resultingly, their exports to Norway may be low while they have low energy prices, putting an upward bias on the foreign price elasticity of Norwegian CO_2 imports. Nonetheless, by including country- and sector-fixed effects, year-dummies and a set of control variables, one could hope that most systematic, unobserved dynamics are controlled for.

Moreover, two forms of selection bias may be partly present in the data. Briefly, sample selection bias occurs when the selected entities in an analysis obtain certain characteristics relevant for the analysis which distinguishes them from the population that the analysis intend to represent (Verbeek, 2004). Selection bias may entail that the derived results become skewed from the true population values. In my case, since the country selection has been restricted by both energy price and wage data, certain characteristics may be over-represented in the selection, such as degree of industrialization. One may imagine that industrialized countries obtain more transparent, systematic and comprehensive wage registers and corresponding statistics[11]. If bilateral CO_2 trade patterns are affected differently from a relative cost change between two industrialized countries than between one industrialized and one developing country, the estimated price elasticities may be skewed from the average elasticities between Norway and all countries. Secondly, as the selection evidently includes a relatively large share of Norway's largest trading partners in terms of CO_2, the derived price elasticities may be skewed from the elasticities corresponding to countries that trade less with Norway. For instance, it may be that Norway's CO_2 trading patterns are less sensitive to energy price changes with less significant trading partners, since the absolute amounts of CO_2 (and thus also production levels themselves) that are affected by the relative changes becomes smaller. However, if the selection-induced skewness in how relative cost changes affect CO_2 trade lie constant over time, the country-fixed effects should have filtered it out.

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[11] The European Comission (2018), for instance, highlight in a development article that less-developed countries often obtain weaker statistical registers and measures.

8.4.2 Theoretical Limitations

The national CO_2 accounting framework assumes that the foreign demand response to Norwegian energy taxation is zero, so carbon leakage through global fossil fuel price effects is neglected. This seems plausible in most cases, since Norway is too small to affect world prices through domestic taxation. However, the neglection of fossil fuel price effects may be wrong for some types of taxation. For instance, if a sizeable CO_2 tax is implemented on Norwegian gas production, the lost profitability will likely reduce Norway's aggregate supply of gas. Since Norway is the world's third largest gas exporter (Norsk Petroleum, 2022), the taxation may reduce the regional supply of gas, unless the lost supply is fully replaced by gas exports from other nations. This would put an upward pressure on regional gas prices and likely reduce nearby importing countries' demand for gas in industrial production. That could have a downward effect on foreign countries' economic incentives to snap Norwegian industrial market shares, and it lowers Norwegian companies' incentives to outsource gas-heavy production. Mathematically, this means that the carbon leakage rate may be slightly overestimated, as foreign demand responses are not accounted for.

Secondly, the theoretical framework assumes constant marginal CO_2 replacement. It predicts that half of Norway's abated industrial emissions will be replaced in foreign countries, independently of the size of Norway's CO_2 abatement. In reality, it seems realistic that larger CO_2 abatements are more likely to be replaced than infinitesimal ones. Firstly, if foreign countries obtain diminishing marginal costs in up-scaling through economies of scale, they should be more willing to scale-up in larger intervals. This also applies to Norwegian companies wishing to outsource production to laxer countries, as relocating production facilities to other countries is a timely process that requires large upfront investments. Secondly, larger CO_2 abatements in Norway are assumably more likely to be noticed in foreign countries than small ones, particularly if the abatement solely is driven by Norwegian down-scaling that releases international market shares. To assume that half of each abated ton of Norwegian CO_2 is replaced uncritically in foreign countries therefore seem a bit wide-eyed.

8.4.3 Takeaway

In spite of both econometrical and theoretical limitations, the estimated carbon leakage rate may have some professional value after all. With significant estimates, it has pinpointed that Norway has outsourced a consequential share of its industrial CO_2 emissions when domestic energy costs have increased, in thread with other empirical papers (Misch and Wingender, 2021) (Næss-Schmidt et al., 2019). Under the bold assumption that the leakage estimate is representative for current and future environmental policies, the next section will offer a brief policy discussion on how Norwegian carbon leakage can be stifled[12].

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[12] Precisely quantifying current and future leakage risk naturally requires updated data, sectoral nuances and simulations of announced policies, but the derived estimate can be used suggestively as an indicative measure of the extent of Norway's carbon leakage rate.

9 Discussion

As elaborated in chapter 2, Norway is legally obligated to cut its CO_2 emissions by 40 % of 1990-levels by 2030. By 2050, the government aims to have reduced CO_2 emissions by 90-95 %. This is set to be succeeded through an intensification and widening of the EU's cap-and-trade system, deepening taxation in other domestic industries and investing heavily in cleaner production technology to decarbonize both offshore and onshore industries (Klima- og miljødepartementet, 2017). An industrial carbon leakage rate of 50 % may pose both direct and indirect implications to the efficiency and success of Norway's pioneering climate scheme.

Prominently, the carbon leakage rate may present direct drawbacks. If the actual leakage from Norway's industrial CO_2 abatement is 50 %, this implies that national abatement policies in emission-intensive industries only become half as effective as intended to be in a scenario where leakage is not accounted for. Evidently, this also implies that the initial cost per ton of CO2 abated through economic policies in Norwegian industry doubles, as half of abated emissions is estimated to return through international trade. In a pure economic sense, direct Norwegian CO_2 taxation may therefore be either a *less* efficient or *more* expensive policy than intended. For Norway's pioneering climate targets, a marginal failure rate of 50 % may therefore greatly reduce the success of the announced CO_2 and fuel tax lifts in the coming decade (Finansdepartementet, 2022).

Secondly, in addition either halved efficiency or a doubling of direct abatement costs, there may exist some negative side effects of CO_2 abatement that become proportionally larger with a leakage rate of 50 %. Babiker and Eckhaus (2007) argue that industrial CO_2 mitigation often is linked to increased short-term unemployment, but that the extent naturally depends on both the degree of transferability and wage rigidities amongst workers. Nevertheless, if Norway's industrial abatement is strongly driven by direct down-scaling through taxation, it seems plausible to believe short-term unemployment to some extent may increase. In 2017, roughly eight percent of Norwegian workers worked in industrial production, so the effect could be substantial (ENOVA, 2017). With a carbon leakage rate of 50 %, the sacrificed employment becomes proportionally *larger* per reduced tonne of CO_2. This has potential to lower overall political support for climate policies, thus making it harder for policy-makers to efficiently win through future policies as well. On the contrary, if Norway's industrial abatement is primarily driven by investments in cleaner production technologies, this effect would be milder, as the effect on employment would be negligible. Nevertheless, the main point is that a positive carbon leakage proportionally strengthens the negative side effects of CO_2 abatement. Nuancing the economical effects of abatement would however call for further analysis.

To counter the negative effects of carbon leakage, one potential policy highlighted is EU's proposed carbon border adjustment mechanism. Briefly, a carbon border adjustment mechanism is a tariff-based trade system that internalizes production-based greenhouse gas emissions in imported goods (European Comission, 2021b). If a country or coalition of countries implement such a mechanism, companies that import goods from outside the coalition will have to pay a tariff corresponding to the CO_2 emitted in production in the exporting country, had it been produced on EU soil. The tariff prices would therefore vary with the permit prices in the EU ETS. The system shall in theory disincentivize companies from outsourcing their emissions, or from generally importing emission-intense raw materials and goods from laxer countries. The system is initially set to cover only the energy-intensive industries of electricity, cement, aluminum, iron, steel and fertilizers (Finansdepartementet, 2021). Norway is set for adopting EU's carbon border adjustment mechanism from 2026.

While a carbon border adjustment mechanism may be efficient in reducing carbon leakage from Norway's most vulnerable sectors, there might be some probable shortcomings. Firstly, since the CBAM in the initial phase only will cover energy-intensive raw material sectors, some argue that carbon leakage may increase in sectors not covered by the system (Koester et al., 2021). When EU and additional countries (incl. Norway) impose the system, the competitiveness of energy-intensive sectors in laxer countries is expected to fall relatively to EU's. The reasoning is that their previous low-cost edge in exports to EU and other CBAM members in theory will be zeroed out from the tariff. The size of laxer countries' lost competitiveness will depend on the share of their aggregate industrial exports that are covered by CBAM, meaning the share of their industrial exports that initially were exported to EU, as well as the size of the tariff itself. If laxer countries do not respond by cleaning up their production, they may rather relocate capital and labor to less energy-intensive industries that are not covered by the system. This could be other industrial raw material sectors, or it may be to production of final manufacturing goods. Economies of scale may boost the foreign exporters' competitiveness in these industries, and they might overtake Norwegian market shares in sectors not covered by ETS or CBAM but covered by Norway's domestic taxation system. In that sense, dampening leakage in the covered industries may increase leakage in other industries. However, it seems plausible to believe that implementing a carbon border adjustment mechanism should lower the overall leakage, since the industries most vulnerable to leakage will be covered by the system. Also, announcements that more industries will be covered by the system in the future may dampen foreign exporters' incentives to relocate resources, and rather incentivize them to invest in greener production technologies in the covered sectors. Quantifying the net leakage effect of the intended carbon border adjustment mechanism however necessitates more comprehensive analysis.

A second potential measure that may reduce carbon leakage from Norway is easier public, financial access for heavy-emission companies in green transition periods, particularly before the CBAM is fully implemented. A company facing a newly implemented tax may naturally seek to lower its CO_2 emission intensity as fast as possible, to minimize its overall tax expenses. This also applies for companies under the EU ETS as compensation is set to phase out gradually. If the tax is large enough, the regulated company will likely wish to invest in innovation and cleaner production technologies, to transition its production CO_2 footprint out of the scope of the tax. As elaborated in chapter 3, when a tax is implemented, regulated companies face an immediate leakage threat through loosing international market shares, but they also face leakage risk from private shareholders shifting their capital to less-regulated regions. If the newly regulated company simultaneously invests much of its current capital in innovation of cleaner technologies, the expected revenue-cost ratio will decline even more in the short-term, so the immediate shareholder withdrawal may be even larger. For instance, Mills et al (2021) from Ernst and Young highlight in their article that transitional, green investments often have risky and lengthy development periods and thus slower returns, as a main reason for why private investors not necessarily want to invest in green innovation. The net result may therefore be an even stronger private capital withdrawal than from just the regulation itself.

To prohibit this excess financial withdrawal in transition periods, quick access to earmarked cheap financing or even governmental subsidies may dampen private investors' withdrawal incentives. It additionally may signalize stronger survival capacity in the longer-term. Actually, a public initiative has already been initiated from Innovasjon Norge, a state-owned industrial development company, whereas they provide cheaper, green loans to industrial companies with clear plans to innovate or lower their carbon footprints (Innovasjon Norge, 2022). The Ministry of Trade, Industry and Fisheries (2022) highlights that such green, governmental loans may attract private investments as well, in co-ordinance with the intuition above. For vulnerable companies aiming to transition out of the scope of implemented regulations, easier access to cheap public funding of green investments may therefore lower the short-term leakage risk by providing financial stability and signalizing future survival for private investors.

10 Concluding remarks

Motivated by UN's climate and poverty goals, this thesis has presented carbon leakage as a potential stumbling rock in international climate efficiency. The thesis has hypothesized that carbon leakage arises in Norway's industrial sectors when domestic operating cost levels increase, as they would from environmental regulations. Through an empirical analysis and a national CO_2 accounting framework, it has estimated an industrial carbon leakage rate from Norway of roughly 50 %. The estimate is subject to uncertainty through potential measurement error, omitted variable bias, sample selection bias and theoretical limitations such as the assumption of constant marginal CO_2 responses from foreign countries. It however paints a picture of how an increasing share of Norway's industrial CO_2 emissions originate from foreign countries when domestic costs increase. Given industrial companies' expected regulatory burden in the coming decades, EU's carbon border adjustment mechanism and easy access to federal loans for industrial companies in transition periods have been fronted as two prospective measures to reduce carbon leakage from Norway.

Future analysis should dive deeper into sectoral differences, and it should to a greater extent reckon with that carbon leakage is a dynamic process that also should vary over time itself. While this thesis has estimated an average industrial carbon leakage rate for eight energy-intensive sectors in Norway over 20 years, further examining sectoral differences and time variation is important from a policy-making perspective. Optimally, it should also use real regulation data to counter potential measurement error issues, although regulation data assumably obtains much less variation. With this, the long-term development of CO_2 trade after structural policies is implemented could be analysed to a further extent. From a policy-makers perspective, more forward-looking analysis determining the risk of *future* carbon leakage should also be of great benefit, such as determining which sectors are at high risk, or which regions domestic production is most likely to shift to. Since global efforts to achieve climate goals only will increase in the decades to come, so will the importance of understanding the dynamics in how CO_2 moves between regions.

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