The mitigating effect of carbon taxation in EU ETS participating countries: A comparative analysis.

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Abstract

This thesis is concerned with the mitigating effects of carbon taxation in EU ETS participating countries over the years 1990-2018. During this time several European countries have introduced carbon taxes in an attempt to curb CO_2 emissions. According to economic theory carbon pricing is an efficient instrument for the mitigation of carbon emissions. Meanwhile, the environmental outcomes of carbon taxation are uncertain ex-ante and only a small amount of empirical studies evaluate the actual mitigating effects of carbon taxes that are already in place. In this thesis it is found that a 1 euro increase in carbon tax rate decreases total CO_2 emissions per capita by 12.6 kg on average in taxed EU ETS participating countries. The average effect of an equivalent increase in carbon tax rate on emissions in the energy sector is 13.2 kg. Furthermore, the results for individual taxed countries do not tell a consistent story. The results suggest that carbon taxation was effective in: Sweden, Denmark, Iceland and Ireland. And in the remaining countries carbon taxes did not have a measurable significant mitigating effect on emissions, which can at least partly be assigned to the tax designs in: Norway, Estonia, Slovenia and Portugal.

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1. Introduction

The planet is warming because of historic high concentrations of heat-trapping greenhouse gasses (GHG's). In this process, carbon dioxide (CO_2) is the most important GHG and it is emitted trough human activity, for example by burning fossil fuels (Solomon et al., 2009). In 2015, after six years of negotiations, 196 countries signed the Paris Agreement; an internationally coordinated, legally-binding, framework to tackle climate change. The overall goal of Paris 2015 is to limit global warming below 2°C and therefore net-zero emissions of GHG's has to be achieved during the second half of the 21th century (European Commission, 2020b). The agreement leaves room for policy makers to come up with appropriate measures in order to achieve these goals. Over the last 3 decades carbon pricing has been an important tool for policy makers to address CO_2 emissions. On a European level, in 2005 the European Commission has set up an Emissions Trading Scheme (EU ETS) for GHG emissions, a cap-and-trade system that limits the emissions of over 11,000 heavy energy-using installations and airlines, which covers about 40% of EU's GHG emmissions (European Commission, 2020a). A cap is set on the total amount of emissions and allowances are tradeable among parties, thereby a price is set for the right to pollute. The cap is decreased gradually in order to increase the carbon price and decrease emissions over time. Additionally, several European countries have introduced explicit taxes on CO_2 emissions. In the 1990's, Finland (1990), Norway (1990), Sweden (1991), Denmark (1992), Slovenia (1996) and Estonia (2000) were the first wave of countries who implemented a carbon tax. And later, after EU ETS was introduced, Iceland (2010), Ireland (2010), France (2015) and Portugal (2014) formed the second wave of countries that introduced a carbon tax (Conway et al., 2017). The national carbon taxes coexist beside EU ETS and vary in design.

According to economic theory, carbon pricing is an efficient instrument for mitigating CO_2 emissions. Authors like Schöb (2003) argue that carbon taxation is preferred over other market and non-market instruments because it does not only mitigate emissions, but also generates tax revenues, which can be used to cut other, distortionary taxes. Nordhaus (2005) points out that an advantage of carbon taxes over allowances trading is stability of the pricing mechanism. Allowances trading, on the other hand, provides certainty on environmental outcomes while these are uncertain under carbon taxation. Meanwhile, the of amount ex-post empirical literature on the actual mitigating effects of carbon taxation are small (Green, 2021) and the literature shows only modest positive results on the mitigating effect of explicit carbon taxes (e.g. Labandeira, Labeaga, and Rodrıguez (2004) and Lin and Li (2011)).

This thesis contributes to the existing empirical literature on carbon taxation by giving insight into the possible mitigating effects in European countries that implemented a carbon tax alongside EU ETS, both before and after the introduction of the ETS. It is highly relevant to keep adding empirical evidence to the debate on the real mitigating effect of explicit carbon taxation since policy makers in countries around the world will be increasingly concerned with the pursuit of efficient carbon mitigation and only few studies address the real effects of carbon taxes that are already in place. An empirical evaluation is performed of all

EU ETS participating countries that introduced a carbon tax; Finland, Sweden, Norway, Denmark, Slovenia, Estonia, Ireland, Iceland, France and Portugal. By using a panel data fixed effects approach the average mitigating effect of carbon taxation in these countries is identified on both a total and a sectoral level. Then, using a difference-in-differences approach the mitigating effects will be estimated for the individual taxed countries. The research in this thesis contributes to the existing literature by: i) Having all EU ETS participating countries under scope, including countries that introduced a carbon tax relatively recently (France and Portugal), ii) using UNFCCC data for the time period 1990-2018 and iii) choices in explanatory variables. This thesis builds on Lin and Li (2011) who estimated the mitigating effect of carbon taxes on total CO_2 emission for the first wave countries and on Hájek et al. (2019) who focused on the effects for emissions in energy industries in a selected subset of EU Member States.

The research question of this thesis is formulated as follows:

What is the mitigating effect of carbon taxation in European Emissions Trading Scheme participating countries?

The remainder of this thesis will proceed as follows. In Section 2, background information will be provided on the EU ETS and national carbon tax designs. In section 3, the theoretical economic models and thereafter the relevant empirical literature will be explained. In Section 4, the data and its sources will be identified and descriptive statistics will be provided. In section 5, the methodology will be discussed. In section 6, the results will be presented. In section 7, robustness of the results will be verified. And lastly, in section 8, concluding remarks, discussion of the results and policy recommendations are provided.

2. EU ETS and carbon taxes

In this section the necessary background information on EU ETS and the design outlines of the national carbon taxes from the treatment group (Finland, Sweden, Norway, Denmark, Slovenia, Estonia, Ireland, Iceland, France and Portugal (World Bank, 2021)) will be provided. EU ETS was introduced in different phases, starting from 2005 in all European Member States and Norway, Iceland and Lichtenstein were added in 2008 (European Environment Agency, 2021). In this scheme, allowances for the emission of CO_2 were first freely endowed and later auctioned under the heaviest polluters in the European Union. The emission allowances are tradeable among the participating parties. EU ETS covers CO_2 emissions from large power and heat generators, energy intensive industries and commercial aviation. The amount of allowances is limited and gradually reduced over time. In total the coverage of the scheme is 40% of all emissions in the European Union (European Commission, 2020b). EU ETS treats all countries equally and therefore creates a 'level playing field' in the process of carbon emissions mitigation (Banet, 2017). The cost-effective mechanism of a trading scheme is straightforward. The costs of reducing emissions varies among participants, auctioning and tradeability of allowances will incentivize emissions abatement by those participants for whom abatement is relatively cheap. In that way emissions will be abated where cost are smallest (Tietenberg, 1985).

Several EU ETS participating countries introduced a carbon tax over the course of the last 30 years. A carbon tax is an indirect tax on the carbon content of energy sources, typically levied at the firm level. National carbon tax designs in EU ETS participating countries vary in coverage and rates. Several countries provide tax exemptions and rebates to firms in competitive industries to protect them from carbon leakage. All historical tax rates are included integrally in appendix A3. In the last decade of the previous century the Nordic countries (Finland, Sweden, Norway, Denmark) where the first to implement carbon taxation and these countries generally tax carbon at high rates, ranging from 28-139 US\$/tCO$_2$. Slovenia and Estonia introduced a carbon tax in 1996 and 2000 respectively, in 2018 Slovenia taxed carbon at 21.44 US\$/tCO$_2$ and in that year Estonia taxed at the lowest rate among EU ETS participating countries at 2.48 US\$/tCO$_2$. In 2010, both Ireland and Iceland introduced a tax on carbon both at medium high recent rates of 24.79 and 35.7 US\$/tCO$_2$ respectively. The most recent European countries that introduced a carbon tax are France and Portugal. France levies a relatively high rate at 55.29 US\$/tCO$_2$ and Portugal taxes the second lowest rate at 8.49 US\$/tCO$_2$. Some countries tax the carbon content of all fossil fuels while other countries only tax designated energy sources or sectors. The coverage of the carbon taxes in the EU ETS participating countries varies from 15% in Finland to 50% in Iceland and Norway. An outline of the most important carbon tax policy parameters is included in table 1 on the next page.

Table 1: Tax designs outline. This table contains the policy parameters for all EU ETS participating countries with a tax on carbon emission. Coverage is included as percentage of total GHG emissions. Tax rates are included as 2018 policy rates in US\$/tCO$_2$

	Year of introduction	Energy sources covered	Approximate coverage as % of total GHG emissions	Latest policy tax rate (2018) in US\$/tCO2
Finland	1990	Power production, transport and heating fuels	15%	76.89
Sweden	1991	All fossil fuels	25%	139.1
Norway	1991	Heating oil, diesel, natural gas, gasoline and LPG	50%	64.28
Denmark	1992	All fossil fuels	45%	28.81
Slovenia	1996	Fossil fuels and transport	24%	21.44
Estonia	2000	Thermal energy production	42%	2.48
Ireland	2010	Residential heat, transport, commercial buildings and small industry	39%	24.79
Iceland	2010	All fossil fuels	50%	35.7
France	2014	Transport and heating fuels	35%	55.29
Portugal	2015	Energy production	26%	8.49

Sources: OECD, World Bank (2017), World Bank (2021) and Hájek et al. (2019)

3. Related Literature

In section 3.1 carbon taxation will be discussed from a theoretical point of view. The theoretical literature gives extensive attention not only to the mitigating effect of carbon taxation, but also to welfare effects. The base-line model of Pigouvian taxation and the theory of second best will be adressed. In section 3.2 the results from existing empirical research on the mitigating effect of a carbon taxation will be discussed, which subsist of ex-post evaluations and model simulations.

3.1 Theoretical framework

The baseline model relevant for carbon taxation is the Pigouvian tax model (Pigou, 1920). Pigou argues that it is socially optimal to tax firms who inflict negative externalities at the value of the marginal external damage. The standard example of a Pigouvian tax setting is a factory that causes air pollution. A factory produces smoke with the production process, which harms the individuals who live down-wind of the factory. The harm that is done to the individuals is a negative externality in the sense that it is a cost caused by the production process that is not included in the private costs of production. In other words; there is a wedge between the private and social costs of production. The existence of a negative externality is a market failure and burdens social welfare. Therefore government intervention might be desirable. Completely prohibiting the factory owner to produce anything is not necessarily desirable, since both the factory owner and consumers might be worse off by complete prohibition. Hence, what should be considered is the optimal, tolerated level of pollution. The government can invoke this by levying a tax on the factory owner that varies with the level of pollution and that is equal to the marginal damage done to the individuals, or in more practical terms: Implement a commodity tax equal to the marginal damage. By levying such a tax, the external costs get internalized for the factory owner. The factory owner always chooses his quantity where his marginal costs equal his marginal benefits. So, with a Pigouvian tax, the generator of the externality will choose the output level where his private marginal benefit of production equals his private marginal costs plus the internalized marginal external damage done to the victims of the externality. In terms of social welfare, this outcome will be Pareto efficient since the external damage will be precisely offset by the private benefit of production.

Coase (1960) argues it is not necessarily evident that it should be the polluter who pays for the externality via a tax. According to Coase, the externality problem can be solved by granting ownership rights. Who pays for the externality then depends to whom the property rights are allocated. Coase's argument stems from the fact that an externality is reciprocal by nature. In the standard example that means the externality problem can not only be solved by closing down the factory, but also by moving away all down-wind neighbours. The Coase argument might seem counter-intuitive because it obviously ignores distributional fairness. However, if many individuals would move towards the down-wind area, the Pigouvian tax becomes very costly and it seems possible that it will lead to a misallocation of resources. Nevertheless, the allocation of property rights only results in Pareto efficiency when transaction and bargaining costs are low enough to allow for efficient bargaining. In reality these cost are very rarely sufficiently low, therefore a Pigouvian tax is the better solution is most cases. Moreover, Baumol (1972) shows the Coase argument is faulty by formalization of the argument. In a model with perfect competition and labor as the only scarce resource, he provides mathematical proof for the Pigouvian approach. The underlying rationale is that a change in behaviour of the victims (i.e. moving away from or towards the down-wind area) does not resolve the externality problem of polluted air. Hence, in the standard Pigouvian setting, the appropriate price the victims of an externality should pay is zero and a tax should be levied only on the generator of the externality.

An underlying assumption of the base-line Pigouvian model is that the only task of the government is to maximize social welfare by efficiently controlling an externality. Obviously, this is a dissatisfying assumption, since in reality the government carries a large variety of responsibilities. The second-best approach deals with this property by assuming the government needs to meet a certain revenue requirement to achieve all other government objectives. As mentioned, a Pigouvian tax is a commodity tax, levied on an externality-generating commodity. In the theory of second-best additional taxes are levied on commodities that do not involve an externality problem. Note that commodity taxes, in absence of an externality problem, are distortionary because they distort decisions concerning consumption, labour supply, investments etc.. Sandmo (1975) shows that Pigouvian taxation remains valid in an altered form in the theory of second-best. According to Sandmo, the optimal pollution tax should be corrected for the costs of public funds in presence of other distortionary taxes. He assumes individuals are homogeneous by modelling one representative agent. The possibility of levying non-distionary individualized lump-sum taxes is ruled out, therefore the setting is second-best by design. He shows that the optimal tax on the externality-generating commodity is a weighted average of the distortionary effect of a commodity tax and the externality-correcting effect of the Pigouvian tax. The weighting factor depends on the marginal rate of substitution between private and social income.

Jacobs and De Mooij (2015) argue that the optimal pollution tax should not be corrected for the costs of public funds in the theory of second-best. They point out that there is no economic reason to rule out individualized lump-sum taxes when assuming homogeneous consumers, since there exist no distributional concerns in a setting with homogeneous consumers. They analyze the optimal corrective tax in a setting where individuals are heterogeneous in their earnings ability, thereby extending the model for optimal taxation of Mirrlees (1971). This is a second-best problem as well, because the government cannot observe earnings ability and must use distortionary non-individualized lump-sum taxes to meet the revenue requirement and redistribute income. They find that, in presence of a non-linear income tax, the optimal second-best pollution tax is equal to the Pigouvian tax rate we know from the baseline model, 'with the relatively weak assumption that consumption of goods and environmental quality are weakly separable from leisure.' The underlying rationale is that the pollution tax should only be used to correct for the externality, since a non-linear income tax is the more efficient instrument to realize the governments redistributional objective. In response, the distributional effect of the corrective pollution tax can be offset by a non-linear income tax. Kaplow (2012) comes to similar conclusions from a perspective of environmental tax reforms (ETR's). He finds that, in presence of a non-linear income tax, a tax reform towards a system where all commodities are taxed at the value of the marginal damage and the distributional effects of the corrective taxes are absorbed by the non-linear income tax can generate a Pareto improvement.

Also, there is substantial literature on the existence of a double dividend for environmental tax reforms, Schöb (2003) provides an extensive survey. The double dividend hypothesis is described in the literature in a strong form and a weak form (Goulder, 1995). The weak form is widely accepted in the field and implies that revenues of an environmental tax reform can be used to cut other distortionary taxes and thereby cut the efficiency costs of the reform. Schöb (2003) argues that for this reason 'green tax reforms are nowadays preferred to other environmental tax instruments which although they are efficient in regulating the environment do not raise public revenues'. The strong form double dividend hypothesis implies that environmental tax reforms benefit non-environmental welfare even if there is no environmental effect of the tax reform. Both the theoretical and empirical results on the existence of a strong double dividend are mixed, although there is a tendency against a double dividend claim (Goulder, 1995). Jacobs and De Mooij (2015) point out that the strong form generally will not hold. Reason is that tax systems are optimized initially and therefore no non-environmental welfare gains should be possible by reforming the tax system.

Furthermore, an important appeal of carbon taxation over allowances trading as argued by, among others, Nordhaus (2005) is the stability of the pricing mechanism. Where allowances trading results in a relatively volatile carbon price due to sensitivity towards fluctuations in energy demand, a carbon tax is only changed by decision of the policy maker, which in practice does not happen often. This price stability is favorable, for example for the planning of long-term investments. On the other hand, an advantage of EU ETS over carbon taxation is that it gives certainty on the environmental outcome by design (Jan Abrell et al., 2011), while the real mitigating effect of carbon taxation is uncertain beforehand. The empirical research in this thesis aims to take away some of that uncertainty and shed light on the real mitigating effect of carbon taxation.

So in conclusion, from the perspective of economic theory, carbon taxation is an efficient instrument to invoke abatement of CO_2 emissions and the optimal rate of a carbon tax is equal to the marginal damage. Furthermore, the commonly accepted existence of a weak double dividend reduces the efficiency cost of an environmental tax reform. The strong double dividend hypothesis is not widely accepted, which means an environmental tax reform does not necessarily grants a 'free lunch'. For that reason the introduction of a carbon tax should be based on the environmental effect of the tax, which is the effect under consideration in this thesis. Lastly, an important asset of an explicit tax on carbon when compared to allowances trading is the stability of the pricing mechanism. Meanwhile, allowances trading has the advantage of providing certainty on the environmental outcome of the policy instrument.

3.2 Empirical literature

An important property for the mitigation potential of carbon taxation and a logical starting point for the review of the related empirical literature for this thesis is the price elasticity of energy demand. The introduction of a carbon tax aims to increase the price of carbon intensive energy and induce a consequential reduction in the use of these energy sources. Labandeira, Labeaga, and López-Otero (2017) provides a meta-analysis on studies concerning the price elasticity of energy demand for both individual and industrial consumption for different energy sources (electricity, natural gas, gasoline, diesel and heating Oil). They find varying price elasticities for different countries and energy goods. For developed countries they find an average short-term elasticity of -0.186 and an average long-term elasticity of -0.515. Meaning the a 1% increase in energy price leads to a 0.186% decrease in energy demand in the long-run and a 0.515% decrease in the short-run. Furthermore, it is found that elasticities are stronger for residential use than for industrial use. Lastly, the economic cycle is identified as an influential factor for the elasticity of energy demand. After an economic crisis (1973, 1978, 2008) for example, energy price elasticities are lower. The underlying rationale being that economic downturn has a downwards effect on energy prices due to reduced demand and meanwhile energy consumption is reduced due to a decline in disposable income trough improved energy efficiency or substitution with other, less expensive types of energy goods.

Despite negative average price elasticities of energy demand, the environmental outcome of carbon taxation is uncertain. On the one hand, low price elasticities for individual energy goods or countries may cause that the costs of carbon taxation simply get shifted towards energy consumers without substantial reduction in energy consumption. In that case carbon taxation will only result in more tax revenue and not in emissions abatement (Lin and Li, 2011). On the other hand, there is growing evidence that consumers respond more heavily to carbon taxes than to regular changes in price. In some cases it is found that the carbon tax elasticity is 4 times higher than the energy price elasticity (Andersson, 2019). This thesis evaluates the mitigating effects carbon taxes that are already in place and thereby it will provide more certainty on the actual environmental outcomes of carbon taxation.

The empirical work of this thesis lies in the line of research of ex-post analyses concerning the real mitigating effects of carbon taxation. An important work concerning the ex-post analysis of the mitigating effect of carbon taxation is Lin and Li (2011), who evaluated the effects in all first wave European countries; Denmark, Finland, Sweden, The Netherlands and Norway. They estimated the effect of a carbon tax on the growth rate of CO_2 emissions per capita for each individual country using a conventional difference-in-differences approach. Their estimation method relies on the premises of conditional β-convergence for CO_2 emission per capita in OECD countries (Strazicich and List, 2003). β-convergence means per capita emissions converge to a steady-state level, so that emissions growth is slower in countries with high initial per capita emissions. Using a system generalised method of moments (system GMM), Lin and Li find mixed results. They find that the carbon tax in Finland had a significant downwards effect on the CO_2 emissions growth.

The effect in Denmark, The Netherlands and Sweden was negative but insignificant, meaning the carbon tax in these countries only had a very limited effect on per capita CO_2 growth. And the effect of the Norwegian carbon tax was slightly positive but insignificant as well. They assign the differences in the mitigating effects of the carbon taxes to 'tax exemption or tax relief of energy intensive industries, differential tax rates and the recycling of tax revenue.' Based on theoretical literature the following covariates are included in the model: GDP per capita, countries gross R&D expenditures, energy prices and industry structure. Also, this thesis is closely related to Hájek et al. (2019), who used a panel data fixed effects model to estimate the effect of carbon taxes on GHG production in selected European countries (Finland, Sweden, Denmark, Ireland and Slovenia) for the energy sector specifically. The panel data used for the analysis covers 2005-2015 and is obtained from the Eurostat database. Controlling for ETS price, household consumption expenditure, corporate investments, solid fuel consumption and renewable energy consumption they found that the carbon tax rate has a significant downwards effect on GHG production; A 1 euro increase in carbon taxation may decrease emissions per capita by 11.58 kg. Green (2021) reviews 37 ex-post evaluations on carbon taxation and emission trading schemes. First of all, she points out that the number of studies on the actual effects on carbon taxation is strikingly small. Furthermore, it is found that on average carbon pricing policies result in a reduction in emissions of 0-2%, which in the opinion of the author is 'quite small'. Bohlin (1998) evaluated the Swedish carbon tax based on evaluation criteria formulated by the OECD. Although the results should be interpreted with caution due to the absence of a causal identification strategy, the paper does point in the direction of a substantial mitigating effect due to the tax, especially in the district heating sector. Metcalf (2019) estimates the carbon tax in the Canadian province British Columbia introduced in 2008 at a rate of 10 US$/$tCO_2$ to have reduced carbon emissions by 5-8% using a conventional difference-in-differences approach. Pretis (2019) finds that British Columbia carbon tax caused a 5% decrease in CO_2 emissions in the transportation sector but did not have an effect on the aggregate emissions. A difference-in-differences approach was used with a synthetic control group, which is constructed by weighing the untaxed Canadian provinces based on baseline characteristics. Abrell et al. (2019) propose an estimation method that predicts a counterfactual by machine learning to estimate the emissions impact of the UK carbon price floor that was introduced in 2013 at a rate of 24 US$/$tCO_2$. They argue that the carbon price floor decreased emission by 6.4% in the 2013-2016.

Another, more numerous, line of empirical research on the mitigating effect of carbon taxation is based on model simulations. Simulation based research has the advantage of isolating the effect of a carbon tax by constructing a clear counterfactual. On the other hand, simulations are based on a relatively large number of debatable assumptions. For example, simulations that use energy price elasticities underestimate the mitigating effect of taxation if in reality the tax elasticity exceeds the price elasticity (Andersson, 2019). Symons et al. (1994) simulate a carbon tax in the UK and finds that it has a significant downward effects on the CO_2 emissions trough increased prices for CO_2 intensive goods. When the adverse redistributional effect of the tax is offset by other taxes, the mitigating effect is lower but still significant. Aasness et al. (1996) show that a carbon tax in Norway, at a rate that stabilizes emissions at the 1990 level will decrease GDP. National disposable income, however, will increase due to an improvement in the terms of trade. Also, low income individuals will be disadvantaged more compared to high income individuals. Labandeira, Labeaga, and Rodrıguez (2004) simulated a revenue neutral environmental tax reform in Spain using a general equilibrium model in combination with a household energy demand model. They found that the introduction of a CO_2 tax and a reduction in social security contributions yields a weak double dividend and redistributive effects are insignificant. Lu et al. (2010) show, with a dynamic general equilibrium model of the Chinese economy, that carbon tax is an effective tool for long-term CO_2 emissions reduction in China. When the tax is complemented with an abatement in indirect taxes, the effect on GDP is limited. Dussaux (2020a) uses model simulations and firm level data to estimate the effect of the French carbon tax on emission in the manufacturing sector. He found that the tax reduced manufacturing emission by 5% in 2018.

The contribution of this thesis to the existing literature is threefold. First, it is the first empirical research that has all EU ETS participating countries under scope, including France and Portugal that recently introduced a carbon tax in 2014 and 2015 respectively. Hájek et al. (2019), estimates the average effect for a number of selected EU Member States. He does not include Iceland and Norway since they are not members of the European Union. Also, Hájek excludes France and Portugal because they introduced a carbon tax recently. Estonia is excluded without adequate explanation. Lin and Li (2011) exclusively investigate the first wave of European countries that introduced a carbon tax. Second, this thesis uses data regarding the time period from 1990 until 2018, the most recent year with complete emissions data. Thereby the time span from Lin and Li (2011), who investigate the effects until 2008, is extended by 10 years. Hájek et al. (2019) narrows the window to 2005-2015. By including more countries and years into the analysis this thesis provides a more complete description of the actual mitigating effects of carbon taxation in EU ETS participating countries. Third, this thesis diverges from previous literature by the selection of explanatory variables. The approach by Lin and Li (2011) will be roughly followed, however with some alteration as will be discussed in more detail in section 4.2.2.. Also, Lin and Li (2011) only use difference-in-differences while this thesis also uses a panel data fixed effects strategy. Thereby this thesis is the first to use a panel data fixed effects model with GDP per capita, R&D expenditures, energy prices and industry structure as explanatory variables.

4. Models, model specifications and hypotheses

In section 4.1 the standard panel data fixed effects and difference-in-differences models will be discussed, including their corresponding key underlying assumptions. In section 4.2 it will be pointed out how these model will be employed on the case of carbon taxation in EU ETS participating countries in the form of testable hypotheses and corresponding model specifications. Section 4.3 will elaborate on the specified models, discussing treatment, treatment group, control group, selection of control variables and identifying assumptions in more detail.

4.1. Models

4.1.1. Panel data fixed effects

For the estimation of the average mitigating effect over all taxed EU ETS participating countries a panel data fixed effects model will be used. Panel data consist of observation of different subject at different points in time, thereby exploiting both variation within one subject over time and variation between different subject. Fixed effects can be either on the subject (country/industry/firm) level or on the time (year/month) level. Subject fixed-effects control for time-invariant heterogeneity among subjects, thereby helping to prevent omitted variable bias and allowing the intercept to differ among countries. Time fixed effects control for factors that change over time and are equal for all subjects. A standard panel data fixed effects model includes both types of fixed effects and is specified as follows:

$$Y_{it} = \beta_0 + \beta_1 * D_{it} + \eta_i + \eta_t + \epsilon_{it}$$

where D_{it} is defined as the fixed effects estimator, also known as the within estimator since the it mostly exploits variation within a treated subject over time. β_1 equals the average effect of the treatment. η_i is defined as the year fixed effects dummies and η_i as the country fixed effects dummies. ϵ_{it} is the error term. Additionally, there can be other factors, outside of the treatment, that effect the outcome variable. To infer the effect of the treatment on the outcome variable there needs be controlled for such covariates. By adding control variables to the model, variations in the outcome variable caused by covariates are controlled for. With control variables a standard fixed effects model is given as follows:

$$Y_{it} = \beta_0 + \beta_1 * D_{it} + \beta_{2j} * X + \eta_i + \eta_t + \epsilon_{it}$$

where X represents the full set of covariates that affect outcome variable Y and the vector of coefficients β_{4j} equals the effects of these covariates on Y. An important identifying assumption of a fixed effects model is that there is no omitted variable bias, meaning there are no relevant variables that our left out of the model. Furthermore there should be no strong multicollinearity, meaning there is no strong correlation between the two independent variables.

4.1.2. Difference-in-differences

For the estimation of the mitigating effect of carbon taxes in individual EU ETS participating countries difference-in-differences estimation will be used. Difference-in-differences is an important estimation technique introduced by Ashenfelter and Card (1984) and used in numerous studies afterwards, especially in economics (see e.g. Card and Krueger (1993)). The difference-in-differences approach can be used in a natural experiment setting where one group receives treatment, a policy change for example, and another group is left untreated. By comparing the cross-differences between the treatment group with the untreated group, or control group, the effect of the treatment on a certain outcome variable is estimated. Formally, a standard difference-in-differences model is specified as follows:

$$Y_{it} = \beta_0 + \beta_1 * T_i + \beta_2 * t_i + \beta_3 * T_i * t_i + \epsilon_i$$

where Y represents the outcome variable, coefficient β_0 equals the mean baseline outcome for the control group, T_i represents the treatment and equals 1 (treated) or 0 (untreated), coefficient β_1 equals the pre-treatment difference between the treatment and control group, t_i represents the time period and equals 0 (pre-treatment) or 1 (post-treatment), coefficients $\beta_2 + \beta_0$ equal the mean post-treatment outcome for the control group, $T_i * t_i$ represents the interaction term between T_i and t_i and equals 1 (post-treatment for the treatment group) or 0 (otherwise). Coefficient β_3 equals the treatment effect on the treated, or the difference-in-differences estimator, and ϵ is the error term.[1] Also, the difference-in-differences estimator β_3 can be defined in terms of expected outcomes. In that case β_3 is given as follows:

$$\beta_3 = [E(Y|T = 1, t = 1) - E(Y|T = 1, t = 0)] - [E(Y|T = 0, t = 1) - E(Y|T = 0, t = 0)]$$

Now it shows that the difference-in-differences estimator is equal to the difference in expected pre- and post-treatment outcomes in the treatment group minus the difference in expected pre- and post-treatment outcomes in the control group. Control variables can be included into a difference-in-differences model as well, with control variables a standard difference-in-differences model is given as follows:

$$Y_{it} = \beta_0 + \beta_1 * T_i + \beta_2 * t_i + \beta_3 * T_i * t_i + \beta_{4j} * X + \epsilon_{it}$$ [2]

where X represents the full set of covariates that affect outcome variable Y and the vector of coefficients β_{4j} equals the effects of these covariates on Y. Fixed effects can be added to the difference-in-differences model as well. With time and subject fixed effects a standard difference-in-differences model is given as follows:

$$Y_{it} = \beta_0 + \beta_1 * T_i + \beta_2 * t_i + \beta_3 * T_i * t_i + \beta_{4j} * X + \eta_i + \eta_t + \epsilon_{it}$$

where η_t represents time fixed effects and η_i represent subject fixed effects. In this model β_3 can interpreted as the causal effect of the treatment on the treated under the identifying assumption of common trend, or parallel trend assumption. Since the control group functions as a counterfactual for the treatment

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[1] For a visual representation of a standard difference-in-differences estimation see appendix A1.

[2] This specification is after the standardized model from Angrist and Pischke (2014)

group, the assumption must be made that both groups would have followed a parallel path in absence of the treatment. To justify this belief, the pre-treatment trends should be inspected visually. Furthermore, anticipatory effects need to be ruled out.

4.2 Model specifications and hypotheses

First, I will estimate the effect of carbon taxes on the total country emissions per capita for the full sample of treated countries using panel data with country and year fixed effects. Unobserved factors that might be absorbed by year fixed effects are the economic cycle or an international economic/health crisis. Unobserved factors that might be absorbed by country fixed effects are differences in environmental regulations outside of the carbon taxes or initial preference for environmental quality. Also, carbon tax rate is set as the independent variable of interest. Thereby allowing for comparison of the different carbon taxes and exploiting the variation in levied tax rates. The model specification is given as follows:

$$CO2/capita = \alpha + \beta_1 * tax\ rate_{it} + \beta_{4j} * X_j + \eta_i + \eta_t + \epsilon_{it}$$

where β_1 equals the average mitigating effect of a marginal increase of 1 US\$/tCO$_2$ of the carbon taxes on CO$_2$ emissions in EU ETS participating countries. This leads to the first hypothesis of this thesis:

Hypothesis 1: The introduction of a carbon tax in EU ETS participating countries has a mitigating effect on total CO$_2$ emissions per capita.

Thereafter, the effect of carbon taxation will be estimated on the sectoral level. Therefore model specification (1) will be estimated for each separate sector, so that the dependent variable is set as sectoral CO_2 emission. Four different sectors are identified, being: Energy, industrial processes and product use, agriculture and waste. It can be expected that the mitigating effect of carbon taxation varies among different emission sectors, since sectors differ in carbon intensity. Furthermore, sectors might differ in how the carbon tax gets inflicted in prices and in the costs of abatement due to differences in technology. The effect of the tax can be expected to be largest in the energy category since it is the most carbon-intensive category. Over 60% of CO_2 emissions is produced for energy purposes (International Energy Agency, 2021). This leads to the second hypothesis of this thesis:

Hypothesis 2: The mitigating effect of a carbon tax varies among different sectors.

Also, since it is on beforehand reasonable to expect that the mitigating effects of carbon taxation are heterogeneous across taxed countries, the effect on all taxed countries will be estimated separately. To estimate the effect of carbon taxation in individual taxed countries a difference-in-differences will be used. Lin and Li (2011) use a difference-in-differences specification to estimate the mitigating effects of carbon taxes which is based on the assumption of β-convergence. This methodology is well-known in growth literature, for example in the analysis of income inequality between countries (Sala-i-Martin, 1996). β-convergence means a certain variable of interest converges to a steady state level. In the case of per capita CO_2 emissions, this results in the fact that growth rates of emissions per capita are negatively correlated with the initial level. Lin and Li (2011) base their assumption of β-convergence on Strazicich and List (2003), who found that emissions were converging among OECD countries from 1960 to 1997. However, the overall literature on convergence of CO_2 is mixed. For example, Kounetas (2018) investigates convergence patterns in 23 EU Member States from 1970-2010 and concludes that convergence is not a credible assumption in this sample. Therefore the assumption of convergence is dropped in this thesis. The used difference-in-differences specification is set up from altering model specification (1) by adding dummy variables for treated countries and post-treatment time periods and the tax rate variable is substituted by the difference-in-differences estimator. The model specification is given as follows:

$$CO2/capita = \alpha + \beta_1 * T_i + \beta_2 * t_i + \beta_3 * T_i * t_i + \beta_{4j} * X_j + \eta_i + \eta_t + \epsilon_{it}$$

This specification is estimated for each taxed country separately, where β_3 equals the mitigating effect of a marginal increase of 1 US\$/tCO_2 of the carbon tax on CO_2 emissions in the individual taxed countries. This leads to the third hypothesis of this thesis:

Hypothesis 3: The mitigating effect of a carbon tax on total CO_2 emissions per capita varies across EU ETS participating countries.

Now, for the panel fixed effects model all explanatory variables can be included. The selection of the control variables will be discussed in detail in section 4.3.3. The final panel fixed effects model specification is defined as follows:

$$(1)\ CO2/capita = \alpha + \beta_1 * tax\,rate_{it} + \beta_4 * GDP/capita + \beta_5 * (GDP/capita)^2 + \beta_7 * Technology + \beta_7 * Technology^2 + \beta_6 * Energy\ Price + \beta_8 * Industry\ structure + \beta_9 * Urbanization + \eta_i + \eta_t + \epsilon_{it}$$

For the difference-in-differences model initially only the key explanatory variables GPD/capita and (GDP/capita)$_2$ will be included to maximize the number of observations. The additional variables include missing values as will be discussed in more detail in section 5. The final difference-in-differences model specification can be defined as follows:

$$(2)\ CO2/capita = \alpha + \beta_1 * T_i + \beta_2 * t_i + \beta_3 * T_i * t_i + \beta_4 * GDP/capita + \beta_5 * (GDP/capita)^2 + \eta_i + \eta_t + \epsilon_{it}$$

4.3. Model elaborations

This section will elaborate in more detail on how the model specifications are employed to estimate the mitigating effects of carbon taxes in EU ETS participating countries. Subsection 4.3.1 is concerned with the treatment. In subsection 4.3.2 the control group is discussed. And subsection 4.3.4 discusses the identifying assumptions.

4.3.1 Treatment

The taxed countries under consideration will be all EU ETS participating countries that introduced an explicit carbon tax, being: Finland, Sweden, Norway, Denmark, Slovenia, Estonia, Ireland, Iceland, France and Portugal. For information on the design of the taxes I refer back to section 2.

4.3.2 Control group

To estimate the effect of a carbon tax when introduced alongside EU ETS, the control group must consists of EU ETS participating countries without an explicit tax on carbon emissions. The countries that participate in EU ETS are the 27 Member States of the European Union plus The United Kingdom, Norway, Iceland and Lichtenstein (European Commission, 2020a). European countries share substantial common similarities in terms of economic properties and environmental policy (e.g. EU ETS), making them sufficiently comparable among each other. The Netherlands introduced a carbon tax in 1990 (Lin and Li, 2011). However, in 1992 the Dutch carbon tax was replaced by a general fuel tax, which is not an explicit carbon tax. Therefore it is not appropriate to include the Netherlands in either the treatment or the control group. The United Kingdom introduced a carbon price floor in 2013 (World Bank, 2017) and although this is not exactly an explicit tax on carbon emission it is quite similar, therefore the United Kingdom is excluded as well. Lichtenstein is not included due to unavailability of data. What remains is a control group of 18 countries: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Germany, Greece, Hungary, Italy, Latvia, Lithuania, Luxembourg, Malta, Poland, Romania, Slovakia and Spain.

4.3.3 Control variables

In the selection of control variables I will roughly follow Lin and Li (2011), who base their control variables on the Kaya identity of global CO_2 emissions. Some alterations to their approach are made based on both theoretical and empirical grounds. For each explanatory variable the theoretical rationale and empirical evidence will be discussed in detail. First of all, there is extensive literature on the relationship between CO_2 emissions per capita and GDP per capita. A frequently studied hypothesis is the existence of an 'inverted-U' shape relationship between environmental degradation in general and economic development, also known as the Environmental Kuznets Curve. The Environmental Kuznets Curve describes environmental degradation increases in early economic development and decreases after development has reached a certain turning point. One possible underlying rationale is that the preference for environmental quality increase with economic development, or in other words; when countries become rich, they can afford to care about the environment. Another explanation might be that countries transform from an industrialized economy to a service economy with economic development. Pollution decrease after a turning point since services are less carbon-intensive than industrial activities. Grossman and Krueger (1995) found evidence that supports the Environmental Kuznets Curve for a number of different air pollutants and Schmalensee et al. (1998) specifically for CO_2 emission. However, later empirical studies predominantly challenge the Environmental Kuznets Curve hypothesis. For example, Dijkgraaf and Vollebergh (2005) find that the slope of emissions per capita over GDP per capita is not homogeneous across countries and thereby they challenge the general hypothesis of the Environmental Kuznets Curve. Nevertheless, although existence of an Environmental Kuznets Curve regarding CO_2 is doubtful, the existing literature does show the relationship between CO_2 and GDP per capita is non-linear in many cases. Lantz and Feng (2006) proposes to include the second power to control for the non-linear relationship between emission per capita and GDP. This non-linear relationship can also be observed in the dataset used for this thesis. Figure 1 shows scatter plots of CO_2 emission per captita over GDP per capita on the horizontal axis for Denmark and Ireland. In the graphs on the left-hand side a linear fitted line is added and to the graphs on the right-hand side a 2th degree polynomial[3] fitted line is added. In these examples, visual inspection clearly affirms that the relationship is indeed non-linear, since the polynomial provides a better fit to the actual data. To control for non-linearity, the second power of GDP per capita is added as covariate in addition to the face value of GDP. Thereby I deviate from Lin and Li (2011), where GDP per capita is included as explanatory variable in logarithmic form. According to (Hájek et al., 2019) their explanation for including the natural logarithm is not adequate. So, based on the Environmental Kuznets Curve literature and Lantz and Feng (2006) it seems more appropriate to include the quadratic form instead.

Additionally, in the literature the possible relationship between industrialization and CO_2 per capita is also approached from the perspective of other indicators of industrialization. For example, Jobert et al.

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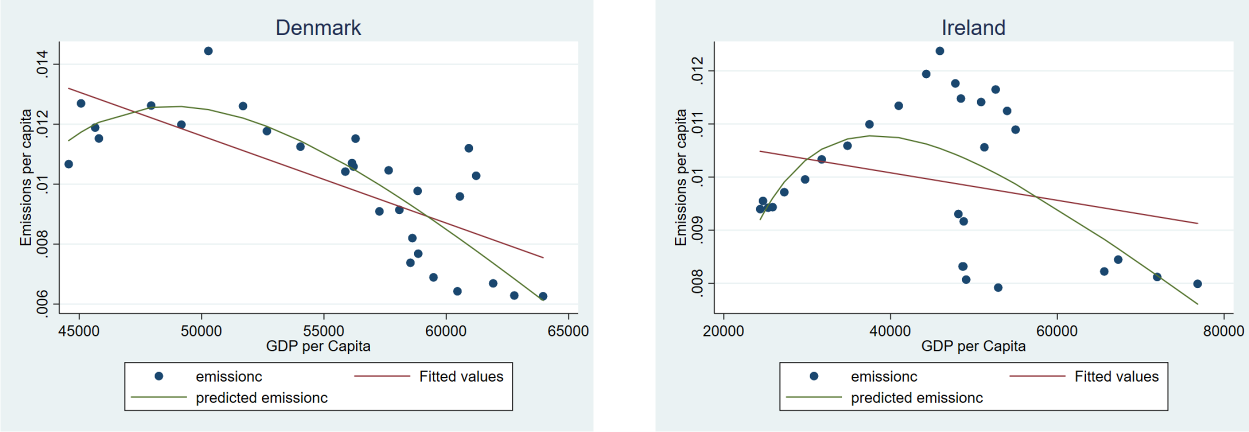
[3] A 2th degree polynomial is of the following functional form: $f(x) = bx^2 + cx + d$

(2010) identified industry share of GDP as a determinant for CO_2 per capita. The underlying rationale is that industrial processes are more polluting than, for example, service activities and therefore countries with a relatively larger industry sector have higher CO_2 emissions per capita. Furthermore, there is mixed empirical work on the effect of urbanization on CO_2 emissions. On the one hand, some studies find a positive effect of urbanization on CO_2 per capita (e.g. Jorgenson and Clark (2012). According to Liddle (2014), the underlying rationale being that urbanization is associated with the transition from agricultural activity to industrial activity. In this process more people move from rural areas to urban areas and that leads to an increase in emission for three reasons: i) agriculture sectors become less labor intensive and therefore require increased machinery use; ii) consumers move away from food production, entailing increased transportation and iii) industry sectors use more energy per worker than agriculture. On the other hand, some studies find an insignificant effect of urbanization on total CO_2 emission in developed countries (Lin and Li (2011), Liddle and Lung (2010)). The reason might be that developed countries have already completed the full urbanization process, with urbanization rates reaching $> 70\%$ (Liddle and Lung, 2010). In the dataset substantial variation in urbanization rates among European countries is observed, ranging from 53.7% (Slovakia) to 98.2% (Belgium) in 2018[4].

Figure 1: Two non-linear relationships between CO_2 emission per capita and GDP per capita. This figure contains scatter plots of emissisions per capita (vertical axis) over GDP per capita (horizontal axis) for Denmark and Ireland. Linear fitted values (red lines) and 2th degree polynomial fitted values (green lines) are included.



Also, numerous studies have examined the effect of technology on CO_2 emissions. The empirical results regarding this relationship are mixed. On the one hand, some studies find a linear negative relationship between technology and CO_2 emissions per capita (e.g. Neumayer (2002). The underlying rationale is that technological improvement increases investments, which leads to more polluting activities. On the other hand, some studies found an opposite relationship (Bruvoll and Medin (2003), De Bruyn et al. (1998)), with the underlying rationale being that technological improvement leads to improvement in energy efficiency. Lantz and Feng (2006) proposes to deal with the ambiguous relationship between technology and CO_2

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[4] See appendix A3 for summary statistics of urbanization rate by country

emissions per capita by adding technology as control in a quadratic form. This adds flexibility to the model by allowing for a non-linear effect. This non-linear relationship is also observable in the dataset, two examples are included in appendix A4. A good proxy for the technological factor is country R&D expenditures.

Furthermore, there is an obvious relationship between energy prices and CO_2 emissions per capita. An increase in energy prices reduces energy consumption, which leads to a reduction of CO_2 per capita. As discussed in section 3.2, Labandeira, Labeaga, and López-Otero (2017) find an average short-term elasticity of energy demand of -0.186 in developed countries. A good proxy for worldwide energy prices is the American imported price for crude oil.

4.3.4 Identifying assumptions

A key identifying assumption for both models is that there is no strong multicollinearity. On theoretical grounds there might be some collinearity issues. For example, GDP per capita might be correlated with industrialization and the technological factor might be correlated with industry structure. To test for these possible collinearity issues the variance inflation indicator (VIF) is computed for each independent variable. The VIF is computed by dividing the variance of the coefficient of a single independent variable by the variance of this coefficient if the single independent variable would be fit in a model without other independent variables. The results of the FIV tests are provided in Table 2 below. Generally, the rule of thumb is that the VIF value should not exceed 10, while others argue that the VIF should not be above 4 (O'brien, 2007). For either threshold the VIF tests shows that collinearity is not problematic.

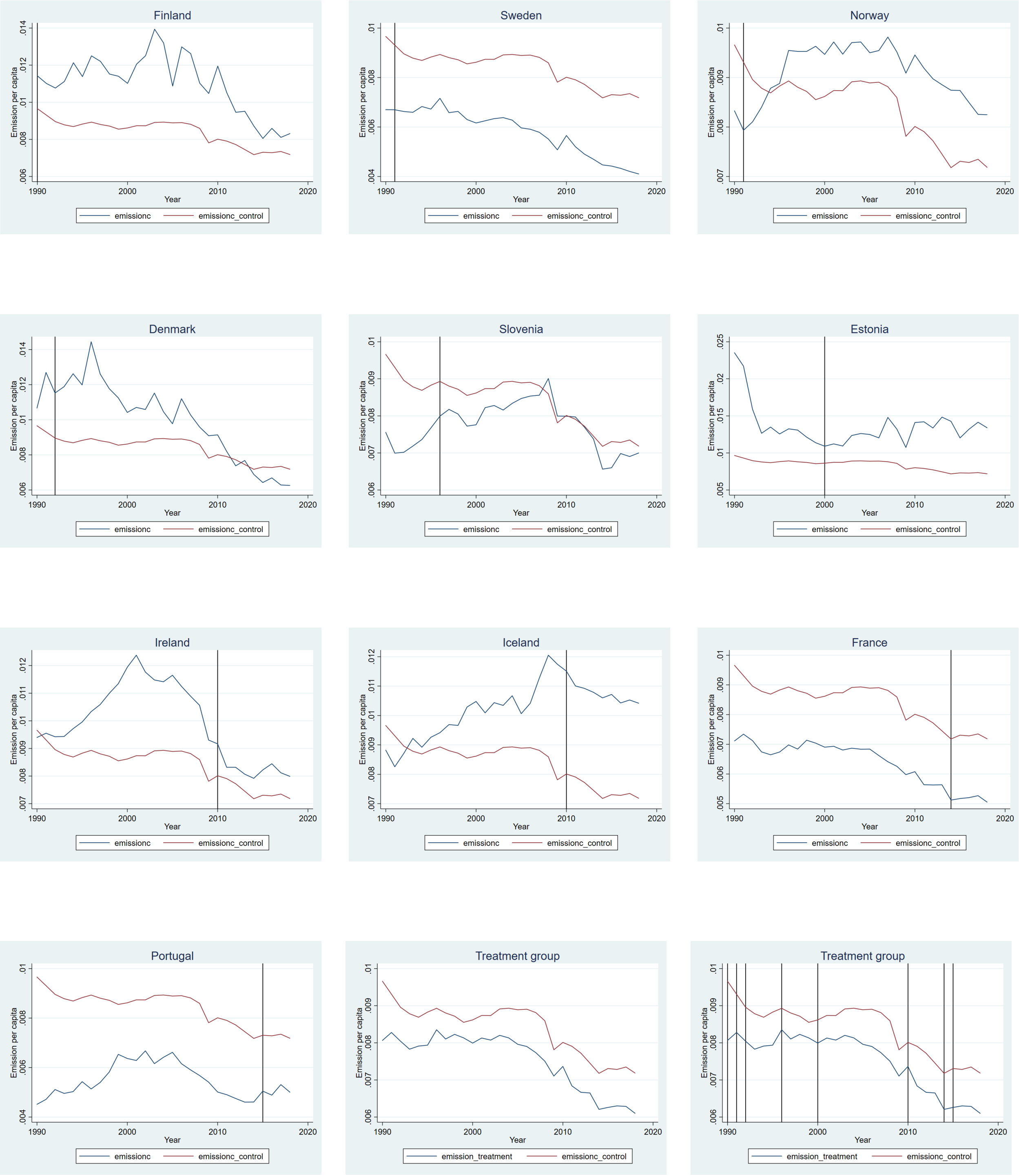
Table 2: Collinearity diagnostics. This table contains the results of VIF tests for all explanatory variables. VIF is an indicator for possible multicollinearity between independent variables.

Variable	VIF	VIF-Squared	R-Squared
Tax rate	1.79	1.34	0.44
GDP/capita	2.50	1.58	0.60
R%D expenditures	1.75	1.32	0.43
Industry structure	1.62	1.27	0.38
Energy prices	1.11	1.05	0.10
Urbanization rate	1.97	1.40	0.49
Mean VIF	1.81		

Besides, a key identifying assumption for the difference-in-differences model (2) is the parallel trend assumption. Parralel trend should be tested by visual inspection of the data. Trend comparisons of total CO_2 emissions per capita between the taxed countries of interest and the control group are provided in Figure 2. Based on the graphs in the bottom right tiles the parallel trend assumption reasonably holds on the level of the treatment group as a whole. On the level of the individual taxed country compared to the control group the parallel trend assumption does not seem to hold for the individual taxed countries. As will follow from the results in section 6.3, the violations of common trend might be problematic for the estimation of the mitigating effect of the individual carbon taxes.

Furthermore, it can be observed that in most countries and in the treatment and control group as whole, emission per capita has declined compared to the 1990 level. However, CO_2 emission per capita has not been declining steadily in all countries. Besides, there is a noticeable sharp decline in emissions in 2008/2009 in both the control group, treatment group and most individual taxed countries. It is known that the economic downturn at that time lead to serious abatement of carbon emissions (Bel and Joseph, 2015). The model controls for the effect of the economic crisis by i) including GDP per capita as a covariate and ii) including year fixed effects.

Figure 2: Trend comparisons of total CO_2 emissions per capita between the taxed countries and the control group. This figure contains plots of CO_2 per capita over time for the single treated country or the treatment group as a whole (blue lines) and the control group (red lines). The black vertical lines correspond to the introduction of carbon taxation.



5. Data and descriptive statistics

5.1 Data

The complete dataset subsists of data from several different databases. The dataset is a panel containing CO_2 emissions data and control variables on urbanization rate, energy prices, industry structure, R&D expenditures and GDP per capita. The panel covers 1990-2018 for 29 countries and 5 sectors.

For annual data on CO_2 emissions I consulted the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC database contains emissions data on all Annex I countries for 1990-2018. The GHG data from UNFCCC are reported by all countries individually conform universally adopted reporting requirements. For annual data on GDP, R&D expenditures as a percentage of GDP and population size I consulted the Organisation for Economic Co-operation and Development (OECD) database. For annual data on urbanization rate, measured as the urban population as a percentage of the total population, and industry structure, measured as value added by the industry as a percentage of total GDP, I consulted the World Bank database. All country characteristics are matched with the corresponding country and year in the final dataset.

At the level of total emissions the dataset is not entirely complete for all variables, all cases that contain missing values in either emission or one of the covariates will be dropped from the analyses. On the total level the emission data from UNFCCC is entirely complete. However, there are some missing values in GDP per capita for the control group only. In the total emission sample there is missing data for R&D expenditures for both the control group and the treatment group. Industry structure contains missing values for 1990-1995 for 15 out of the 28 countries in the dataset, including Estonia, Slovenia, Iceland, Ireland and Portugal from the treatment group. Omitting all these cases effectively means estimating for the 1995-2018 time period for 5 of the 10 taxed countries. For the other variables the dataset is complete. What remains is an unbalanced panel, since not all countries are observed an equal amount of years.

5.2 Descriptive statistics

Descriptive statistics for the total emissions sample are provided in Table 2 on the next page. The sample contains all EU ETS participating countries except The Netherlands, United Kingdom and Lichtenstein over the period 1990-2018. The countries in the sample that introduced a carbon tax are: Finland, Sweden, Norway, Denmark, Estonia, Slovenia, Ireland, Iceland, France and Portugal. The countries in the sample without a carbon tax are: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Germany, Greece, Hungary, Italy, Latvia, Lithuania,Luxembourg, Malta, Poland, Romania, Slovakia and Spain. Number of observation, mean, spread, min and max are included for all model variables. It can be observed that emissions per capita is higher among taxed countries compared to untaxed countries. GDP per capita is higher in the taxed countries as well, indicating that the EU ETS participating countries with a carbon tax are further in economic development.

To compare the means between the taxed and untaxed countries, t-tests for the equality of means on all control variables are provided in Table 3. Only the t-test on industry structure reaches significance. For all other explanatory variables(GDP per capita. R&D expenditures and urbanization rate) the null-hypothesis of equal means can be rejected. The fact that means are unequal for these variables emphasizes the importance of including them as covariates into the estimation models. Furthermore, it can be observed that GDP per capita is significantly higher in the taxed countries, which is conform the rationale often mentioned in Environmental Kuznets Curve literature that environmental preference increases with economic development.

Table 3: Descriptive statistics of the complete dataset. This table contains the number of observation, mean, standard deviation, minimum and maximum for each variable in the treatment group (taxed countries) and the control group (untaxed countries).

N	812
Number of countries	28
Number of years (1990-2018)	29

Taxed countries	Obs	Mean	Std. Dev.	Min	Max
Emission per capita (Kg CO_2)	290	8923.92	2829.27	4104.70	23520.17
Tax rate	290	23.23	35.20	0	168.80
GDP per capita	287	40799.94	20063.32	6738.50	92119.52
R&D expenditures (% of GDP)	260	1.96	0.82	0.46	3.87
Energy price (American Imported Crude Oil)	290	46.88	30.11	13.18	102.91
Industry sructure (VA-% of GDP)	265	25.44	4.83	17.07	40.29
Urbanization rate	290	73.87	13.29	47.92	93.81

Untaxed countries	Obs	Mean	Std. Dev.	Min	Max
Emission per capita (Kg CO_2)	522	8347.63	4389.48	2983.98	32211.42
Tax rate	522	0	0	0	0
GDP per capita	505	25458.78	21218.83	3582.86	111968.60
R&D expenditures (% of GDP)	450	1.10	.68	.20	3.14
Energy price (American Imported Crude Oil)	522	46.88	30.08	13.18	102.91
Industry structure (VA-% of GDP)	468	25.22	6.71	9.98	51.27
Urbanization rate	522	71.89	13.09	49.87	98.23

Table 4: Two sample t-test with unequal variances. This table contains t-statistics for each explanatory variable, comparing means between the treatment group and the control group.

Variable	t-stat	H_0 (diff=0)
GDP per capita	29.84	Reject
R&D expenditures (% of GDP)	41.19	Reject
Industry sructure (VA-% of GDP)	-1.74	Not reject
Urbanization rate	7.49	Reject

6. Results

In this section the results following from the methods and materials as discussed in previous sections will be presented and compared to the results from the existing literature. In section 6.1 the effect of carbon taxation on total CO_2 emissions for the treatment group as a whole will be discussed, which is the main result of this thesis. In section 6.2 the mitigating effects on a sectoral level will be discussed. In section 6.3 the estimated effects of carbon taxation in the individual taxed countries will be discussed.

6.1 Total emissions approach

To identify the marginal mitigating effect on the treatment group as a whole model specification (1) is employed on total CO_2 emissions as dependent variable, the regression results are provided in Table 5. Explanatory variables are added to the model step-by-step to give more insight into their statistical power. The tax rate coefficient only reaches significance in Model (4) where all explanatory variables except urbanization rate are included. First of all, all explanatory variables except urbanization rate have a statistically significant effect on per capita CO_2 emission and all signs correspond to the described underlying rationales. Thereby the statistical significance of the explanatory variables correspond to the findings by Lin and Li (2011). Urbanization rate lacks significance and is dropped from the model. As noted earlier, urbanization rate is related to the process of industrialization and the effects of industrialization are also controlled for by industry structure and possibly by GDP per capita. Therefore it is justified to exclude urbanization from the model on both theoretical and statistical grounds. For the remaining covariates with presumed linear effects (energy prices, industry structure) the interpretation is straightforward. An increase in the American imported crude oil price, which functions as a proxy for global energy prices, of 1 US$/barrel leads to a decrease in CO_2 of 56.5 kg/capita. At the mean this approximately corresponds to a 4% increase in oil prices leading to 1% decrease in emissions per capita. Furthermore, an increase in value added by the industry of 1 percentage point leads to an increase in CO_2 emissions of 102 kg/capita, which approximately corresponds to a 0.1% increase at the mean. The interpretation of the explanatory variables with a presumed non-linear relationship to CO_2 emissions per capita is slightly less intuitive. For both GDP per capita and R&D expenditures the linear term entails a positive coefficient while the quadratic term entails a negative coefficient. For sake of interpretation, a useful remark is that the marginal effect of a quadratic term increases in the level of the variable while the marginal effect of the linear term remains constant. The effects of GDP per capita and R&D expenditures can be described by an inverted-U shape curve based on their coefficients, since the marginal effects will be positive for low levels of the explanatory variable and negative from the turning point where the quadratic term starts to dominate the linear term and onwards. Thereby two important remarks on the interpretation of the coefficients for GDP per capita must be made. First, in this model they do not provide convincing evidence for a general Environmental Kuznets Curve since the relationship between GDP per capita is known to be heterogeneous across countries (Dijkgraaf and Vollebergh, 2005).

Second, GDP per capita as well as industry structure might both be controlling for the same process of industrialization. Knowing this, the causal interpretation of the coefficients for these explanatory variables is blurred. Nevertheless, as discussed earlier, both the existence and the precise underlying rationale of a general Environmental Kuznets Curve are uncertain. Therefore it is useful to include GDP per capita and industrialization rate both into the model, baring in mind the above mentioned remarks when interpreting the results.

The marginal mitigating effect of carbon taxes on total CO_2 emissions per capita in EU ETS participating countries on average is given by the regression coefficient of the tax rate in model (4). It follows that a 1 US\$/tCO_2 increase in carbon taxation leads to a decrease of 10.52 kg in annual CO_2 emissions per capita, which is the main result of this thesis. Employing the 2018 exchange rate it equals a 12.60 kg decrease in CO_2 per capita for a 1 EUR/tCO_2 increase in carbon taxation. Although this equals the effect at the margin an impression of the order of magnitude of the total mitigating effect of carbon taxation can be given. At the mean (23.23 US\$/tCO_2) and maximum tax (168.8 US\$/tCO_2) rate it corresponds to a total mitigating effect of 244 kg and 2126 kg in annual CO_2 emission per capita respectively. In terms of percentages this equals 2.7% and 23% of mean emissions per capita in taxed countries EU ETS participating countries. Compared to the existing literature these results are relatively low. For example, Metcalf (2019) found that the British Columbia carbon tax reduced emissions by 5-8% at a rate of 10 US\$/tCO_2 and Abrell et al. (2019) found that the UK price floor reduced emissions by 6.4% at a rate of 24 US\$/tCO_2.

Table 5: The mitigating effect of carbon taxation on total CO_2 emissions. This table contains the regression results of model specification (1) employed when employed on total CO_2. Emissions per capita in kg is set as the dependent variable. Both country and year fixed effects are included. Explanatory variables are add step-by-step.

	(1)	(2)	(3)	(4)	(5)
Tax rate	-4.54	-10.13*	-10.13*	-10.52**	-10.73*
	(5.42)	(5.47)	(5.47)	(5.08)	(5.33)
GDP/capita		0.24***	0.24***	0.24***	0.24***
		(0.08)	(0.08)	(0.08)	(0.08)
(GDP/capita)^2		-0.00000157**	-0.00000157**	-0.00000176**	-0.00000180**
		(0.000000758)	(0.000000758)	(0.000000672)	(0.000000661)
R&D expenditures		2660.50***	2660.50***	2268.70**	2251.70**
		(728.20)	(728.20)	(888.00)	(916.40)
R&D expenditures ^{2}		-574.80***	-574.80***	-534.50**	-530.10**
		(200.60)	(200.60)	(214.80)	(215.70)
Energy prices			-82.46***	-56.52***	-57.57***
			(14.76)	(16.65)	(16.99)
Industry structure				101.90***	101.50***
				(31.88)	(32.30)
Urbanization rate					9.67
					(55.79)
_cons	10057.50***	2650.60	4513.30***	1323.40	608.30
	(532.20)	(1609.10)	(1395.90)	(1490.20)	(3992.00)
N	812	708	708	668	668
Country FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes

Robust standard errors in parentheses

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

6.2 Sectoral approach

To identify how the mitigating effect on total emissions disaggregates over different sectors model specification (1) is employed on sectoral CO_2 emissions. The results are provided in Table 5. It can be observed that carbon taxation only has a significant mitigating effect in the energy sector. In the other sectors both the tax rate and the explanatory variables lose significance. The explanation for this is twofold: i) First, energy is by far the most carbon-intensive emission category, thereby it is important to note that transportation is subdivided to the energy category in the UNFCCC data. ii) Second, carbon taxes are predominantly aimed at fuel combustion and energy and heat production. The marginals mitigating effect of carbon taxation in EU ETS participating countries on average is provided by the coefficient corresponding to the tax rate in the model employed on CO_2 per capita in the energy emission category. It follows that a 1US$/tCO2 increase in carbon taxation leads to a decrease of 10.52 kg in annual CO2 emissions per capita. Employing the 2018 exchange rate it equals a 13.20 kg decrease in CO2 per capita for a 1 EUR/tCO_2 increase in carbon taxation. Interestingly, this result approximates the estimation by Hájek et al. (2019). They found that a 1 EUR/tCO_2 increase in carbon taxation may decrease emissions per capita by 11.58 kg in the energy sector. Hájek et al. (2019) employed a similar model employed on a selected treatment group of EU Member States for the period 2005-2015 controlling for ETS price, household consumption expenditure, corporate investments, solid fuel consumption and renewable energy consumption. The fact that similar results are found with substantial differences in identification strategy strengthens the evidence provided by Hájek et al. (2019).

Table 6: Mitigating effects of carbon taxation on sectoral CO_2 emissions. This table contains the regression results of the panel data fixed effects model specification (1) employed on sectoral CO_2. Emissions per capita is set as the dependent variable. Both country and year fixed effects are included.

	Energy	Industrial Processes and Product Use	Agriculture	Waste
Tax rate	-11.03**	0.65	-0.17	0.03
	(5.33)	(1.71)	(0.17)	(0.04)
GDP/capita	0.17**	0.06**	-0.0000339	0.000136
	(0.0747)	(0.0294)	(0.000917)	(0.000230)
$(GDP/capita)^2$	-0.00000141**	-0.000000346***	-5.31e-09	-1.45e-09
	(0.000000667)	(9.65e-08)	(5.38e-09)	(2.52e-09)
R&D expenditures	2321.60**	-52.70	0.14	0.41
	(849.50)	(151.70)	(5.71)	(2.11)
R&D expenditures ^{2}	-527.00**	-6.20	-1.29	-0.20
	(207.20)	(24.97)	(1.36)	(0.57)
Energy prices	-44.92***	-11.27*	-0.22	-0.16
	(14.86)	(5.52)	(0.31)	(0.12)
Industry structure	105.20***	-3.08	-0.02	-0.21
	(30.05)	(10.16)	(0.54)	(0.29)
_cons	1110.20	142.80	55.64***	19.26*
	(1379.50)	(307.20)	(17.66)	(9.579)
Country FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	668	668	651	556

Robust standard errors in parentheses

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

6.3 Individual effects

To estimate the effect of carbon taxation in individual taxed countries, the difference-in-differences specification (2) is employed on emissions from the energy sector. A time dummy (t), treatment dummy (T) and difference-in-differences estimator (t*T) are included for each taxed country. Emissions from the energy sector is set as dependent variable since it appears from section 6.2 that carbon taxation in EU ETS participating countries predominantly has an effect in this sector. Furthermore, to make the effects interpretable as percentage change and thereby better comparable across countries, the dependent variable in model (4)-(6) is set as the natural logarithm of emissions in the energy sector. Also, to maximize the number of observations only the key explanatory variables GDP/capita and $(GDP/capita)^2$ are included. Lastly, year and country fixed effects are included in model (3) and (6). The results are provided in Table 7 on next page.

Table 7: Mitigating effects of carbon taxation in individual taxed countries on emissions from the energy sector. This table contains the regression results of model specification (2) when employed on emissions from the energy sector. The dependent variable is set as energy emissions in model (1)-(3) and as the natural logarithm of energy emissions in model (4)-(6). All explanatory variables except GDP/capita and (GDP/capita)^2 are omitted. Year and country fixed effects are included in model (3) and (6).

	(1)	(2)	(3)	(4)	(5)	(6)
Sweden	630.4	-193.7	-178.2	-0.007	-0.119***	-0.119***
	(522.2)	(342.2)	(365.0)	(0.0546)	(0.0381)	(0.0388)
Norway	2384.8***	2464.7***	2641.9***	0.290***	0.197***	0.201***
	(522.2)	(538.2)	(645.7)	(0.0546)	(0.0455)	(0.0486)
Denmark	-335.4	-959.5***	-928.4**	-0.038	-0.132***	-0.132***
	(506.2)	(353.6)	(383.9)	(0.0527)	(0.0332)	(0.0339)
Slovenia	1496.6***	944.0***	917.7***	0.181***	0.136***	0.135***
	(331.7)	(239.6)	(247.8)	(0.0344)	(0.0298)	(0.0303)
Estonia	-1238.3***	295.2	249.3	-0.025	0.064**	0.0609*
	(220.2)	(265.6)	(240.4)	(0.0271)	(0.0312)	(0.0320)
Ireland	-742.8***	-1378.2***	-1273.2***	-0.058**	-0.142***	-0.142**
	(259.4)	(353.2)	(418.0)	(0.0257)	(0.0530)	(0.0614)
Iceland	-394.6	-709.2***	-684.4**	-0.093***	-0.129***	-0.129***
	(259.4)	(240.5)	(265.4)	(0.0257)	(0.0347)	(0.0368)
France	236.3	337.0	323.2	-0.037	-0.029	-0.029
	(306.7)	(286.2)	(255.5)	(0.0307)	(0.0293)	(0.0287)
Portugal	1226.3***	1413.4***	1378.0***	0.144***	0.165***	0.165***
	(314.6)	(309.4)	(249.3)	(0.0332)	(0.0298)	(0.0287)
GDP/capita		0.20***	0.20***		0.0000158***	0.0000162**
		(0.0621)	(0.0491)		(0.00000595)	(0.00000746)
(GDP/capita)^2		-0.00000143***	-0.00000149***		-8.99e-11**	-9.39e-11**
		(0.000000445)	(0.000000394)		(3.91e-11)	(4.53e-11)
_cons	8964.8***	5346.3***	4897.0***	-4.836***	-5.172***	-5.191***
	(1179.2)	(832.3)	(908.3)	(0.0994)	(0.134)	(0.143)
Country FE	No	No	Yes	No	No	Yes
Year FE	No	No	Yes	No	No	Yes
N	812	792	792	812	792	792

Robust standard errors in parentheses

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

It can be observed that the results from the difference-in-differences estimation are rather mixed. Therefore, additional explanation is necessary. First of all, the effect in Finland can not be estimated by difference-in-differences estimation since the dataset does not entail pre-treatment data. The Finish carbon tax was implemented in 1990, which is the first year in the dataset.

For Sweden the coefficients are negative after controlling for GDP/capita and $(\text{GDP/capita})^2$. Significance is reached when the natural logarithm is used as dependent variable. This result suggests that the Swedish carbon tax caused an average reduction in annual per capita CO_2 emissions in the energy sector of 11.9%. The results in the existing literature on the Swedish carbon tax is mixed. On the one hand, Lin and Li (2011) found that the tax did not have a significant effect on emissions. On the other hand, Andersson (2019) found an average annual reduction of 6.3% between 1990 and 2005 using a synthetic control method. The result in thesis supports the evidence provided by Andersson (2019) but yields a substantially higher estimation of the mitigating effect of the Swedish carbon tax.

For Norway the coefficients are positive in all estimated models, which suggests that, despite relatively high tax rates, emissions in the energy sector actually increased substantially (approximately 20%) after the carbon tax was introduced. This finding is in line with what was found by Lin and Li (2011). They assign the increase in emissions to a vast growth (86%) in exports of oil and natural gas, with rising energy prices having a simulating influence on energy exports. Thereby it is important to note that Norway stands out for being one of the largest suppliers of natural gas worldwide, supplying 20-25% of total EU gas demand (Norwegian Petroleum, 2021). Furthermore, the Norwegian carbon tax exempts some competitive, energy-intensive industries, including pipeline transportation of natural gas, which weakens the mitigating effect of the tax.

For Denmark a significant mitigating effect of carbon taxation on emissions from the energy sector of approximately 13.2% is found. This result is a not in line with most empirical work. Lin and Li (2011) found that the carbon tax in Denmark had a statistically insignificant effect on total emissions, assigning the limited emissions abatement to substantial reimbursements and exemptions incorporated in the tax design. Hájek et al. (2019) did not find an individual effect for Denmark due to the absence of variance in $_2$ tax rates for the energy sector during the researched time span. On the other hand, Andersen and Skou (2010) found that the Danish carbon tax did have a substantial mitigating effect on total GHG emissions of approximately 4%. This thesis thus support the evidence by Andersen and Skou (2010), but yields a substantially higher estimate.

For Slovenia it is found that emissions per capita in the energy sector increased after the tax was implemented. This result suggest the Slovenian carbon tax was not successful in inducing CO_2 emissions mitigation. This finding is in line with what is found in the literature. Andersen and Skou (2010) find no reduction in GHG emissions in Slovenia due to the tax and Markovič-Hribernik and Murks (2007) confirm this. Thereby Andersen and Skou (2010) rightfully points out that with the introduction of the carbon tax

Slovenia mainly relabelled the mineral oil tax that was already in place. The main driving factor behind the increase in emissions is the vast growth in road transportation after Slovenia and other Eastern European countries joined the European Union (UNFCCC, 2020b), passenger transport has increased by 23.6% since the carbon tax was introduced in 1996 (OECD data, 2021).

For Estonia the coefficient of carbon taxation is insignificant at the 5% level after controlling for year and country fixed effects. It suggests that the Estonian carbon tax only had a very limited mitigating effect on emissions. In the existing literature there are no ex-post analyses of the Estonian carbon tax. The author assigns the limited effect of the tax to low rates in the design of the tax. Estonia levies a the lowest rates of all taxed EU ETS participating countries at 2.48 US\$/tCO_2 in 2018.

For Ireland the results suggest that the introduction of the carbon tax had a substantial average mitigating effect on annual per capita CO_2 emissions of approximately 14.2%. This finding is in line with Hájek et al. (2019). He found a substantial partial coefficient for Ireland in his panel fixed effects model, although he does not give an idea about the order of magnitude of the effect. Generally, 14.4% is a relatively high estimate when compared with ex-post analyses of carbon taxation in other countries (Green, 2021).

For Iceland the results suggest an average mitigating effect of 12.9% of annual CO_2 emissions. There are no ex-post analyses in the existing literature on the Icelandic carbon tax. Likewise, 12.9% is a relatively high estimate compared to other ex-post analyses.

For France the effect of the tax is insignificant in all models, suggesting that the French carbon tax only had a very limited effect on emissions. Dussaux (2020b) is the only ex-post analysis of the carbon tax in France and focuses on the manufacturing industry. He finds that the tax caused a reduction in emission by 1-5% between 2014-2018. It could be expected that emissions in the energy sector decrease consequentially since the manufacturing sector is an important energy consumer. However, this effect is not significantly proved based on the difference-in-differences estimation. Furthermore, it can be observed that the tax rate coefficients switch signs when the natural logarithm is set as dependent variable, which might be a indication of omitted variable bias data.

For Portugal all coefficients are positive and highly significant, which suggest that the carbon tax was not yet successful in emissions mitigating and CO_2 emissions substantially increased after the implementation of the tax. Thereby it must be noted that the emissions per capita in Portugal entail a high level of inter-annual volatility. This volatility can to a large extent be assigned to varying production of hydroelectric energy due to large year-to-year differences in precipitation (UNFCCC, 2020a). In 2017, two years after the introduction of the Portuguese carbon tax, hydroelectric energy in Portugal was exceptionally unproductive due to limited rainfall. This led to a vast increase in the use of coal and a consequential increase of CO_2 emissions in the energy sector of 20%. Also, Portugal levies a relatively low carbon tax rate of 8.49 US\$/tCO and the tax was only put in place fairly recently in 2015.

Overall, the difference-in-differences estimation does not tell a consistent story on the mitigating effects of carbon taxation in EU ETS participating countries. Clearly, there are confounding factors that heavily influence CO_2 emissions and are not controlled for in the model, like oil exports in Norway, Slovenia's entry to the European Union and rainfall in Portugal. However, the results do suggest that carbon taxation did have a mitigating effect in Sweden, Denmark, Iceland and Ireland. Although the possibility that these effects are a result of confounding factors as well can not be entirely ruled out. Also, it is reasonable to conclude that the absence of a mitigating effect of carbon taxation in Norway, Estonia, Slovenia and Portugal can at least partly be assigned to the tax designs. The mitigation potential of the carbon taxation is reduced by tax exemptions, rebates and low tax rates. Furthermore, the results cast doubts on the causal interpretation of other studies that use difference-in-differences estimation with untaxed European countries functioning as a control group for individual European countries with a carbon tax, like Lin and Li (2011). Although they did include some more explanatory variables, these additional covariates do not substantially improve the model, as will become clear from the robustness checks in the next section of this thesis.

7. Robustness checks

In this section some robustness checks will be provided for the results from both the panel data fixed effects model and the difference-in-differences model. As a robustness check of the panel data fixed effects model, the model is estimated on two subgroups of countries. The sample is subdivided into the Nordic and the non-Nordic EU ETS participating countries. This subgroup analysis investigates whether the effect of an increase in tax rate differs among the two sub samples. As mentioned, the Nordic countries were pioneers in the implementation of carbon taxation and all introduced a carbon tax before 1995. Nordic countries typically tax carbon at the highest rates. The non-Nordic countries introduced carbon taxation after 1995, of which 4 from 2010 on wards, and typically levy at lower rates. The results of the subgroup analysis is provided in table 8 below.

It can be observed from table 8, the tax rate has a significant effect in the Nordic countries sub sample only and that the insignificant effect in the non-Nordic countries is substantially lower. It could suggest that carbon taxes are more effective when they are in place for a longer period of time and/or when tax rates are higher. Furthermore, it can be observed that all explanatory variables are robust against the subgroups estimation since there are no substantial changes in the magnitude or variance of their coefficients.

Table 8: Robustness check for the panel data fixed effects model: subgroup estimation. This table contains the regression results of model specification (1) when employed on the Nordic and non-Nordic taxed countries separately. Emissions in the energy sector are set as dependent variable. Country and year fixed effects are included.

	Initial model	Nordic countries	Non-Nordic countries
Tax rate	-10.52**	-13.74**	-5.90
	(5.078)	(5.717)	(16.92)
GDP/capita	0.24***	0.20**	0.21***
	(0.0806)	(0.0745)	(0.0556)
$(\text{GDP/capita})^2$	-0.00000176**	-0.00000129**	-0.00000201***
	(0.000000672)	(0.000000613)	(0.000000411)
R&D expenditures	2268.7**	1939.8*	1929.6**
	(888.0)	(1061.1)	(869.2)
R&D expenditures ^{2}	-534.5**	-485.0**	-362.7*
	(214.8)	(214.4)	(176.8)
Energy prices	-56.5***	-55.3***	-48.1***
	(16.65)	(18.30)	(15.54)
Industry structure	101.9***	93.8**	92.2**
	(31.88)	(35.16)	(35.46)
_cons	1323.4	1305.0	1517.0
	(1490.2)	(1364.4)	(1486.2)
Country FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
N	668	526	567

Robust standard errors in parentheses

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

As a robustness check for the difference-in-differences model more explanatory variables will be added to the initial model. The results of this robustness check is provided in table 9. As mentioned in section 6.3, omitted variables are an important issue in the conducted difference-in-differences estimation. To investigate to what extend this issue can be solved with the data at hand, all explanatory that were discussed in section 4 are added to the model. Thereby the new model roughly corresponds to the estimation by Lin and Li (2011).

It can be observed that adding these variables does not substantially improve the model. Almost all coefficients remain more or less unchanged in magnitude and variance after adding the additional variables. One exception is the coefficient for Estonia's difference-in-differences estimator, which decreases substantially and loses significance after controlling for R&D expenditures. From the robustness check it follows that in order to eliminate omitted variable bias entirely, more confounding factors need to be controlled for. After adding these extra explanatory variables, the set of covariates roughly corresponds to the estimation technique of Lin and Li (2011), and thereby the results cast doubt on the causal interpretation of their results. What complicates the estimation of individual effects in countries with a carbon tax is the fact that some factors are too a large extend country specific. Examples of such country specific confounding factors are rainfall in Portugal and oil exports in Norway. Lastly, it can be observed that key explanatory variables GDP/capita and $(\text{GDP/capita})^2$ lose significance and the effect for Sweden and Norway can not be estimated when more variables are added, which might be due to missing values in these variables. For that reason these variables were omitted from the initial model.

Table 9: Robustness check for the difference-in-differences model: Additional explanatory variables. This model contains the regression results of model specification (2). The natural logarithm of emissions in the energy sector is set as the dependent variable in all model. Model (1) in this table is the original model which corresponds to model (6) from Table 7.

	(1)	(2)	(3)	(4)	(5)
Sweden	-0.119***	-0.119***	-0.161***	-0.162***	0
	(0.0388)	(0.0388)	(0.0537)	(0.0523)	(.)
Norway	0.201***	0.201***	0.090	0.078	0
	(0.0486)	(0.0486)	(0.0766)	(0.0753)	(.)
Denmark	-0.132***	-0.132***	-0.179***	-0.176***	-0.176***
	(0.0339)	(0.0339)	(0.0475)	(0.0469)	(0.0421)
Slovenia	0.135***	0.135***	0.052*	0.048*	0.062**
	(0.0303)	(0.0303)	(0.0278)	(0.0274)	(0.0234)
Estonia	0.061*	0.061*	0.077**	0.089**	0.029
	(0.0320)	(0.0320)	(0.0323)	(0.0352)	(0.0347)
Ireland	-0.142**	-0.142**	-0.171***	-0.179***	-0.151***
	(0.0614)	(0.0614)	(0.0538)	(0.0554)	(0.0529)
Iceland	-0.129***	-0.129***	-0.142***	-0.141***	-0.113**
	(0.0368)	(0.0368)	(0.0348)	(0.0353)	(0.0485)
France	-0.029	-0.029	-0.038	-0.045	-0.0005
	(0.0287)	(0.0287)	(0.0293)	(0.0310)	(0.0276)
Portugal	0.165***	0.165***	0.116***	0.082	0.101**
	(0.0287)	(0.0287)	(0.0281)	(0.0507)	(0.0428)
GDP/capita	0.0000162**	0.0000162**	0.0000114	0.0000136	0.0000151
	(0.00000746)	(0.00000746)	(0.00000891)	(0.00000931)	(0.0000106)
(GDP/capita)^2	-9.39e-11**	-9.39e-11**	-5.85e-11	-7.54e-11	-1.06e-10
	(4.53e-11)	(4.53e-11)	(5.50e-11)	(5.91e-11)	(7.66e-11)
Energy prices		-0.0014***	-0.0014***	-0.0014***	-0.0019***
		(0.000420)	(0.000413)	(0.000464)	(0.000613)
Industry structure			0.0072***	0.0074***	0.0160***
			(0.00228)	(0.00229)	(0.00531)
Ubanization rate				0.0060	-0.0009
				(0.00730)	(0.00631)
R&D expenditures					0.271***
					(0.0688)
R&D expenditures ^{2}					-0.0599***
					(0.0197)
_cons	-5.191***	-5.159***	-5.324***	-5.806***	-5.738***
	(0.143)	(0.141)	(0.159)	(0.571)	(0.474)
Country FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
N	792	792	733	733	668

Robust standard errors in parentheses

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

8. Concluding Remarks, Discussion and Policy Recommendations

First some concluding remarks, then discussion of the validity of the results and lastly recommendations for policy makers will be provided.

Climate change is one of the most pressing concerns in post modern society. In order to curb global warming below 2°C policy measures regarding the mitigation of carbon dioxide emissions are of great importance. Over the past three decades several carbon pricing policies have been implemented in Europe, both a European allowances trading scheme and several national carbon taxes. As follows from economic theory, carbon pricing is an efficient instrument for the mitigation of carbon emissions. On the one hand, carbon taxation has an advantage over allowances trading since prices under taxation are more stable. On the other hand, the environmental outcome under carbon taxation is uncertain, where allowances trading does provide certainty on that matter. This thesis is concerned with ex-post analysis of the actual mitigating effects of carbon taxes that are in place in EU ETS participating countries and thereby aims to eliminate some of the uncertainty on the environmental outcomes.

For the evaluation of the mitigating effects two commonly used models are employed on annual UNFCCC emissions data for 1990-2018: i) panel data fixed effects and ii) difference-in-differences. The panel data fixed effects model finds that an 1 euro increase in carbon tax rate decreases total emissions per capita by 12.6 kg on average in taxed EU ETS participating countries. When this model is employed on sectoral emissions data it follows that carbon taxation is predominantly effective in the energy sector. The average effect of an increase in carbon tax rate of 1 euro on emissions in the energy is 13.2 kg of CO_2. This result strengthens the evidence found by Hájek et al. (2019). Furthermore, from the subgroups analysis robustness check it follows that carbon taxation might be particularly effective when the taxes are in place longer and/or get levied at high rates. The difference-in-differences model does not tell a consistent story on the mitigating effects in individual taxed countries. The results suggest that carbon taxation was effective in: Sweden, Denmark, Iceland and Ireland. The results also suggest that in the remaining countries carbon taxes did not have a measurable significant mitigating effect on CO_2 emissions, which can at least partly be assigned to the tax designs in: Norway, Estonia, Slovenia and Portugal.

Caution should be exercised with the causal interpretation of the results of the difference-in-differences estimation. Using difference-in-differences analysis one should always be considerate about heteroskedaticity, multicollinearity, omitted variables and common trend. From the trend comparison in section 4 it follows that the common trend assumption does not hold for most individual taxed countries when compared to the control group, which could be problematic. From elaboration on the results of the difference-in-differences estimation it follows there are serious omitted variable issues. Thereby the results cast doubt on the causal interpretation of the results from other difference-in-differences approaches that use untaxed European countries as a counterfactual for European countries with a carbon tax, like Lin and Li (2011). For the panel data fixed effects model omitted variable issues are less severe since differences in country characteristics are averaged out within the treatment group. Furthermore, the panel data fixed effects specification uses the full variation in tax rates, making it less vulnerable for confounding factors.

For future research, an obvious suggestion is to include more explanatory variables to reduce omitted variable bias. What complicates is that some confounding factors are country specific. Therefore a relevant sequential analysis could be focused on one taxed country with a detailed assessment of the determinants of carbon emissions in that particular country and possibly with use of a synthetic control method. Furthermore, it appears that analysing the effects of carbon taxes in France and Portugal is still quite early, they introduced carbon taxation in 2014 and 2015. An analysis of the mitigating effects of carbon taxation in these countries after some years have past, when there is more post-treatment data available, could add relevant insights.

In conclusion, on theoretical grounds carbon taxation is an effective instrument for the mitigation of carbon taxation. The empirical results of this thesis confirm that on average this is true for EU ETS participating countries that introduced carbon taxation. The results for individual taxed countries do not tell a consistent story and suffer from confounding factors. However, the effectiveness of the tax can most likely be improved by limiting tax exemptions, levying high tax rates and keep the tax in place for a longer period of time. Therefore, based on the results of this thesis, carbon taxation is recommended as an instrument to mitigate carbon emissions, although policy makers should regard the above mentioned factors in the tax design.

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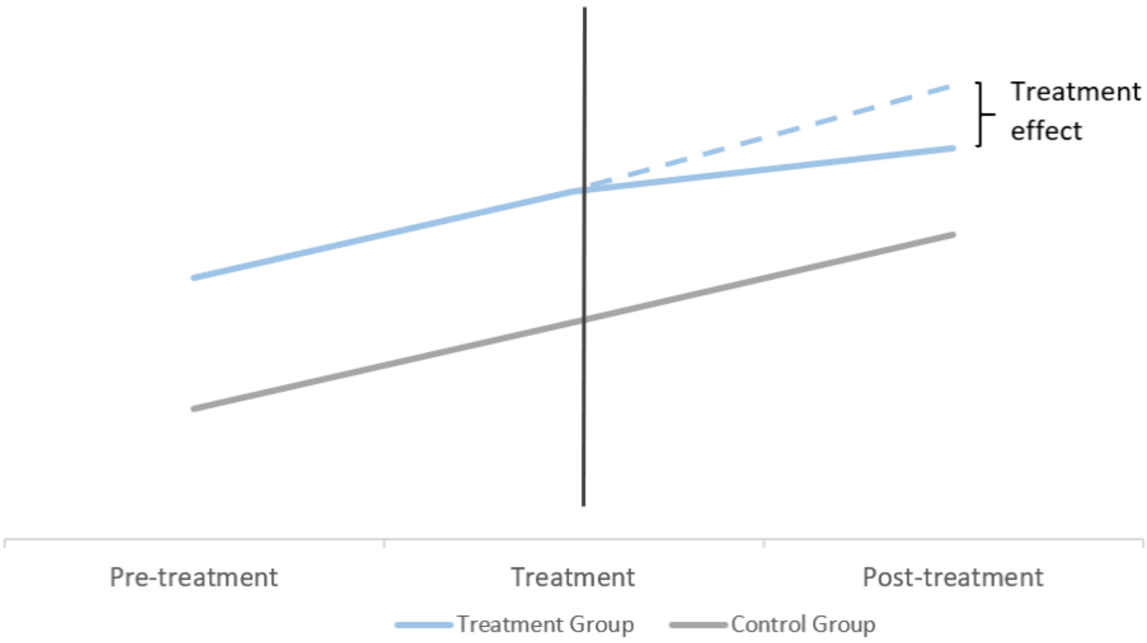
Appendix

A1. Visual representation of a standard difference-in-differences estimation.



Source: Own elaboration

A2. Historic carbon tax rates in the treated countries in US$/tCO2

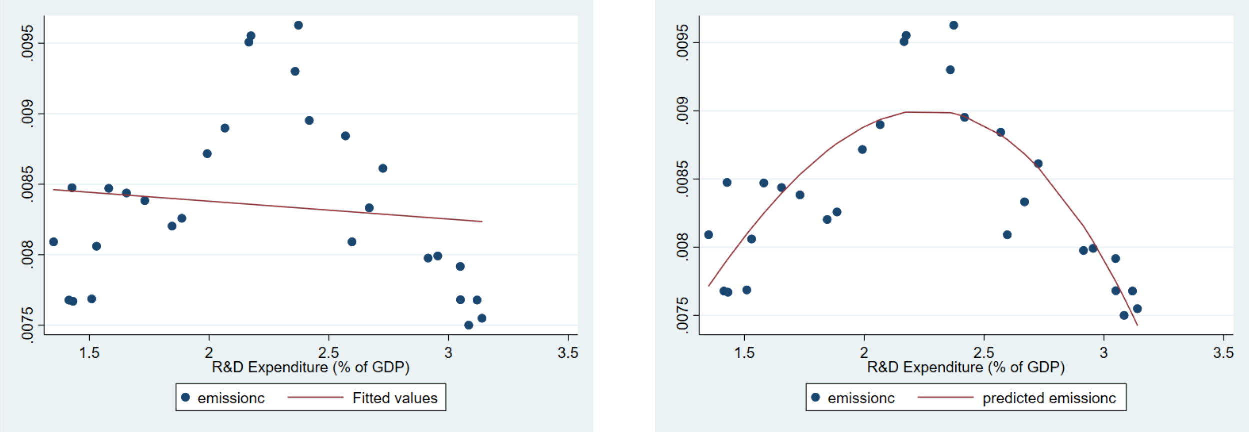
	Finland	Sweden	Norway	Denmark	Slovenia	Estonia	Ireland	Iceland	France	Portugal
1990	1.745									
1991	1.732	41.21	38.97							
1992	1.552	41.64	53.12	15.57						
1993	2.405	41.95	50.56	16.23						
1994	4.047	43.48	48.62	15.24						
1995	8.927	46.13	58.38	18.41						
1996	8.272	55.54	66.59	17.48	7.458					
1997	14.08	48.64	65.19	15.72	6.554					
1998	14.59	46.15	50.24	14.18	17.23					
1999	18.57	45.01	51.40	14.55	16.96					
2000	16.42	42.84	48.01	12.85	14.17	0.305				
2001	15.16	51.34	34.10	11.84	12.28	0.422				
2002	14.96	60.81	35.66	11.73	11.66	0.418				
2003	19.65	89.64	44.52	14.66	14.06	0.522				
2004	22.23	120.5	47.68	16.54	15.41	0.592				
2005	23.39	128.8	53.13	15.65	16.21	0.936				
2006	21.77	117.4	51.96	14.54	15.14	1.210				
2007	24.12	132.9	56.84	16.29	16.70	1.331				
2008	31.02	168.8	68.67	31.50	19.57	2.342				
2009	27.03	126.5	54.11	27.15	16.55	2.646				
2010	27.48	145.4	62.02	27.96	16.83	2.708	20.20	8.509		
2011	70.70	166.0	68.84	30.00	17.67	2.828	21.21	14.27		
2012	79.91	163.5	67.73	28.83	19.17	2.663	19.97	17.09		
2013	64.20	166.6	70.50	28.24	18.48	2.568	25.68	17.50		
2014	79.98	167.4	70.23	30.82	19.85	2.757	27.57	19.66	9.652	
2015	62.37	129.8	53.95	24.47	18.58	2.151	21.51	16.00	15.59	5.474
2016	64.75	130.5	51.53	25.61	19.31	2.232	22.32	18.65	24.56	7.446
2017	73.23	139.8	56.25	27.38	20.43	2.362	23.62	22.57	36.02	8.091
2018	76.86	139.1	64.28	28.81	21.44	2.479	24.79	35.70	55.29	8.492

Source: World Bank Carbon Pricing Dashboard (World Bank, 2021)

A3. Summary of urbanization by country

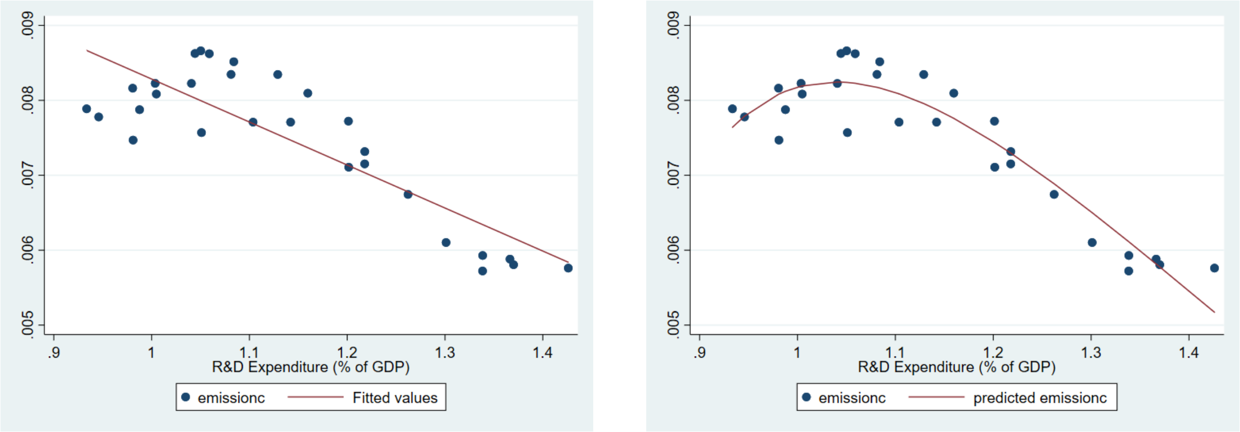
Country	Mean	Std. Dev.	Freq.
Austria	59.504289	1.8421072	232
Belgium	97.374562	.58021235	232
Bulgaria	70.453207	2.594425	232
Croatia	53.976124	1.8671899	232
Cyprus	91.471145	2.2899185	203
Czechia	73.871567	.6569163	232
Denmark	86.04148	1.0764906	232
Estonia	69.229627	.99588484	232
Finland	82.774962	1.7890001	232
France	77.241433	1.8533529	230
Germany	75.588384	1.4377717	232
Greece	74.56781	2.4410072	232
Hungary	67.154318	2.2870571	232
Iceland	92.687594	.95916578	231
Ireland	60.275184	1.9445974	232
Italy	67.918343	1.0828697	232
Latvia	68.222696	.4396089	232
Lithuania	67.079939	.30677411	232
Luxembourg	86.011698	3.2093478	232
Malta	93.440897	.94738447	229
Norway	77.144194	3.037725	203
Poland	61.074049	.97716384	232
Portugal	56.764482	5.219272	232
Romania	53.58082	.40347016	203
Slovakia	55.400264	1.0800449	232
Slovenia	51.814764	1.3382819	232
Spain	77.412203	1.5615594	232
Sweden	84.70024	1.1874291	203
Total	72.509665	13.137567	6,374

A4. Two non-linear relationships between CO_2 emission per capita and R&D expenditures as a percentage of GDP



(a) Austria, linear fit.

(b) Austria, 2th degree polynominal fit.



(c) Italy, linear fit.

(d) Italy, 2th degree polynominal fit.