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Master Thesis Policy Economics

Estimating the Impact of Carbon Pricing Policies on CO2 Emissions

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Abstract

Economists and others have proposed carbon pricing as a central pillar in decarbonisation and the solution to climate change. However, this raises the question; what has been the impact of carbon pricing policies on emissions reductions thus far? This thesis investigated the effect of carbon pricing policies on the CO2 emissions growth rates of countries using an ex-post evaluation. Building on the novel World Carbon Pricing Database, emissions data from 128 countries, of which 40 have implemented carbon pricing policies, were analysed using a panel regression analysis. The results show that carbon pricing is related to a reduction of two to three percentage point reduction in the annual emissions growth rate, yet the additional effect of a dollar increase in the carbon price is limited to only around 0.1 percentage point. Moreover, specific attention is paid to countries that recently implemented carbon pricing. Their emissions growth rate reduction is limited, only about 1.5 percentage points. From the findings, it can be concluded that carbon pricing can be a valuable tool towards reducing emissions but might not be effective enough in reaching the required goals as stated in the Paris Climate Accord. Additionally, countries that still have to start pricing carbon emissions might not see sizeable results quickly.

Keywords: Carbon taxation, ETS, environmental policy, growth rate regression

Contents

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List of Abbreviations

Abbreviation	Meaning
ETS	Emissions Trade System
ECP	Emissions-weighted carbon price
EU	European Union
CO2	Carbon Dioxide
GDP	Gross domestic product
WCPD	World Carbon Pricing Database
OECD	Organization for Economic Co-operation and Development
TEU	Taxing Energy Use
IEA	International Energy Agency
ESMAP	Energy Sector Management Assistance Program

1. Introduction

In the 2015 Paris Climate Agreement, countries from all over the world agreed to limit global warming to below two degrees Celsius on average. Moreover, countries pledged to take measures to reach the global peak of greenhouse gas emissions as soon as possible. Economists have proposed carbon emissions pricing as the most cost-effective method to reduce CO2 emissions. However, while 43 countries apply a carbon pricing policy, there is little empirical evidence to support the claim that carbon pricing can substantially lower emissions to net-zero levels.

In the last decade, more countries have implemented carbon pricing, and emissions prices have risen. Various studies estimate the impact on future emissions, the economy, and innovation investments. However, there are only a few ex-post studies on such policies' effectiveness in a cross-country setting (Best et al., 2020; Lin and Li, 2011; Rafaty et al., 2020). Moreover, most existing empirical research has focussed on the effects in advanced economies, while emerging countries are considering carbon pricing too. The literature gap between advanced and emerging economies has primarily been a problem of comparable data availability and the limited set of countries that have implemented carbon pricing policies. Thus, there remains a lack of knowledge on the emissions reduction potential of carbon pricing. Without substantial empirical evidence on carbon pricing, countries might implement ineffective policies, which raise economic costs with little benefit for the environment. Even worse, effective policies may well not be implemented at all. Any delay in reducing carbon emissions will increase the threat of climate change.

Last year, the World Carbon Pricing Database was published, overcoming the challenge of the lack of comparable carbon price data (Dolphin and Xiahou, 2022). This novel database allows for more detailed analysis than was previously possible. Researchers can use this cross-country data to study the effectiveness of carbon pricing over a long period of time. Additionally, the dataset is structured by national jurisdictions, so differences between countries can be explored.

This research applies the novel dataset and aims to assess the effectiveness of carbon pricing policies in an international context over a 30-year period. This thesis uses quantitative regression methods to determine the impact of carbon pricing policies, i.e., carbon taxes and emissions trade systems, on CO2 emissions reductions.

This thesis answers the following question: *What is the impact of carbon pricing policies on CO2 emissions?* To answer the main research question, the following sub-questions are addressed:

1) What are carbon pricing policies?
2) Through which channels does carbon pricing affect CO2 emissions?
3) Do carbon pricing policies lead to a reduction in CO2 emissions growth rates?
4) What is the effect of carbon price levels on a country's CO2 emissions growth rate?

5) Do countries implementing carbon pricing since 2010 have different emissions growth rate reductions than countries with such policies in place for longer?

To answers these questions, first an overview of carbon pricing policies in theory and practice is presented. The effects of carbon pricing is discussed using Kaya’s identity (Kaya and Yokobori, 1997). Building on relevant empirical research, a methodology is developed to estimate the effectiveness of carbon pricing policies and the effect of the carbon price on emissions reduction.

The effectiveness of carbon pricing policies is estimated using a panel regression of 128 countries, with the World Carbon Pricing Database as the primary source of carbon prices. The average annual emissions growth rate is regressed on a dummy of the carbon pricing policy, the carbon price and several controls related to Kaya’s identity. In addition to national emissions, the following four sectors are also analysed: electricity generation, manufacturing, road use and buildings. Finally, the differences between different carbon pricing mechanisms and their time of implementation are analysed using interaction effects.

The results indicate that countries that have implemented carbon pricing see a two to three percentage point reduction in the annual emissions growth rate, yet the additional effect of a dollar increase in the carbon price is limited to only around 0.1 percentage point. Countries that have implemented carbon pricing since 2010 see a reduction of around 1.5 percentage points, which is lower than countries that have implemented these policies earlier.

This research contributes to policymaking on carbon pricing by estimating the past effectiveness of pricing policies. The research focus on the international context of carbon pricing provides more valuable insight into the effects of carbon pricing for emerging economies. Likewise, this research emphasis on price effects can improve the alignment of emissions reduction goals with the price level set by the government. This improves policymaking on the delicate balance of economic and environmental interests.

This thesis continues with the following section on the theory and practice of carbon pricing. Then, the relevant literature is reviewed, and the hypotheses developed. Next, section 4 presents this paper's primary carbon pricing data. The methodology and variables are discussed in section 5. The results and analysis are presented in section 6. The meaning and implications of these results are discussed in section 7. Finally, section 8 concludes.

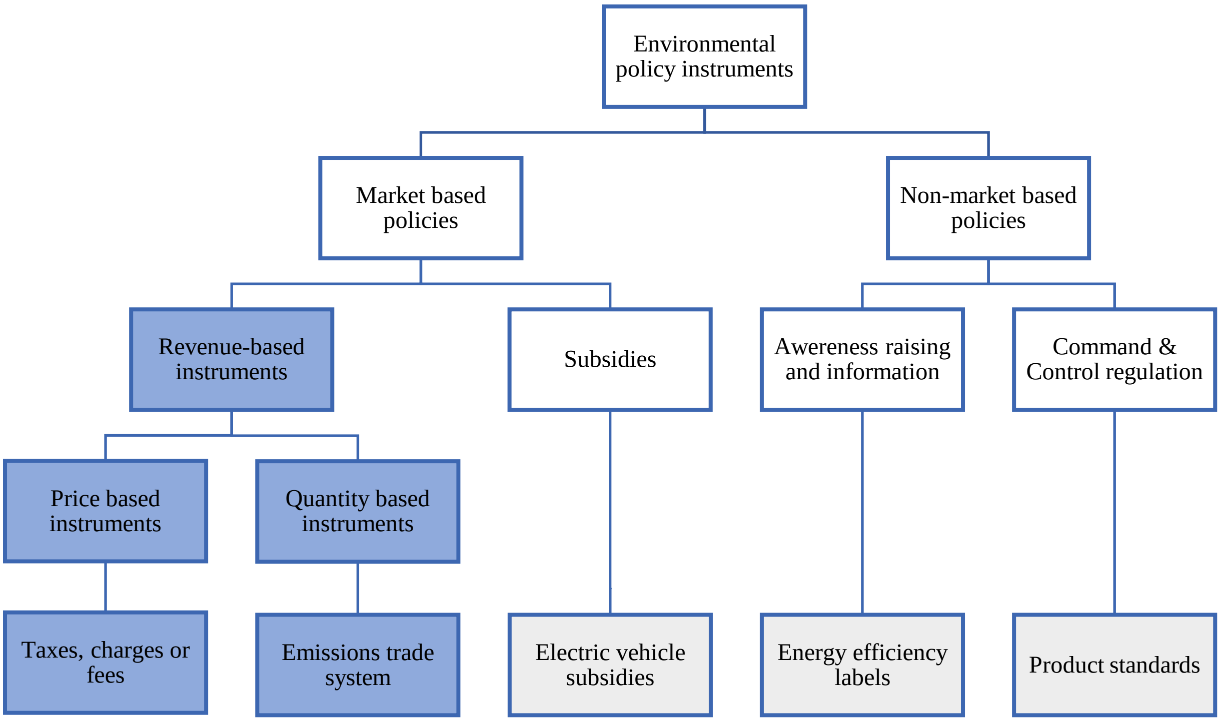
2. Theory and Practice of Carbon Pricing

2.1. An overview of environmental policy

Governments have a wide range of environmental policy instruments available, which can be classified into market-based and non-market-based approaches. The former includes fiscal instruments like taxes and subsidies, while the latter concerns regulatory mechanisms such as product standards (European Commission and Ecorys, 2021). Various types of environmental policy instruments are presented in Figure 2.1, and examples of the policies are given in the bottom row. Market based policies revolve around increasing or decreasing the price of goods and services. Specifically, revenue-based instruments increase the price of goods, which should lower demand, or induce different production methods.

Figure 2.1

Overview of environmental policy instruments



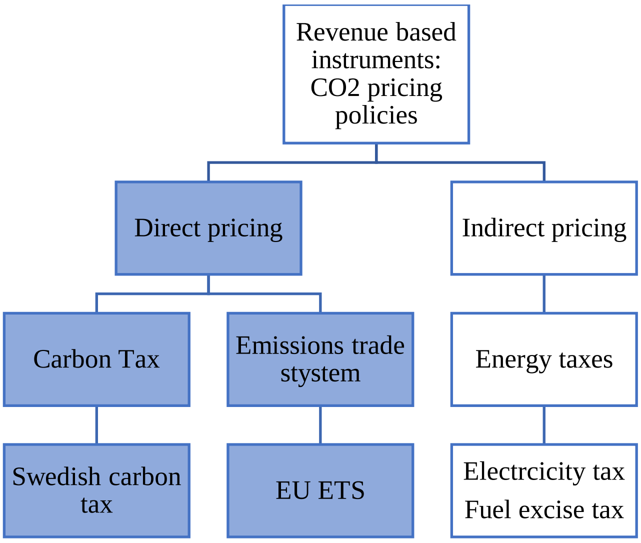
Source: European Commission and Ecorys (2021) and own modifications

The carbon taxes implemented by the Nordic countries and the European Union's ETS are well-known examples of carbon pricing initiatives. Carbon pricing policies put an external price on CO2 emissions emitted during the production or consumption of goods to reduce environmental damage. Figure 2.2 highlights the revenue-based policies aimed at CO2 reduction. Economists and environmentalists make a difference between direct and indirect pricing of CO2 emissions. Direct carbon pricing refers to price incentives that are directly proportional to the CO2 emitted by a product or activity. Direct pricing applies the same price for each unit of CO2 across different sources and sectors. This leads to equal and cost-effective reduction incentives, i.e. the highest efficiency with respect to emissions reduction (World Bank, 2022). In contrast, indirect carbon pricing does increase the price of products associated with CO2 emissions, but not directly proportional. For example, fuel excise taxes on gasoline indirectly increase the cost of the associated carbon emissions. However, relative differences in tax rates with respect to the carbon content create a tax differential between energy types that could hinder emissions reduction, and thereby lowering the tax efficiency. For example, diesel is taxed lower in most countries, even though diesel emits up to 13% more CO2 than gasoline. Moreover, these indirect taxes are often implemented for other policy goals rather than emissions reduction, e.g. revenue raising or air pollution reduction (European Commission and Ecorys, 2021).

This thesis focuses on direct carbon taxation policies, i.e., carbon taxation and emissions trade systems (ETS). These are the primary market-based policies used by the government to reduce emissions. Indirect carbon pricing is not considered, as these taxes are often implemented for other reasons than emissions reduction.

Figure 2.2

Policies aimed directly at CO2 emissions



2.2. Emissions trade systems and carbon taxes

From a theoretical economic perspective, carbon taxation and emissions trade systems are similar under the assumptions of complete and perfect markets. In practice, both emissions trade systems and carbon taxes are used to price the CO2 emitted. Countries may also use both instruments to price carbon emissions from different types of polluters. For example, France applies the EU-ETS to large industries, while fossil fuel use by households is subject to carbon taxes (World Bank, 2022).

Carbon taxes are most straightforward; an amount of tax is charged for each unit of CO2 emitted, either by burning fossil fuels or in some industrial processes. The functioning of emissions trade systems is different. The government sets the maximum quantity of emissions (the cap), after which pollution rights are sold on a marketplace. For each unit of CO2 that firms emit, they must submit an emission right. The carbon price is determined by the market. Though, the systems can be hybrid. For example, some ETS contain a price floor for emissions rights, which results in a de-facto carbon tax. Most emissions trade systems reduce the maximum emissions limit to reach set political reduction goals, but this does not need to be the case.

The policy choice between the instruments is often based on political constraints. An advantage of emissions trading systems is that these are usually not part of the tax code, and therefore be subject to a different regulatory framework. For example, the EU ETS did not require the unanimity of all member states to be implemented, as it is not a tax. In addition, an ETS allows for free permits to be given to companies facing international competition and is more flexible than carbon taxes on this respect. On the other hand, carbon taxes can have more practical benefits, especially for developing or smaller countries. Carbon taxes require less institutional capacities to organise a carbon permit market. Instead, carbon taxes can be (more easily) levied on the consumption of fuels, for which the administrative and legal framework is often already in place (Black and Zhunussova, 2022).

Recently, there has also been an increase in carbon crediting initiatives. Carbon credits can be generated by removing CO2 from the atmosphere, for example, through reforestation projects. These carbon credits can then be sold to businesses looking for ways to offset their emissions (World Bank, 2022). These mechanisms are not part of this research, as these initiatives are not adapted by governments. This new trend may be promising with respect to CO2 reduction from the atmosphere, it does not reduce emissions from the source.

2.3. The theoretical foundation of environmental taxation

Economists have advocated for market-based policies as cost-effective strategies to reduce the harmful effects of consumption and production. Environmental taxation is based on the idea by Pigou that externalities which are not taken into account in the market price lead to socially inefficient outcomes (Pigou and Aslanbeigui, 2017). Rational economic theory suggests that businesses and consumers equate the marginal cost to the marginal benefits. When there is a wedge between the social and the private marginal costs of goods, consumption will be too high. Therefore, Pigouvian taxes should equal the social marginal cost to reach the social optimum. As the harmful externalities become internalised in the price of goods, demand for such goods will be reduced (European Commission and Ecorys, 2021).

However, to what price carbon emissions should be taxed is unclear. In line with Pigou, some argue that the tax should equal the social marginal cost of emissions, as this would result in the highest efficiency, i.e., the social optimum. The social (marginal) cost of carbon is defined as the economic damages that would result from emitting one additional ton of CO2. Yet, it is extremely difficult to establish the social marginal cost of carbon emissions. Various modelling assumptions lead to a broad range of optimal carbon prices. High levels of uncertainty on the effects of climate change and technological developments limit the feasibility of conventional cost-benefit analysis. Moreover, ethical assumptions on the discount rate of human lives determine the costs to a large extent (van der Ploeg and Rezai, 2019).

Marron and Toder (2014) suggest that the carbon price should be such that political emissions reduction targets are achieved. This strategy does not guarantee that the outcome is the social optimum, as the political targets could be set too low (or too high). Yet, it still ensures a cost-effective emissions reduction strategy. International organizations, such as the UN and the OECD, have calculated that a carbon price of around 60 euros per ton in 2020 and 120 euros per ton will be required to reach net-zero in 2050 (OECD, 2021). Importantly, the earlier carbon emissions reductions are realised, the lower the need for extreme interventions later. This was already the key message in the Stern Review in 2007 (Stern, 2007).

2.4. Channels through which carbon pricing affects emissions

2.4.1. Kaya's Identity

The Kaya identity expresses total human carbon emissions in four factors: population, GDP per capita, energy intensity and carbon intensity (Kaya and Yokobori, 1997). The identity is stated in equation (1) and in Figure 2.3. The Kaya identity is a specific application of the more general IPAT formula.

Energy intensity measures the amount of energy used in the economy to produce (or consume) one unit of GDP. This measure captures many different things. First, the type of economy o a country, and relevantly the levels of industrialisation and the size of intensive industries and the service sector. Second, the country's climate determines to some extent how much energy is needed for heating or cooling. Yet, it also includes the energy efficiency of factories, household appliances, cars and more. In essence, energy intensity captures how effective energy can be transformed into useful goods or services.

Carbon intensity captures the amount of CO2 emitted per unit of energy consumed. This measure describes the total energy system, and which shares of fossil fuels, nuclear and renewable energy are used. Carbon intensity is also called the fuel mix of a country. Not all fossil fuels emit equal levels of CO2 per unit of energy. Coal, for example, emits up to 60% more CO2 than natural gas for each unit of electricity produced. Thus, countries highly dependent on coal plants for their electricity use have higher carbon intensities than countries with high shares of natural gas, nuclear or renewable energy sources.

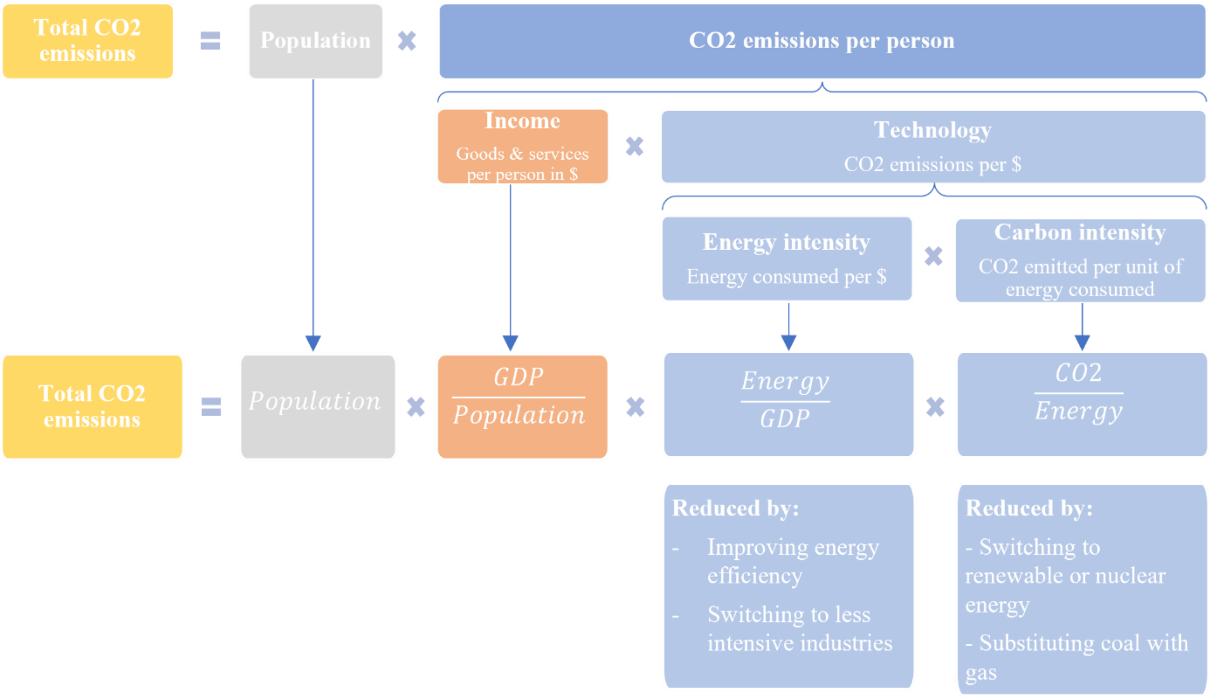
The identity can also be used to understand how changes in these factors contribute to changes in CO2 emissions. Equation (2) states how growth (or changes) over time increase or decrease total emissions. Historically, energy and carbon intensities have reduced, but GDP per capita and population size have grown at a faster rate, thereby increasing total emissions (Tavakoli, 2018; Ritchie et al., 2020). Environmental policy is targeted at both reducing the energy intensity and carbon intensity. For example, investing in renewable energy sources reduces carbon intensity, while improving energy efficiency in factories reduces the energy intensity.

$$Emissions \;=\; Population * \frac{GDP}{Population} * \frac{Energy}{GDP} * \frac{CO2}{Energy} \tag{1}$$

$$C\dot{O}2 \;=\; P\dot{o}p * GD\dot{P}\ pc * Ener\dot{g}y\ \imath nt * Carb\dot{o}n\ \imath nt \tag{2}$$

Figure 2.3

Kaya's identity



Source: Ritchie et al. (2020) and own modifications

2.4.2. Reduction in carbon intensity

Without carbon pricing initiatives, consumers and businesses face no monetary incentive to prevent or reduce carbon emissions. Carbon pricing policies therefor provide a reason to become more economical and to substitute energy types that contain less carbon and become relatively cheaper. Carbon pricing results in carbon-heavy energy types becoming relatively more expensive than energy sources that emit less CO2. As a result, carbon-intensive fuels will be substituted for other energy types. For example, a tax on CO2 contents will dramatically increase the price of coal energy. For consumers, this might be a change from cooking using natural gas towards induction or switching a gasoline car to an electric version. These different energy forms have lower carbon content per unit of energy and are thus relatively cheaper. Likewise, producers in the steel industry might switch from coal-fired plants to natural gas. Best and Burke (2018) indeed find that the energy mix in the EU and other similarly developed countries moved away from high-emissions energy towards lower-polluting energy sources once carbon pricing is implemented. The energy substitution possibilities for various users largely determine the effects of carbon taxation, as not all energy types can be substituted easily.

2.4.3. Reduction in energy intensity

Carbon pricing policies affect the energy intensity less directly, but in general, the price of energy is increased. Therefore, the incentive to save energy becomes larger. The energy intensity captures the amount of total energy used over GDP. The total energy consumed depends on how efficiently energy is used. The increased cost of carbon-intensive energy can increase investments in energy efficiency because the investments become relatively cheaper, the rate of return on energy savings is higher.

For consumers, this could be investing in home insulation or buying new household appliances with higher efficiencies. These investments result in lower energy use for the same amount of comfort. Similarly, businesses can improve manufacturing facilities to use less power while keeping the same production levels. Using an ex-post evaluation, Enevoldsen (2005) finds that the Danish industry has become 30% more energy productive in the first ten years after introducing carbon taxes.

Moreover, the behavioural response of investments in energy efficiency with respect to the carbon tax might be larger than a similar increase in the energy price itself. In other words, the tax elasticity is larger than the price elasticity. This implies that a 1% increase in the price, due to a (carbon) tax increase, reduced demand more than a similar increase in price, due to e.g. oil price shocks. Carbon taxes are long-term commitments by governments, and the tax rates often increase with time. Rivers and Schaufele (2015) found that the carbon tax in British Columbia on gasoline had a seven times larger short-run tax elasticity than the price elasticity. Overall, these efficiency investments lead to lower energy use for the same amount of production or consumption.

2.4.4. Income effect

Carbon pricing may also have an effect on the total disposable income of households. Additional carbon taxes reduces the total disposable income. Overall, as households become poorer, the consumption of all normal goods will reduce, and thereby related emissions of these goods. However, this effect occurs only when the tax is additional, and the revenue is not used to lower other taxes, e.g. on labour. The revenue of carbon taxation is often used to alleviate the effects on (the poorest) households, or on other environmental support programs, or a combination of both (Köppl and Schratzenstaller, 2022).

The reduced availability of income may also have negative effects on emissions reduction. A reduction in disposable household income may reduce investment capabilities in energy efficiency or fuel switching. Exemplary of this are recipients of social benefits that are unable to finance home insulation due to low credit scores. This leads to an energy poverty trap (Bourgeois et al., 2021).

2.4.5. Transitional economy

Most studies find that the macroeconomic effects of carbon pricing on GDP have been negligible, at least in the short run and based on current carbon prices (Köppl and Schratzenstaller, 2022).

However, carbon pricing is also implemented with the promise to transform the economy. Consumers will switch from carbon-intensive products towards relatively cheaper low-emissions products. For producers, it might not be beneficial to produce certain goods anymore due to increased costs. Overall, activities with low economic value and high energy use that cannot be substituted towards cleaner energy types will seize. These forces will reduce total emissions, but it is difficult to say whether these effects will mainly transpire via changes in energy or carbon intensity.

The transition towards a different economy may also result in lower productivity and lower GDP. In that case, there will be less demand for (all) products, resulting in lower emissions. The effects of a lower GDP can also be seen in the Kaya identity. By analysing the effects of carbon price signals on consumer and producer behaviour, it becomes easier to see how carbon taxation helps shape the green transition.

The extent carbon taxation can transform the economy is questioned by Tvinnereim and Mehling (2018) in their paper on deep decarbonisation. They argue that carbon taxation can be useful in incremental emissions reduction but is insufficient to reach net-zero. Mainly due to the very short time horizon for decarbonisation and political economy constraints on setting radically high carbon prices.

2.4.6. Carbon leakage

Carbon leakage can occur when countries implement carbon taxation or other stringent environmental protection standards. Leakage happens when firms move production facilities to countries with lower standards or taxes. As a result, although direct carbon emissions may decrease on a national scale, on a global scale, emissions remain the same. Moreover, firms might have even less incentive to invest in carbon-efficient technologies. Taxing immobile emissions bases reduces the risk of carbon leakage. For example, taking electricity plants will not change their location. However, manufacturing and industry may be more mobile regarding their production. Overall, the extent and size of carbon leakage are still unclear (Naegele and Zaklan, 2019).

The EU has proposed the Carbon Border Adjustment Mechanism to combat carbon leakage. The policy is analogous to an import tariff on carbon emissions concealed within imported products (European Commission, 2023). Through this tariff, the potential carbon price difference will reduce, therefor making it less attractive for firms to produce in other parts of the world.

3. Literature Review

3.1. Evaluation of empirical studies on carbon taxations effectiveness

3.1.1. Overview of the literature

Recently, two literature reviews on carbon pricing have been published. First, Köppl and Schratzenstaller (2022) present an overview of the empirical literature on various environmental, economic and political impacts of carbon taxes. Green (2021) reviews ex-post studies on the effectiveness of carbon pricing on CO2 emissions reduction. Both literature reviews note that there is a large body of literature on carbon pricing, which exists mainly of ex-ante studies, and to a lesser extent ex-post studies.

The ex-ante studies are used to estimate the (potential) effects of government tax plans on economic and or environmental outputs. Ex-ante studies can be based on Input-Output models or Computable General Equilibrium models. In such models, several parameters are changed, and the outcome is evaluated. The effects carbon pricing can be evaluated for employment, growth, trade, government finances, and more. The models used in these studies rely on numerous assumptions. For example, the assumption on the price elasticity of energy demand is crucial to estimate the reductions in energy related emissions when the price increases. The validity of the assumptions is crucial to judge the outcome of the model. The assumptions in the model are calibrated using the results of ex-post research. However, according to Köppl and Schratzenstaller (2022), ex-post studies find smaller effects for carbon taxation. This may lead to an overestimation of the expectations of carbon pricing policies.

Most ex-post studies on carbon pricing focus on a single country or on a specific sector. Moreover, the majority of studies focus on EU countries or the EU ETS. The dif-in-dif method and, more recently, synthetic control groups are used most often. Generally, studies that target emissions reductions use regression analysis to produce counterfactual CO2 levels. There are only a few studies comparing carbon taxes cross-country. Finally, most studies estimate the impact on CO2 levels or their growth rates, although some focus on fuel-specific variables or energy savings as dependent variables (Green, 2021; Köppl and Schratzenstaller, 2022)

In addition to scientific research, policy evaluation papers are also sometimes published by governments. These papers often target both the implementation and policy process and the estimated effectiveness. However, the results are not always quantified, and these reports are not peer-reviewed. In addition, they may be subject to politically motivated outcomes. Therefore, these evaluations are not considered as empirical studies.

Four gaps can be identified in the current literature available. First, geographically, countries outside the EU have been understudied, according to Green (2021). Second, cross-country comparison studies have been limited. Third, the effect of the carbon price on emissions reduction remains unclear. Fourth, although carbon-efficient technology has improved over the last decades, the impact on carbon price effectiveness has not gained much attention.

3.1.2. Challenges for ex-post research

The four gaps identified above are related to the challenges that carbon pricing research faces. Historically, most carbon pricing mechanisms were in Europe. Also, the lack of comparable price data constrained cross-country research and price effect estimates (Green, 2021; OECD, 2018). Likewise, the role of (specific) technological developments is difficult to include in ex-post research. Finally, carbon pricing is, ideally, compared to different mitigating strategies, e.g. subsidies or command and control regulation. However, as these policies are even more difficult to compare between countries and sectors, it is increasingly difficult to evaluate their effectiveness in comparison to carbon pricing (Green, 2021).

Comparing carbon tax rates and ETS prices between countries is challenging, which explains the lack of cross-country studies (OECD, 2018). Comparing nominal tax rates is insufficient because carbon taxes often only target industries and contain many tax exemptions and rebates. Emissions trade systems are even more complex. First, the emissions permits can be resold on an open market, which leads to significant price volatility. Moreover, most ETSs are based on multi-year phases. Hence there is an even larger uncertainty on which price was paid for emissions. Second, many industries get free emissions allowances, reducing the average carbon price paid. Finally, the tax base differs between countries, and some countries apply both a carbon tax and an ETS.

There have been developments to overcome the problem of comparable carbon price data. In 2012, the OECD initiated the taxing energy use database. This database allows for international comparisons of energy tax and carbon pricing levels. However, it focused only on OECD countries, and tax rates are only available for 2012 and 2018.

Focusing specifically on carbon pricing, the World Pricing Carbon Database was developed by Dolphin and Xiahou (2022) to study cross-country effects. The authors collected the scope and price of all carbon pricing policies worldwide from 1990 up to 2020. In addition, they calculated an emissions-weighted carbon price (ECP) for each country, which allows for easy comparison between countries and developments over time. Section 4 of this thesis provides a further explanation of the database.

Finally, ex-post research should establish a credible counterfactual for emissions to compare the effectiveness of a policy. However, this poses several difficulties as carbon pricing policies are not randomly assigned to countries. As the counterfactual can never be observed, it must be inferred. The synthetic control and dif-in-dif methodology are convenient for this type of estimation. However, the equal trend assumption might not hold in the longer term, as the emissions reduction can occur over relatively long periods in which many confounding variables and policies can be implemented.

3.1.3. Country and sector studies

The effectiveness of the UK Carbon Price Support, a carbon tax on the energy sector, has been studied by Leroutier (2022). The author uses a synthetic control group of other EU countries' power sectors to find the counterfactual UK power sector emissions between 2013 and 2017. Leroutier (2022) finds that the emissions reduction attributable to the carbon tax was between 20.5% and 26% in this time period. The data comes from the EU ETS system, which records all electricity plants' CO2 emissions. Price data was available because tax levels were set in advance, and there were no exemptions for (any) power plants. The reduction of CO2 emissions was realized by the (unplanned) closure of high-emitting power plants, and by fuel switching, mostly from coal to natural gas-fired power plants. The results are controlled for other EU-wide air quality policies that required coal plants to shut down or innovate. The emissions from power plants that were already foreseen to be renovated or closed in the same period as mandated by the EU air quality regulations were subtracted from the total emissions reduction observed. Thus, the remaining reductions are not related to the air-quality policies, but rather to the UK carbon tax. Finally, several other UK policies, such as wind power stimulation, enacted simultaneously are found to have had limited effects on emissions reduction in the time horizon of the study.

Jun et al. (2021) analyse the first phase of the South Korean ETS in 2015-2017 using a first difference model and data on firm-level emissions and prices. The authors find that the electricity sector did not reduce its emissions as there were too many free allowances granted. This also resulted in low prices for emissions permits. Due to this low price, it was not economically attractive to switch fuels for electricity production. The authors argue this may be due to effective lobbying. For example, Jun et al. (2021) also show that the ETS had been more effective in the building and manufacturing sectors as fewer free emissions rights were granted there. Jun et al. (2021) do not quantify the emissions reduction for the whole of Korea.

Gloaguen and Alberola (2013) study the emissions reductions under the first and second phases of the EU-ETS. Their methodology is based on a fixed effects country panel model for 2005 to 2011. They regress the ETS sector's log-level emissions on the switching price between coal and gas and several controls such as GDP, energy intensity, and the share of renewable electricity. In various specifications, they find no evidence that the CO2 price helped reduce emissions or played only a minimal role. Instead, they point to other policies in energy efficiency and an increase in renewable energy as the main drivers of emissions reduction. Over the period, the economic recession also reduced emissions, by lowering consumption and production. In addition, the lower production resulted in a surplus of emissions permits, which reduced the carbon price significantly.

Bayer and Aklin (2020), in contrast, find that EU emissions under the ETS have decreased by 8.1% to 11.5% between 2008 and 2016, compared to a world without the EU-ETS. On the whole EU emissions base, this implies a 3.8% reduction in emissions over the period. The authors apply a synthetic control between EU-ETS sectors and those outside the ETS. All sectors faced the same economic recession in this period. The sectors outside the ETS may also have faced national or other EU regulations to reduce emissions. Thus, the additional emissions reductions cannot all be attributed to the ETS alone, if both sectors faced different regulations. The authors note that the carbon price has been low in this period and that the future effectiveness may be smaller at similar prices as the observed emissions reduction may have been ‘low-hanging fruit’. Finally, the electricity sector sees substantial emissions reduction, which is an argument against carbon leakage, as electricity plants are highly immobile.

3.1.4. Comparing countries with dif-in-dif regression

Lin and Li (2011) used cross-country analysis to study the effectiveness of carbon taxes in Finland, Denmark, Sweden and the Netherlands. They use dif-in-dif regression analysis on the growth rate of per capita emissions with binary indicators for the carbon tax and a control group of 17 OECD countries with data from 1981 to 2008. Countries that implemented carbon taxes or similar environmental policies were excluded from the control group. The dif-in-dif regression equation is shown in equation (3).

$$Ln(E_c^t) - Ln(E_c^{t-1}) = \lambda + \beta_1 dB_t + \beta_2 dT_t + \delta_1 dB_t * dT_t + \gamma LnE_c^{t-1} + \theta X_t + \varepsilon_c^t \qquad (3)$$

The regression first establishes the growth rate of emissions in country c by taking the difference in logarithms of the yearly per capita emissions E_c^t. dB_t is a dummy for the control and treatment group, dT_t a dummy for pre- and post-treatment. $dB_t * dT_t$ is an interaction term that equals one when both dB_t and dT_t are one. β_1 captures the differences between the groups before the policy, and β_2 captures the changes to the emissions growth rate even in absence of a policy change. Finally, δ_1 captures the change attributed to the policy implementation and is called policy effectiveness. If the value of δ_1 is significantly more than zero, the carbon taxes have reduced the emissions growth rate. The emissions convergence rate is included as γLnE_c^{t-1}. The regression equation includes also a constant λ. To control for heterogeneity between the control and treatment groups several control variables are included in vector θX_t, such as GDP per capita, industry structure, expenditure on R&D, and energy price level. These controls have been proven to relate to the emissions growth rates.

The authors find that only the Finish carbon tax significantly reduced the emissions growth rate by 1.69 percentage points annually; the Swedish tax effect is estimated at 1.16%-point but is not significant. The authors argue that the carbon taxes in the other countries might be ineffective due to tax exemptions, differential tax rates or the use of tax revenue. However, this specification does not allow for price effects or exemptions levels. Hence, this study cannot test the differences between the tax regimes further.

3.1.5. Panel regression methods

Recently, two studies have overcome the challenges related to cross-country research using novel carbon price databases. Best et al. (2020) use the OECD’s Effective Carbon Rates database, while Rafaty et al. (2020) build on the World Pricing Carbon Database developed by Dolphin and Xiahou (2022). Their methodological approach is also different.

3.1.6. Best et al. (2020)

Best et al. (2020) study the effectiveness of carbon pricing using various econometric models with many countries. The authors calculate the impact through two different models: a panel regression using binary carbon pricing indicators and a cross-sectional regression including price levels.

In the first model, the emissions growth rate is regressed on a carbon pricing policy dummy and other controls. This is a fixed effects panel regression that starts in 1990 and ends in 2017 and includes around 130 countries. The emissions growth rates are calculated for 1, 2 and 3-year periods. The fixed effects model for a three-year growth period is presented in equation (4).

$$\frac{Ln(E_c^{t+3}) - Ln(E_c^t)}{3} = \lambda + \delta\, CP_c^t + \mu\, EnvrP_{\boldsymbol{c}}^{\boldsymbol{t}} + \gamma\, LnE_c^t + K_c'\theta + I_c + I^t + \varepsilon_c^t \qquad (4)$$

The left-hand side of the equation states the average yearly emissions growth rate of country *c* for time *t* to *t+3*, as the growth rate is calculated for three-year periods. The 3-year growth rate is divided by three to get a comparable average yearly growth rate. CP_c^t is a dummy which equals one if a carbon pricing policy is implemented in country *c* at time *t*. The presence of other environmental policies, like feed-in tariffs, is controlled by including the dummy $EnvrP_c^t$. The emissions level at the beginning of the growth period, LnE_c^t, is included to control for possible convergence. In addition, $K_c'\theta$ is a vector of controls related to the Kaya identity, such as GDP (growth), population (growth), and fossil fuel shares. Finally, country- and time-fixed effects and an error term with mean zero are included. The effectiveness of the carbon pricing policy is defined as δ. This coefficient states the difference in emissions growth rates between countries with and without carbon pricing policies.

The authors find that countries with carbon pricing have between 3.5 and 2.9 percentage points lower CO2 growth rates than countries without such policies, all else equal. In addition, the controls for feed-in tariffs and other renewable energy policies are also found to significantly reduce the emissions growth rate. Moreover, the authors note that other policies which are not directly controlled for could also have contributed to the emissions reduction. This relates to the potential omitted variable bias, as governments that implement carbon pricing may also be more likely to impose other non-included environmental policies. This estimate, however, does not take the carbon price itself into account. Thus, the different stringencies of carbon pricing policies between countries cannot be tested directly.

The second regression model analyses the effects of the carbon price. The price data is from the OECD's effective carbon rates database (OECD, 2018). This dataset contains the effective carbon rates for 41 OECD countries, which includes direct carbon pricing and indirect energy taxes. Energy taxes, particularly excise taxes, are expressed as the price signal on the carbon content of the fuels they are levied. However, the price level data is only available for 2012. Therefore, the regression is converted to a cross-sectional analysis. Again, the average emissions growth is calculated for the five years (2012-

2017) and regressed on the effective carbon rate and the other controls. They also include the 2007-2012 emissions growth rate to control for persistence effects, as can be seen in equation (5).

$$\frac{Ln(E_c^{17}) - Ln(E_c^{12})}{5} = \lambda + \delta Price\,_c^{12} + \mu\, EnvrP_c^{12} + \gamma\, LnE_c^{12} + \frac{\Delta LnE_c^{07-12}}{5} + K_c'\theta + \varepsilon_c^t \tag{5}$$

The authors find that a one euro increase in the effective carbon price rate leads to a 0.23%-point reduction in the CO2 emissions growth rate. However, the effects of the other environmental policies are not significant, although this may come from cross-correlation with carbon pricing. In the robustness controls, the binary indicator for carbon pricing (CP_c^t) is added to the regression equation (5). This reduces the price coefficient to only -0.2 %-point and the carbon policy effect to -2.4.%-point. Best et al. (2020) explain that this might indicate a regime effect and a separate price-level effect. This implies that a carbon pricing scheme reduces the emissions growth rate by 2.4%-point independent of the carbon price. An increase in the carbon price leads then to an additional 0.2 percentage point reduction in the emissions growth rate.

The identification strategy of Best et al. (2020) is based on correlational evidence between countries. Although the authors control some environmental policies, they cannot include all relevant policies for each country that might reduce emissions growth rates. Therefore, one should be careful to interpret these results as causal. Moreover, the binary carbon pricing indicator cannot capture the differences between countries' pricing stringencies. Still, as an early exploratory study, the findings of Best et al. (2020) are relevant.

3.1.7. Rafaty et al. (2020)

Rafaty et al. (2020) can research the carbon price effects much better using a novel dataset on comparable carbon prices. For this paper, the authors use a previous version of the World Carbon Pricing Database, which includes data on carbon taxes and ETS from 1990 to 2016 in 39 countries (Dolphin et al., 2020).

First, the authors estimate the average treatment of introducing a carbon pricing policy using an interactive fixed effects model on the growth rate of emissions. They use the 1-year emissions growth rate for multiple sectors, including manufacturing and industry, electricity and heating, and control for population and GDP growth. The interactive fixed effect panel model as stated in equation (6) is based on Bai (2009). The vector F represents unobserved common factors that may be correlated with the emissions growth rate, the threated or other control variables. F may for example represent common shocks, national trends, and technological developments. The factor loadings ω' capture the heterogenous effects that common factors in each country may have. The number of factors is determined by solving the least squares objective function of Bai (2009). The optimum number of factors is between 1 and 3.

At the same time, the authors estimate counterfactual emissions for all countries using a generalised synthetic control method proposed by Xu (2017). This way, the results can be compared to a counterfactual baseline. The generalised synthetic control method relaxes the standard dif-in-dif assumption that the control and treatment group follows parallel paths in the absence of the treatment. The approach uses the pre-treatment period to estimate the IFE factor loadings $\omega' F$, which is then used to project the counterfactual emissions growth rate outcome for the treated countries.

$$Ln(E_c^{t+1}) - Ln(E_c^t) = \delta\, CP_c^t + X'\theta_c^t + I_c + \omega' F + +\varepsilon_c^t \tag{6}$$

The left-hand side states the annual emissions growth rate. CP is a dummy for carbon pricing policies. The vector of controls $X'\theta_c^t$ includes GDP, GDP square, and population growth rates. Country-fixed effects are included as I_c and the error term ε_c^t has mean of zero. The coefficient of interest is δ, which states the difference in emissions growth rates for countries that have implemented carbon pricing, the average treatment effect.

The authors find a 1.5%-point reduction in emissions growth rates after implementation compared to the estimated counterfactuals. The results for the electricity sector suggest a 2.5%-point yearly growth rate reduction. The estimates for the other sectors are not significant and smaller in size.

Second, the authors estimate the effect of the carbon price level using both the binary indicator for carbon pricing policies and the carbon price, see equation (7). In this regression, α represents the implementation effect of carbon pricing policies, while β indicates the effect of a 1-dollar higher (emissions-weighted) carbon price on emissions growth rates.

$$Ln(E_c^t) - Ln(E_c^{t-1}) = \alpha\, CP + \beta\, Price + X'\theta + I_c + I^t + \omega' F + \varepsilon \tag{7}$$

The β is imprecisely estimated at around 0.07%-point growth rate reduction when increasing the average carbon price by 1 dollar. Moreover, the authors find evidence that primarily the price level influences emissions rather than price increases. Finally, the authors argue that not considering introduction effects can bias the estimates of emissions elasticities.

The findings by Rafaty et al. (2020) are relatively low. They argue that additional effects of carbon price increases are minimal when allowing for introduction effects, at least on the current carbon levels observed. Still, the findings do not take into account the recent increases in EU-ETS prices, as price data is only used up to 2016. Moreover, they control for relatively few factors, relying on the interactive fixed effects model to capture many country-level differences.

In summary, several studies show the effect of carbon pricing policies on emissions. However, these effects are relatively small, at around a 0 to 3%-point reduction in emissions growth rates. Studies on the carbon price level have been scarce and show relatively minor effects compared to business-as-usual scenarios. However, it is difficult to compare results between studies due to differences in methodological design, data used, and the time periods included. Though recent advances have been made in cross-country comparable pricing data, the challenges of counterfactual estimation and separating the effects of various policies remain.

3.2. Hypotheses building

Based on the current academic literature and the theoretical framework, carbon pricing policies are expected to reduce emissions growth rates. Moreover, next to an introduction effect, a higher price of emissions is expected to reduce emissions even further. These expectations lead to the formulation of hypotheses 1 and 2. Although hypothesis 1 has generally been accepted in the literature, the size of the effect is still debated and unknown. This gap in the literature has been identified in the previous section.

H1) Countries that implement a carbon pricing policy see a reduction in the CO2 growth rate.

H2) A higher carbon price level leads to a reduction in the CO2 growth rate beyond the introduction effect.

According to the literature review by Green (2021), most studies have researched the effectiveness in Europe or the EU-ETS. However, recent adopters of carbon pricing, such as Japan, Korea and Mexico, have not yet received many academic evaluations. This raises the question of to what extent the effectiveness of early and late adopter countries differs.

On the one hand, technological developments in carbon and energy efficiency lowered carbon abatement costs significantly over the past decades. For example, the learning curves in solar and wind energy production have yielded dramatic cost reductions. This would increase the effectiveness of carbon pricing, even at relatively low price levels.

On the other hand, carbon pricing policies are complex instruments and might take considerable time before they become effectively operational. For example, this has been seen with the EU ETS and in Korea. Jun et al. (2021) find that the first phase of the Korean ETS has been ineffective for the power sector due to too many free allowances. In addition, many ETS are subject to trial phases or are tested sub-nationally first. Therefore, substantial emissions reduction might not be yet observable immediately after implementation.

Hypothesis 3 tests if there are differences in treatment effects between early and late adopters of carbon pricing.

H3) Countries that implemented carbon pricing after 2010 see a different reduction in CO2 growth rates compared to countries that implemented such policies before 2010.

Using 2010 as the cut-off point is a combination of historical and geographical arguments. Carbon pricing policies have been adopted in roughly three waves. The first were the Nordic countries in the early 1990s, then the EU-ETS was implemented between 2005 and 2009. The third wave consists of various countries outside Europe that implemented after 2010, and these countries may differ substantially in terms of implementation and effectiveness. From a practical point, the 2010 cut-off point also splits the sample in roughly two-thirds, as to make sure both groups are of sufficient size. Also, the cut-off point ensures that sufficient data is available after the implementation of the policy to measure the effects.

4. Primary Carbon Pricing Data

4.1. World Pricing Carbon Database

The World Carbon Pricing Database by Dolphin and Xiahou (2022) contains a record of sectoral coverage and prices of carbon pricing mechanisms put into effect worldwide. This novel database provides the price level and scope of carbon taxes and ETSs implemented from 1990 – 2020. Crucially, it is structured by country instead of by pricing mechanism. Moreover, it includes sub-national carbon pricing policies for Canada, China and the USA. The pricing mechanisms are specified for each of the IPCC-classified sectors. These include CO2 emissions from energy use and industrial processes, respectively IPCC sector classification codes 1A and 2 (Eggleston, 2006). The CO2 emissions from energy use are further specified and include the sectors; electricity and heat generation (1A1a), road transportation (1A3b), and energy used by residential and commercial buildings (1A4a and 1A4b).

When possible, these carbon policies' scope and institutional design are taken from primary legal documents retrieved from the Climate Change Laws of the World database. In addition, secondary sources such as the State and Trends of Carbon Taxation by the World Bank were also used.

The price data of ETS is retrieved from the International Carbon Action Partnership through its Allowance Price Explorer. The carbon tax rates are again resourced from legal sources. All prices are expressed in 2019 USD per ton of CO2. These rates are calculated with World Bank conversion rates.

The dataset provides the marginal price of emissions. The marginal rates represent the price that must be paid for one additional unit of CO2 emissions. If this price is paid on all companies’ emissions, this price is equal to the average rate. However, companies' average rates are often lower due to allowances, free permits or rebates. For carbon taxes, the dataset presents discounts for specific (IPCC) sectors or fuels as price rebates. Free emissions allocations under an ETS are not considered in this version. However, records of free allowances are publicly available so that they might be added to a future dataset. Currently, only CO2 prices are included in the dataset, although the structure can also accommodate the pricing of other greenhouse gasses.

The development of this broad overview of carbon pricing policies for an extended period is crucial in overcoming the data constraints on comparable carbon taxation initiatives. Moreover, IPCC sector-specific carbon prices allow for fast integration with other databases.

4.2. Emissions-weighted Carbon Price

The World Carbon Pricing Database contains the price level and coverage of all pricing policies implemented worldwide. However, the considerable variation in price, scope and coverage makes a direct comparison between countries difficult. Therefore, the authors of the database also calculate the emissions-weighted carbon price (ECP) (Dolphin, 2022). The ECP provides a transparent method of capturing the average price paid on CO2 emissions in a country, which allows for straightforward comparison. The ECP can be calculated on the IPCC sector level or for the whole country.

Three sources of information are required to calculate the ECP; the scope of carbon pricing mechanisms in place, i.e. on which emissions the tax is levied; the nominal emissions price for each mechanism; the verified CO2 emissions for each sector or country. The scope and price data are collected in the World Carbon Pricing Dataset. The CO2 emissions for each sector or country are retrieved from the International Energy Agency (IEA).

The coverage of a pricing mechanism can be calculated by multiplying the scope of a mechanism with emissions in the specific sector divided by the total emissions in a country. The emissions-weighted carbon price can be found by multiplying the coverage for each mechanism at the sector level with the specified price and summing for all mechanisms in force. Then, this can be aggregated further to the country level.

The advantage of the emissions-weighted carbon price is that it allows for consistent and cross-national comparison. Now, panel regressions can include the price level of CO2 emissions per year for all relevant countries. Previous pricing databases, such as the Effective Carbon Rates, lacked price data for long periods. The 30-year time span of the database allows for better panel regression than was previously possible.

5. Methodology

5.1. Variables and controls

5.1.1. Emissions and the emissions growth rate

The primary dependent variable is the growth rate of CO2 emissions from fossil fuels. The data on carbon emissions by country is collected by the International Energy Agency (IEA) and retrieved from the OECD iLibrary (IEA World Energy Statistics and Balances, 2022). The emissions data is available from 1990 for most countries. In addition, the emissions for each of the IPCC 2006 sectors were also retrieved from the IEA.

5.1.2. The carbon pricing variables

The primary independent variable is the emissions-weighted carbon price (ECP) per year by country. In summary, the ECP measures the nominal price of CO2 emissions that fall under a carbon pricing policy, weighted by total emissions in a country. It thus reflects the average price paid for emissions in a country. There are sector-specific carbon prices available as well. The data is provided by Dolphin and Xiahou (2022).

Gasoline taxes can be controlled for in addition to the ECP variable to improve the estimate of carbon pricing on emissions in a country. Gasoline taxes are considered to be indirect carbon taxes, as they are levied on carbon-emitting products and provide a positive price signal. Gasoline taxes are included to improve the estimate of the effect of direct carbon taxes. For example, in the transport sector, high gasoline taxes may be implemented by similar countries with carbon pricing. Omitting gasoline taxes would then cause emissions reductions to be attributed to the carbon pricing policy, while actually, it is due to the gasoline tax. Ross et al. (2017) provide data on gasoline taxes and cover a period between 2003 and 2015.

Similarly, fossil fuel subsidies are negative carbon price signals making fossil fuels cheaper. These subsidies are, for example. implemented to protect industries or decrease poverty. The size of fossil fuel subsidies varies by country and should be considered when estimating the effect of positive price effects. However, there is debate on what is classified as fossil fuel subsidies, creating significant country differences. Thus, it is difficult to compare countries and different datasets over time. Yet, through a collective effort of the OECD, the IEA, and the IMF, relatively reliable cross-country data is now available from 2010 onwards (FossilFuelSubsidyTracker.org, 2022).

5.1.3. Kaya identity controls

Following Kaya's identity, carbon emissions from human behaviour can be expressed in GDP, population, energy intensity and carbon intensity. Changes in population size will lead to lower or higher emissions. Similarly, if the economy grows, emissions increase, all else equal (Kaya and Yokobori, 1997). These changes are, however, not related to carbon pricing policies. To control for these changes during the time period, both the initial level and the growth rate of GDP and population must be included in the regression.

However, the changes in energy and carbon intensities are the channels through which carbon pricing affects emissions. Thus, it is not possible to include these changes directly in the regression. Still, the energy and carbon intensity levels are essential to explaining the level of CO2 emissions; they might also be directly related to the future emissions growth rate. For example, lower energy-intensity countries often have a more extensive service sector, are less dependent on heavy industry, and thus could have lower emissions growth rates. Therefore, controlling these variables' values at the start of each growth period is critical.

5.1.4. Convergence of emissions

Similarly to income convergence between countries, there is a considerable academic debate to what extent per capita emissions are converging over time (Payne, 2020). It has been well documented that countries with high CO2 emissions have lower emissions growth rates than countries with initially low levels of per capita emissions (Best et al., 2020). In other words, the level of emissions in a country is indicative of the future growth rate. Measuring this relationship is essential for modelling growth paths and finding proper counterfactuals. A common method to test this relationship is called β-convergence. The absolute convergence rate can be found by regressing the growth rate over initial emissions values in a country. However, absolute convergence assumes that all countries have the same emissions level in the steady state. Allowing for country differences, such as colder or warmer climates, results in conditional convergence. Still, absolute convergence is a sufficient condition for conditional convergence and adding the initial emissions levels will control for the convergence effect (Lin and Li, 2011).

5.1.5. The environmental Kurnitz curve

The theory of the environmental Kurnitz curve states that there is a non-linear relationship between GDP and pollution. At first, economic activity is low, and pollution is infrequent. Then, as the economy grows, factories pollute more, and the environment degrades. Next, as citizens get richer, they start to value their (direct) environment more and are more willing and able to pay for pollution reduction. This effect has been most strongly observed in relatively local air and water pollution (Shahbaz and Sinha, 2019). However, while local pollution reduction can be valuable to citizens and result in improved living conditions, a reduction in CO2 is not measurable on a local level. Therefore, the willingness to pay for CO2 emissions reduction might be limited. There is still an academic discussion as to the extent the environmental Kurnitz curve holds for carbon emissions. This relationship is important to capturing the effect of economic growth on emissions properly.

Stern (2017) criticizes the theory and proposes that it is a statistical artefact. He stresses the importance of convergence in emissions growth rates but rejects that raising income levels are the driver of emissions reduction. Instead, he suggests that environmental degradation is monotonically rising with income, but it is not only a function of income. International developments over the past 50 years have increased environmental awareness in all countries. For example, the Kyoto protocol stated the need to reduce emissions globally in 1992. However, in middle-income countries that see high economic growth, the income effect dominates international developments, showing large emissions growth. Conversely, international developments and the need for emissions reduction may be dominant for richer countries with lower economic growth rates. Stern (2017) argues that this results in the inverse U-shape where middle-income countries do not seem rich enough to reduce emissions.

Overall, while the true relationship between GDP and emissions might be unknown, it can be controlled by adding a quadratic control variable of GDP in the regression, similar to Rafaty et al. (2020).

5.1.6. Environmental policies

There is a need to include other environmental policies implemented by the government. For example, governments implementing carbon pricing might also be more inclined to initiate other policies that reduce greenhouse gas emissions. Excluding such policies from a panel regression could lead to biased estimates of the effectiveness of the carbon pricing policy. However, there is limited information available on the policy framework within countries. The Environmental Performance Index classifies countries based on their performance, i.e. the policy outcome, and therefore is not valid as a control. The RISE scores of ESMAP reflect a country’s policies and regulations in the energy sector but are only available from 2010. The scores are available for 110 countries and are published yearly (ESMAP, 2020).

5.2. Growth rate regression analysis

5.2.1. Growth rate regression

This thesis uses a growth rate regression model to estimate the effects of carbon pricing policies on emissions. Growth rate regressions are used more often in the economic literature (Barro, 2015) and have become more common in the energy sector (Best et al., 2020; Best and Burke, 2018; Csereklyei and Stern, 2015).

Growth rate regressions have several advantages. Using growth rates of 1-, 3- and 5-year periods can capture the subsequent emissions reductions both in the short and medium term. Some manufacturing or electricity generation investments can take several years before emissions reduction begins. Growth rate regressions also prevent unit-root problems (Best et al., 2020). Several authors have found emissions and energy use to be non-stationary (Csereklyei and Stern, 2015). Stern et al. (2017) argue further that longer-term growth periods filter out short-run variance and allow for more focus on longer-run variation between countries. Best and Burke (2018) also note that including the initial values of the independent variables lowers the chance of reverse causation. However, this seems less relevant in the case of emissions growth, as CO2 is mostly a by-product of economic growth. Lastly, growth regressions allow for the control of convergence in emissions, as discussed in the previous section.

Barro (2015) critically notes that using county-fixed effects in growth rate regressions is not recommended when estimating effects that change only little in countries over time. For example, educational levels do not vary much within countries over 30 years. However, in the case of carbon pricing policies, there is sufficient variance within countries over time to include the country-fixed effects.

5.2.2. The model

Like Best et al. (2020), the subsequent average yearly emissions growth rate of a 1-, 3- and 5-year period is calculated by taking the log difference and dividing over the length of the time period for each country *c*. The growth rate represents the subsequent emissions growth rates from *t* to *t+x*, as presented in equation (8).

$$Average\ yearly\ emission\ growth\ rate = \dot{E}_c^t = \frac{\ln(E_c^{t+x}) - \ln(E_c^t)}{x} \tag{8}$$

$$x = \{1, 3, 5\}$$

We are interested in the effect of carbon pricing policies on the emissions growth rate, represented by δ_c^t. Similar to Rafaty et al. (2020) the effectiveness of the carbon policy is defined as the difference in emissions growth rate between the observed growth rates and the counterfactual growth in country *c* at time *t* had not adopted a carbon policy. The true $\delta_{c,t}$ can thus be heterogeneous with regard to time and country, as seen in equation (9).

$$\delta_{c,t} = \dot{E}_{c,t|CP_{c,t}=1} - \dot{E}_{c,t|CP_{c,t}=0} \tag{9}$$

The proposed model is a two-way fixed effects model, as in equation (10). This model is analogous to the panel regression in Best et al. (2020) using the dummy pricing variable. It includes the effectiveness coefficient δ_c^t and a dummy variable CP_c^t whether a country *c* has implemented carbon pricing at time *t*. The convergence control, the log of emissions, lnE_c^t is added, and a vector of controls K related to the Kaya identity. The vector includes the log of GDP per capita, the log population, the log energy intensity, the shares of energy supplied by each fossil fuel of total energy used at time *t*, and the growth rates of the population and GDP per capita during the same growth period. I_c and I^t are country- and time-fixed effects, which control for time-invariant country effects and global time-varying effects. ε_c^t presents the error term with a mean zero. λ represents the constant.

$$\dot{E}_c^t = \lambda + \delta_c^t CP_c^t + \gamma lnE_c^t + K'\theta + I_c + I^t + \varepsilon_c^t \tag{10}$$

The effectiveness of the carbon policy can be a function of an implementation effect, the elasticity of emissions with respect to the price, and the price itself, as specified in equation (11). Following the argumentation by Rafaty et al. (2020), the implementation effect $\alpha_{c,k}^t$ captures the expectations on (future) carbon pricing, regardless of price level. Even very low levels of carbon taxation could potentially create incentives for companies to reduce emissions, as they might face higher rates later. The elasticity $\beta_{c,k}^t$ captures the emissions response to the carbon price.

$$\delta_c^t = f(\alpha_{c,k}^t, \beta_{c,k}^t, Price_{c,k}^t) \tag{11}$$

The function in equation (11) could be in any form. To estimate the effects, it must be restricted to a linear function with an intercept α_c^t and slope β_c^t, as in equation (12). If δ_c^t is restricted further to be constant between countries and over time, it results in equation (13). Then, equation (13) can be inserted into the fixed effects model of equation (10) and we can use a panel regression to estimate δ.

$$\delta_c^t = \alpha_c^t + \beta_c^t Price_c^t \tag{12}$$

$$\delta = \alpha + \beta \, Price_c^t \tag{13}$$

This leads to the panel regression equation (14). Note that β actually captures $\beta * CP_c^t$ but as CP_c^t is a dummy it is always one when the price is non-zero, and thus can be omitted. Naturally, when no carbon policy is implemented, the $Price_c^t$ is zero and α and β are excluded.

$$\dot{E}_c^t = \lambda + \alpha \, CP_c^t + \beta \, Price_c^t + \gamma ln E_c^t + K'\theta + I_c + I^t + \varepsilon_c^t \tag{14}$$

The model in equation (14) provides the coefficients of interest α and β, which can be used to test hypotheses 1 and 2. First, hypothesis 1 states that δ is significantly negative, which will be the case if the combined effect of α and β is negative and significant. Second, hypothesis 2 can be accepted if β is negative and significant. The estimate of β provides the effect of a dollar increase on countries' emissions growth rate for countries that have implemented a carbon pricing policy.

In addition to the total emissions, this regression will also specifically analyse the following sectors: manufacturing and industry, electricity and heat production, residential and commercial buildings, and road transport. More insight can be gained into sector-specific effects by further decomposing the emissions base and the carbon price. For each industry, the possibilities to reduce emissions might be different so that δ_c^t is sector-dependent. Sector-specific emissions and price levels are used. However, no sector-specific economic growth rates were available, so countrywide economic indicators are used as a proxy.

5.2.3. *An example*

An example is provided for a 5-year period regression, specifying the dates for the 2000-2005 period. The average yearly growth rate is calculated in equation (15), which is then regressed on the carbon policy's initial levels and the control variables in equation (16). Equation (17) specifies the variables used, including time indicators.

$$\dot{E}_c^{2000-2005} = \frac{\ln(E_c^{2005}) - \ln(E_c^{2000})}{5} \tag{15}$$

$$\dot{E}_c^{2000-2005} = \lambda + \alpha\, CP_c^{2000} + \beta\, Price_c^{2000} + \gamma\, lnE_c^{2000} + K'_c\theta + I_c + I^t + \varepsilon_c^t \tag{16}$$

$$\begin{aligned} Emission\ growth\ rate^{2000-2005} = \quad & \lambda \\ + \quad & \alpha\, CP^{2000} \\ + \quad & \beta\, Price^{2000} \\ + \quad & \gamma\, Ln(Emissions^{2000}) \\ + \quad & \theta_1\, Ln(GDP\ per\ capita^{2000}) \\ + \quad & \theta_2\, Ln(Population^{2000}) \\ + \quad & \theta_3\, Ln(Energy\ intensity^{2000}) \\ + \quad & \theta_4\, Energy\ system^{2000} \\ + \quad & \theta_5\, Population\ growth^{2000-2005} \\ + \quad & \theta_6\, GDP\ per\ capita\ growth^{2000-2005} \\ + \quad & Country\ effects \\ + \quad & Time\ effects \\ + \quad & \varepsilon_c^t \end{aligned} \tag{17}$$

5.2.4. *Time of implementation differences*

As stated in equation (11), the effectiveness of the policy δ_c^t can depend on the country and over time. In the most general form, the time of implementation is part of the effectiveness function, as presented in equation (18). In essence, the time of implementation is an interaction term between the effectiveness estimates. Therefore, it is multiplied by those terms in the regression. The countries with carbon pricing can be split between early and late adopters. The main focus is on the different effects for countries implementing carbon pricing after 2010. The restrictions of linearity and constant treatment effects between countries within each group remain in place.

$$\delta_c^t = f(\alpha_c^t, \beta_c^t, Price_c^t, Time) \tag{18}$$

$$\dot{E}_c^t = \lambda + \alpha_1 CP + \beta_1 Price + \alpha_2 T_{2010} CP + \beta_2 T_{2010} Price + \gamma\, lnE_c^t + K'_c\theta + I_c + I^t + \varepsilon_c^t \tag{19}$$

Where T_{2010} is a binary variable indicating whether the pricing policy has been implemented after 2010, for brevity, the controls, country, and time indicators are concealed in equation (15). Now, the coefficients on the interactions terms α_2 and β_2 allow for a different policy effect for countries that implemented carbon pricing after 2010. Due to a limited sample of countries implementing carbon pricing after 2010, the regression is only analysed for the 1-year growth period. Hypothesis 3 suggests that the interaction coefficients should be different. If there is a significant interaction of T_{2010}, it can be concluded that the countries that have implemented the policy later react differently to carbon pricing policies than the early adopter countries.

5.3. Identification strategy and assumptions

Panel regression analysis can be used to find causal relations, but only under strict assumptions. Generally, the error term should be uncorrelated with the dependent and main independent variables. In addition, the policy effect should be additively causal. However, these assumptions are challenging to maintain in the case of carbon pricing. Thus, the results can only be interpreted as correlational evidence, which is built on explaining variance in emissions growth rates by various countries. Furthermore, the validity of the results depends on to what extent omitted variable bias poses a threat. As countries are not randomly assigned to the treatment of a carbon policy, there is always a risk that variables which correlate with carbon pricing and determine emissions growth rates are excluded from the regression. Still, using a large number of countries for 29 years increases the reliability and accuracy of the findings. Moreover, the controls for the Kaya identity help capture a large part of the variance between countries, as well as developments over time. That way, the longer-term changes in countries' energy systems are controlled for.

6. Results and Analysis

6.1. Data analysis

6.1.1. Data analysis procedure

The available data has been downloaded and processed in Stata. The variables in log terms were transformed by taking the natural logarithm. The emissions, population and GDP growth rates were calculated similarly to equation (8). Outliers in growth rates were identified by visual inspection of boxplots. Year-to-year emissions or GDP growth rates larger than 50% were treated as outliers and excluded from the panel regression to improve data quality. Countries with more than ten years of missing emissions or GDP values were also omitted from further analysis. In total, data on 140 countries have been collected. Several countries were not included in the IEA emissions data. The largest of these countries are Afghanistan and Uganda. Then, due to missing data, several other countries were omitted from the regression. This resulted in 128 complete countries. The sample of countries collectively represented 95% of total global CO2 emissions in 2019.

The sample includes the years 1990 to 2019. The year 2020 is excluded from the sample due to the covid pandemic, which causes unreliable emissions and GDP data. For the 1-year period, there are 28 periods, starting in 1990, and the last growth period ended in 2019. The 3-year regressions start in 1992, so the emissions growth rate ends in 2019. To end the 5-year period in 2019, 1994 is selected as starting year. These time periods have been chosen to capture the most recent trends. The sensitivity to the time period chosen is addressed in the robustness tests.

6.1.2. Classification of countries with carbon price policies

An overview of countries with implemented carbon pricing policies can be found in the appendix (Table A1). The United States and China do not have a national carbon pricing framework but only regional initiatives. Although the ECP is non-zero in the data, they are not treated as having a pricing policy. Kazakhstan implemented an ETS in 2014 but temporarily deactivated it from 2016 to 2018 to improve its functioning. For Ukraine, there is no data available for 2015 and 2016. The carbon tax was still in place, so the carbon policy dummy has been set to 1, while the price level remained at zero. Australia is the only country that implemented a carbon tax in 2012 and ended it in 2014.

Overall, 9 countries have implemented a carbon tax, 20 apply an ETS and 15 use both a carbon tax and an ETS. In 2019, the final year of the data, 43 countries applied a form of carbon pricing. These countries together emit 21.6% of emissions in the sample.

6.1.3. Model specification

At first, the Hausman test was performed to check if the preferred model was fixed or random effects. The null hypothesis was rejected at $p<0.01$, so the fixed effects model was chosen. The results of the

Wald test indicate that the time-fixed effects are required ($p<0.01$). Finally, the regression analysis used the xtreg command. Robust and country-clustered standard errors are used.

6.1.4. Descriptive statistics

Table 6.1 describes the variable characteristics. It includes the total and sectoral annual CO2 emissions data for each country in kilotons. The control variables include the country's GDP in constant 2017 USD purchasing power parity, GDP growth, population and population growth. Energy intensity is expressed as the total megajoule of energy used yearly in a country, over the GDP. Fossil fuel shares are expressed as the shares of total final energy consumption within a country that is supplied by the fuel type. Net gasoline tax in USD indicates the net tax on gasoline for consumers. Fossil fuel subsidies are expressed as USD over the tons of oil equivalence, which is a measure of energy. Finally, the carbon pricing variable for each sector is the mean carbon price over the policy's lifetime, weighted by active years.

Table 6.1

Variable description

Variables	Unit	Countries	Mean	Min	Max	S.D.
Emissions	kiloton of CO2					
Total		140	184,625	13.9	10,081,336	721,209
Electricity and Heat		139	78,410	0.1	5,376,578	335,005
Industry and manufacturing		140	35,954	2.7	3,094,686	183,911
Buildings		140	19,233	0.2	616,372	63,709
Road		140	33,644	2.5	1,544,553	127,068
Controls						
GDP per capita	2017 USD PPP	133	20,231	437	120,648	20,300
GDP per capita growth	%		1.8	-100	65	5.8
Population	Million	140	45	0.25	1,411	148
Population growth	%		1.4	-4.5	18	1.5
Energy intensity	M.J. TEC/ 2017 USD PPP	131	6.0	1.2	41.0	4.4
Coal share	%	138	0.04	0	0.85	0.09
Oil share	%	138	0.41	0.02	0.94	0.19
Natural gas share	%	138	0.12	0	0.86	0.16
Net gasoline tax	2015 USD	131	0.48	-0.90	2.10	0.53
Fossil fuel subsidies	Million USD/ToE	135	62	0	746	94
Regulatory indicators	0-100	110	40	0	97	25
Carbon Price	2015 USD					
Total		45	11,00	0.00	77.20	13.40
Electricity and Heat		43	12.80	0.00	68.40	11.80
Manufacturing		43	16.70	0.00	99.70	16.60
Buildings		16	34.40	0.00	130.00	36.90
Road		14	37.50	0.00	130.00	39.10

Note. TEC: total energy consumption; ToE: Tons of oil equivalence; For the carbon price, the mean price over the policy's lifetime is reported.

6.2. The effectiveness of carbon pricing policies

6.2.1. Main regression results

In Table 6.2, the results of the main panel regression are presented for the 1, 3 and 5-year growth periods. The main coefficients of interest are the carbon policy dummy and the carbon price, which are both significant for all periods. The controls for initial GDP, initial population controls and their simultaneous growths are significant. The energy intensity control is not significant, while the shares of fossil fuel types are not significant in the 1- and 3-year growth periods. The oil and natural gas shares become significant in the 5-year growth period. The R^2 increases with longer growth periods, as there is less variance in the underlying data.

The carbon policy coefficients have a value between -0.033 and -0.021 This implies that countries see roughly a three percentage point lower annual emissions growth rate after implementing carbon pricing policies, regardless of the price level. The 5-year period effect is smaller, around a 2.1 percentage point lower annual growth rate. This means that countries that implemented carbon pricing policies have significantly lower emissions growth rates than countries that do not have such policies, controlling for differences in GDP, population and the Kaya identity. This result is in line with hypothesis 1.

The carbon price estimate range between -0.016 and -0.011 and is significant for all three growth periods. The coefficients of the carbon price indicate that, on average, a 1$ emissions-weighted carbon price leads to roughly an additional 0.1 percentage point decrease in the emissions growth rate of a country. This finding supports hypothesis 2, that a higher carbon price is associated with even lower emissions growth rates. It must be noted that the ECP cannot be directly compared to nominal carbon tax rates. A 1$ ECP increase relates to a 100% scope carbon tax of 1$ or, for example, a 5$ increase on a sector which emits 20% of emissions. The average ECP globally is around 11.00$, thus a 1-dollar increase is relatively substantial.

Table 6.2

Main regression on the total emissions growth rate

	Total emissions growth rate		
	(1)	(2)	(3)
VARIABLES	1 year	3 year	5 year
Time- period:	1990-2019	1992-2019	1994-2019
Carbon policy	-0.0333***	-0.0294***	-0.0212***
	(0.00774)	(0.00719)	(0.00619)
Carbon price	-0.00113**	-0.00160***	-0.00109**
	(0.000496)	(0.000602)	(0.000471)
Initial log CO_2	-0.131***	-0.101***	-0.137***
	(0.0302)	(0.0145)	(0.0147)
Initial log GDP per capita	0.105***	0.0661***	0.119***
	(0.0377)	(0.0210)	(0.0201)
Initial log population	0.197***	0.147***	0.220***
	(0.0472)	(0.0264)	(0.0285)
Initial log energy intensity	0.00827	-0.0227	0.0167
	(0.0355)	(0.0184)	(0.0182)
Initial coal share	-0.0589	-0.0602	0.0779
	(0.152)	(0.0972)	(0.0912)
Initial oil share	0.107	0.0400	0.132***
	(0.0788)	(0.0693)	(0.0442)
Initial natural gas share	0.0738	0.00876	0.0940**
	(0.0724)	(0.0458)	(0.0404)
GDP per capita growth	0.525***	0.618***	0.538***
	(0.0798)	(0.0905)	(0.0944)
Population growth	1.024***	1.159***	1.136***
	(0.218)	(0.192)	(0.185)
Observations	3,623	1,132	625
R-squared	0.196	0.401	0.508
Number of countries	128	128	128
Fixed effects	Yes	Yes	Yes

Clustered robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6.2.2. *Sectoral regression results*

The sectoral regression gives more insight into the effects of carbon pricing policies. Results are presented in Table 6.3, for each of the four sectors, the 1- and 3-year growth rates are shown. Carbon policy is significant for the sectors of electricity and heating, industry and manufacturing, and road transport. The coefficients are largest in industry and manufacturing, and electricity and heating. These coefficients imply that, when carbon pricing is mandated, the emissions growth rates for the sectors decrease by four to six percentage points. These two sectors represent an important portion of a country's total emissions. The electricity and heating sector account for around 40-50%, and the industry and manufacturing for 15-35% of carbon emissions, depending on the country and time. Most carbon pricing policies specifically target these two sectors. The effect for road transport is also significant, but smaller in scale than the other sectors, with coefficients of -0.034 and -0.028. The effects of carbon pricing are not significant in the building sector, as the *p*-value > 0.05. This implies that no effect of carbon taxation has been found in reducing the sectoral emissions growth rate. In conclusion, there is evidence found for hypothesis 1 in three sectors, while no evidence is found for the buildings sector.

The coefficients for the carbon price are never significant, which is a surprising result. The carbon price for the electricity sector has a *p*-value < 0.1, but the 1-year estimate is positive (column 2). This suggests that the estimate are not reliable. These results indicate that a higher carbon price is not correlated with lower sector-specific emissions growth rates. Thus, the sector-specific regressions do not provide further evidence to support hypothesis 2. The potential cause of this lack of significance is addressed in the discussion.

On a general note, initial CO2, GDP per capita, population, and economic and population growth are all significant, just as in the main regression. The sectorial regressions have an R2 of between 0.121 and 0.340, which is lower than the main regression. This might be because population and GDP are less directly related to the emissions growth rate for each sector.

Table 6.3

Sectoral regression on emissions growth rates

	Electricity and heating		Industry and manufacturing		Building		Road transport	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES	1 year	3 year	1 year	3 year	1 year	3 year	1 year	3 year
Carbon policy	-0.0415**	-0.0343**	-0.0593**	-0.0592***	-0.0328*	-0.0440	-0.0345**	-0.0287**
	(0.0159)	(0.0136)	(0.0231)	(0.0182)	(0.0188)	(0.0277)	(0.0134)	(0.0125)
Carbon price	0.000198	-0.00145*	-0.000740	-0.0000345	-0.000997	-0.000815	-0.000285	-0.000185
	(0.000912)	(0.000843)	(0.000541)	(0.000337)	(0.00103)	(0.00116)	(0.000501)	(0.000468)
Initial log CO_2	-0.148***	-0.119***	-0.255***	-0.161***	-0.167***	-0.190***	-0.147***	-0.143***
	(0.0336)	(0.0172)	(0.0700)	(0.0326)	(0.0238)	(0.0519)	(0.0194)	(0.0242)
Initial log GDP per capita	0.116*	0.0682	0.229***	0.128**	0.116***	0.185***	0.104**	0.108***
	(0.0611)	(0.0517)	(0.0719)	(0.0497)	(0.0425)	(0.0629)	(0.0426)	(0.0321)
Initial log population	0.276***	0.203***	0.405***	0.234***	0.192***	0.204**	0.182***	0.176***
	(0.0837)	(0.0694)	(0.128)	(0.0619)	(0.0667)	(0.0829)	(0.0335)	(0.0298)
Initial log energy intensity	0.0301	-0.0109	0.0446	0.00989	0.0271	0.0832	-0.0200	-0.0143
	(0.0711)	(0.0499)	(0.0578)	(0.0527)	(0.0422)	(0.0676)	(0.0299)	(0.0196)
Initial coal share	0.375	0.314	0.443	-0.00719	0.0370	0.161	0.0997	-0.00891
	(0.256)	(0.254)	(0.518)	(0.269)	(0.254)	(0.281)	(0.132)	(0.0880)
Initial oil share	0.337**	0.345**	0.388	0.0165	0.716**	0.488	0.163	0.157
	(0.140)	(0.135)	(0.340)	(0.184)	(0.324)	(0.343)	(0.100)	(0.114)
Initial natural gas share	0.250**	0.304***	0.235	0.107	0.216	0.205	0.0106	0.0563
	(0.111)	(0.0964)	(0.219)	(0.142)	(0.149)	(0.194)	(0.0847)	(0.0583)
GDP per capita growth	0.475***	0.428***	0.462***	0.447**	0.496***	0.425**	0.611***	0.701***
	(0.0905)	(0.145)	(0.126)	(0.187)	(0.0972)	(0.210)	(0.109)	(0.117)
Population growth	0.707*	0.917**	0.00196	0.619	2.329**	1.927	1.818***	1.805***
	(0.382)	(0.371)	(0.593)	(0.492)	(1.090)	(1.377)	(0.410)	(0.395)
Observations	3,339	1,043	3,444	1,076	3,533	1,103	3,623	1,105
R-squared	0.121	0.226	0.154	0.317	0.123	0.380	0.158	0.340
Number of countries	118	118	122	122	125	125	128	125
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Clustered robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

6.2.3. Time of implementation differences

The list of countries that have implemented carbon pricing after 2010 is shown in Table 6.4, as well as details on the mean carbon price and years the policy is active. In the restricted sample, Australia, Kazakhstan, and Ukraine were omitted from the regression to improve data quality. Australia only implemented a carbon tax in 2011 and 2012, Kazakhstan paused their ETS in 2015 and 2016, and Ukraine has extremely low levels of carbon taxation.

Table 6.4

Countries with carbon pricing policies after 2010

Country	Mean carbon price 2017 USD	Years effective	Restricted sample
Argentina	4.71	1	Yes
Australia	9.71	3	No
Chile	2.76	2	Yes
Colombia	0.57	2	Yes
Croatia	3.03	6	Yes
Japan	1.32	7	Yes
Kazakhstan	0.61	2	No
Korea	9.86	4	Yes
Mexico	1.49	5	Yes
New Zealand	7.30	8	Yes
Ukraine	0.02	6	No

The regression results of equation (19) can be found in Table 6.5. The results are presented two-fold to show the differences in the selected sample. Columns (1) and (2) present the results for all countries that have implemented carbon pricing after 2010, and columns (3) and (4) show the results for the restricted sample. The double hashtags indicate the interaction terms.

Hypothesis 3 is tested using the regression model, including the interaction effects between implementation times. Overall, the main results from the general regression still hold. The carbon policy dummy and the carbon price are significant in all columns. In the unrestricted sample, no significant coefficient is found between the interactions of the carbon policy or price variables in column 2. This could be due to the inclusion of Australia, Kazakhstan, and Ukraine, which have fluctuating carbon prices. In the restricted sample, the interaction between policy and after 2010 is significant at the $p<0.05$ level (column 4). Still, there is no significant effect between the interaction and the carbon price.

Hypothesis 3 can be rejected for the unrestricted sample, as there are no significant interactions. Using the restricted sample, however, there is a significant interaction for the policy variable, while there is no effect for the carbon price. The restricted sample thus shows significant evidence that these countries have lower growth rate reductions. This implies that countries that have implemented carbon pricing after 2010 have a *lower* effectiveness of their policies. Still, the combined total effect is -0.015, and carbon taxation still reduces the growth rate for these countries. Interestingly, no significant interaction effect is found for the carbon price, which is further analyzed in the discussion.

Table 6.5

Total emissions growth rate, including interaction effects

	Emissions growth rate, including interaction effects			
	(1)	(2)	(3)	(4)
VARIABLES	1 year	1 year	1 year	1 year
	1990 - 2019	1990 - 2019	1990 - 2019	1990 - 2019
Carbon policy	-0.0333***	-0.0373***	-0.0341***	-0.0387***
	(0.00774)	(0.00857)	(0.00812)	(0.00879)
Carbon policy ## after 2010		0.0123		0.0231**
		(0.0115)		(0.0104)
Carbon price	-0.00113**	-0.00111**	-0.00118**	-0.00114**
	(0.000496)	(0.000510)	(0.000519)	(0.000530)
Carbon price ## after 2010		0.00193		0.00119
		(0.00123)		(0.000911)
Initial log CO_2	-0.131***	-0.131***	-0.132***	-0.133***
	(0.0302)	(0.0302)	(0.0305)	(0.0305)
Initial log GDP per capita	0.105***	0.104***	0.100***	0.101***
	(0.0377)	(0.0378)	(0.0380)	(0.0381)
Initial log population	0.197***	0.197***	0.192***	0.192***
	(0.0472)	(0.0472)	(0.0467)	(0.0467)
Initial log energy intensity	0.00827	0.00787	0.00628	0.00596
	(0.0355)	(0.0355)	(0.0356)	(0.0356)
Initial coal share	-0.0589	-0.0633	-0.0209	-0.0271
	(0.152)	(0.153)	(0.163)	(0.163)
Initial oil share	0.107	0.106	0.116	0.116
	(0.0788)	(0.0789)	(0.0812)	(0.0813)
Initial natural gas share	0.0738	0.0732	0.0800	0.0807
	(0.0724)	(0.0724)	(0.0736)	(0.0737)
GDP per capita growth	0.525***	0.524***	0.522***	0.521***
	(0.0798)	(0.0796)	(0.0817)	(0.0814)
Population growth	1.024***	1.021***	1.017***	1.016***
	(0.218)	(0.218)	(0.226)	(0.227)
Observations	3,623	3,623	3,536	3,536
R-squared	0.196	0.196	0.193	0.193
Number of countries	128	128	125	125
Fixed effects	Yes	Yes	Yes	Yes
Restricted sample	No	No	Yes	Yes

Clustered robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6.3. Robustness checks

Several robustness specifications were analysed to check the possibilities of alternative explanations.

6.3.1. Additional carbon price signals

In Table 6.6, the specification of 3-year growth periods is regressed including the controls for either gasoline taxes or fossil fuel subsidies. Note the different time periods due to limited data on the control variables. The results of the carbon policy are in line with the main regression, although smaller in size, especially for the 2010-2019 period. In addition, the carbon policy variable has a *p-value* < 0.1, which is not significant anymore. However, as these results occur also in the regression without the additional controls, thus it is likely that this is due to the shorter time period. Importantly, in the main regression, countries' emissions data before the implementation of carbon pricing policies are also part of the regressions, while this data is not included in the shorter time periods (i.e. 2003-2018). The coefficient for the carbon price is never significant. This insignificance of the carbon pricing variable can be explained by the shorter time period as well. Still, the inclusion of gasoline taxes and fuel subsidies might influence the effects of the carbon price too.

The coefficient estimates for net gasoline tax and fossil fuel subsidies are not significant. In the appendix, the same table can be found for the 1-year growth period (see Table A2). In addition, both controls are included, but this causes a small time frame, which should warrant caution with the interpretation of the coefficients (see Table A3). In those regressions, the included controls do not considerably change the results of the carbon policy or price coefficients. From this, it can be concluded that the inclusion of controls for gasoline taxes and fossil fuel subsidies does not impact the outcomes of the main regression. In other words, including various other fossil fuel price signals does not change the effects of the carbon pricing policies.

Table 6.6

Total emissions with gasoline price or fossil fuel subsidies as additional controls

Emissions growth rate with gasoline price or fossil fuel subsidies as additional controls				
	(1)	(2)	(3)	(4)
VARIABLES	3 year	3 year	3 year	3 year
Time- period:	2003-2018	2003 - 2018	2010 - 2019	2010 - 2019
Carbon policy	-0.0258***	-0.0269***	-0.0142*	-0.0144*
	(0.00859)	(0.00906)	(0.00787)	(0.00781)
Carbon price	0.000018	0.000111	0.000896	0.000961
	(0.000642)	(0.000823)	(0.000967)	(0.000959)
Initial gasoline tax		-0.00854		
		(0.0138)		
Initial fossil fuel subsidies				-0.0000388
				(0.0000355)
Initial log CO_2	-0.127***	-0.143***	-0.189***	-0.190***
	(0.0371)	(0.0377)	(0.0340)	(0.0341)
Initial log GDP per capita	0.116**	0.119**	0.218***	0.217***
	(0.0478)	(0.0483)	(0.0529)	(0.0530)
Initial log population	0.164***	0.173***	0.215***	0.205**
	(0.0578)	(0.0599)	(0.0797)	(0.0819)
Initial log energy intensity	-0.0249	-0.0309	0.0237	0.0223
	(0.0418)	(0.0425)	(0.0439)	(0.0444)
Initial coal share	-0.126	-0.00641	0.189	0.201
	(0.149)	(0.177)	(0.229)	(0.232)
Initial oil share	-0.0323	0.0129	-0.0616	-0.0417
	(0.0968)	(0.105)	(0.145)	(0.142)
Initial natural gas share	-0.000223	0.0571	-0.0754	-0.0583
	(0.104)	(0.109)	(0.141)	(0.140)
GDP per capita growth	0.596***	0.614***	0.742***	0.750***
	(0.104)	(0.105)	(0.140)	(0.142)
Population growth	0.905***	0.949***	0.210	0.142
	(0.262)	(0.260)	(0.434)	(0.446)
Observations	615	592	384	384
R-squared	0.318	0.334	0.413	0.415
Number of countries	123	123	128	128
Fixed effects	Yes	Yes	Yes	Yes

Clustered robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

6.3.2. Regulatory controls

The estimates of the carbon policy and the carbon pricing the regressions with the ESMAP (2020) controls on countries' regulatory framework are insignificant (see Table A4). Similarly to the results in Table 6.6, a period of 9 years seems to be too short to capture the effects of carbon pricing policies. Even more, in this sample, 18 countries are excluded due to missing data, of which eight have carbon pricing policies and ten without. Therefore, the carbon policy coefficient may become insignificant due to the smaller sample of countries and years. Still, the estimate for the renewable energy policies indicator is significant. As the indicator is a 0-100 score, a 10-point increase is correlated with a 1 percentage point lower emissions growth rate. This is a substantial reduction in the emissions growth rate. However, it is challenging to assess the effect on the carbon pricing variable, as these are not significant in the regression. The indicator for energy efficiency policies is not significant in the regression.

6.3.3. *Excluding the EU ETS*

The EU ETS is the largest international emissions trade system and could be the main driver of the effects found in the main regressions. However, in this version of the World Carbon Pricing Database, the pricing data for the first years of the ETS implementation is poor. This is due to volatile prices and many free allowances. Therefore, Table A5 presents the main regression without the EU ETS. The results remain significant and of similar magnitude. In addition, the results for the carbon policy hold when excluding all EU countries from the regression (see Table A6). However, due to the smaller country sample size, the carbon pricing variable becomes insignificant. This gives confidence that the results also are geographically robust as well.

6.3.4. *Convergence and the environmental Kurnitz curve*

The non-linear relation of GDP with respect to emissions growth rates is tested by adding a squared control to the regression. The results can be found in the appendix (Table A7). The squared GDP variable has a significant negative estimate. This implies that a higher GDP increases the emissions growth rate but at a diminishing rate. The main results of the carbon policy and carbon remain significant. Yet, the estimates decrease in size, especially for the 1- and 3-year growth periods.

The need to include the initial emissions level in the regressions is tested by excluding it from the main regression equation (see Table A8). The coefficients for initial emissions levels are always significant in the main regression. The regression without initial emissions level results in higher coefficients for carbon policy. This suggests that there is a convergence between emissions levels and that omitting the convergence effect creates an upward bias in the effectiveness estimates. Therefore, the convergence control is important to include in the regression.

6.3.5. *Time periods robustness*

The results are robust for different time intervals, as seen in the appendix (see Table A9 and A10). For the three-year growth period, the policy estimates are between -0.027 and -0.031, and for the price between -0.0007 and -0.0016, and are all significant at minimum $p<0.05$. For the five-year period, the carbon policy is significant for all periods with a range of -0.021 to -0.030. The carbon pricing variable is insignificant for the periods 1990-2015 and 1990-2020. For the other periods, the estimates are significant. This finding mainly highlights that there is much missing data for countries in 1990. Overall, the main findings are robust to the selection of different periods.

7. Discussion

Carbon pricing is an essential pillar in climate policy. However, the extent to which carbon pricing has reduced emissions has been unclear. Although the effects of individual policies have been researched, a cross-country comparison between countries has been limited due to data constraints.

This thesis aims to answer the research question: what is the effect of carbon pricing policies on emissions growth rates? The results indicate that countries see lower growth rates after implementing carbon pricing. Furthermore, a higher carbon price leads to additional reductions in emissions, though this price effect is relatively small.

7.1. Interpretation of results

7.1.1. The main regression

The results of the main regression show that countries see lower growth rates after the implementation of carbon pricing policies, as stated in hypothesis 1. In line with hypothesis 2, this reduction effect increases with higher carbon prices. The results are relatively similar to previously published studies on the general effect of carbon policies but are in between the estimates for the carbon price effects.

The results of this thesis are largely similar to the findings of Best et al. (2020). The panel regression of Best et al. (2020) results around a 3-4 percentage point reduction of the emissions growth rate for the 1- and 3-year periods. However, the carbon price variable is not included in these regressions. Therefore, it is difficult to directly compare the two carbon policy indicators. Still, taking the combined effect of the binary indicator for carbon policies and the carbon price into account, the estimates of three- to four-percentage-point growth rate reductions are in line with the findings of this thesis. The cross-sectional regression for the growth period 2012-2017, Best et al. (2020) do include price and find an implementation effect of 2.4 percentage points. In comparison, the 5-year period regression in this study is lower at a 2.1 percentage point growth rate reduction. However, this is a 5-year estimate for the period 1994-2019. Although they may not be directly comparable, the results are of similar magnitude.

Compared to Rafaty et al. (2020), the results in this study are larger, especially for the carbon price. In a regression that only includes a binary indicator for carbon pricing policies, Rafaty et al. (2020) estimate an effect of a 1.5 percentage point growth rate reduction for the 1-year growth period. In contrast, the 3.3 percentage point growth rate reduction found in this paper is double the reduction size. This difference could be from the methodology used: Rafaty et al. (2020) use a synthetic control method to estimate counterfactual emissions reduction. In addition, Rafaty et al. (2020) use fewer controls in their regressions.

The results are difficult to compare to Lin and Li (2011) as their regression addresses the specific reductions of countries. However, the regression in this paper analyses a wide variety of countries with carbon pricing, which overall finds a significant effect. Still, the period covered is also different and the EU-ETS might have been a more important driver of emissions reduction that the national carbon taxes.

The coefficients for the carbon price are in between estimates from the literature. Best et al. (2020) estimates the price effects only for the 5-year growth period from 2012 to 2017. They find a coefficient of 0.2 percentage points reduction on the annual rate of emissions growth, for every euro increase in effective carbon price rate per tonne of CO2. In comparison, the result in Table 6.4 for the 5-year period indicates a 0.1 percentage point reduction. It must be noted that Best et al. (2020) use a different typology of carbon price that does include some forms of energy taxes. On the other hand, Rafaty et al. (2020) find a non-significant estimate of 0.07 percentage points for a 1-dollar increase in the emissions-weighted carbon price. These findings may not be significant as their data only includes the years up to 2016. Though, especially the most recent years have seen carbon price increases.

The general findings of the study are similar to previously published papers and academically not surprising, the result has large practical implications. Especially the small effects of carbon price increases limit the emissions reduction potential of carbon pricing policies. Section 7.2 discusses the implications these findings have further.

7.1.2. Sectorial regressions

The sectoral regressions show an unexpected result: the carbon price effect becomes insignificant. There may be several explanations for this change. First, the electricity and industry sectors are primarily subject to volatile emissions trade systems, which results in a higher variance in the carbon price. In addition, developments towards the decarbonisation of electricity networks are relatively stable as they depend on large and longer-term investments. Thus, the price of carbon emissions is not (directly) related to the emissions reduction in a given year. Noticeably, the carbon policy effects are substantial, with a four to six percentage points reduction. This may indicate that, although the carbon price itself is not directly relevant, the pricing mechanism itself is essential to emissions reduction.

Second, the insignificance of the carbon price could be related to different types of tax regimes in countries. To target emissions from energy use by buildings, most countries use energy taxes, which are not classified as carbon taxes in the dataset used. Thus, the regression compares countries with carbon pricing to countries that use other types of energy taxes. This may explain why the carbon policy itself is not significant for the emissions reduction of the building sector. Third, the carbon taxes on gasoline and diesel for the transport sector are relatively low. For example, the Swedish carbon tax on a litre of gasoline is around 25 euro cents, which is equivalent to other fuel excise taxes. In addition, gasoline prices are relevantly volatile, and consumers change their behaviour to a limited extent to price changes for oil, the impact of carbon taxes may also be limited.

In summary, the lack of significance for the carbon price can have various implications. Either, the methodology and data used have not been able to capture the true effects. On the other hand, it could also be that the carbon price itself has a limited to small effect on decarbonisation. Just the fact that companies are facing (low) carbon taxes may induce them to reduce emissions. Finally, it could also be that the carbon price is important, but not yet at the observed levels. This option is supported by the expectations of future carbon price increases, and companies want to prevent these high taxes.

In the study by Rafaty et al. (2020) the electricity sector also reduced emissions most effectively, with an estimate of -2.7 percentage points. Thus again, the effect found in this thesis has almost double the magnitude. Yet, their results also show no significant effects on the carbon price. The estimate for the manufacturing and industry sector is around a 1.4 percentage point reduction, but not significant. The effects on road transport and buildings are even smaller and also not significant.

The power sector analysis by Leroutier (2022) indicates that the U.K. carbon tax reduced emissions by 25% over the 5-year period. Although a lower growth rate cannot be directly compared to the emissions reduction, it could be relatively in line. However, the U.K. carbon tax was an additional tax beyond the EU-ETS, which was active in the whole E.U. but at deficient price levels during this period.

7.1.3. Time of implementation differences

The positive and significant interaction term between the time of implementation and the carbon pricing policy indicated that countries which have implemented carbon pricing more recently see lower decreases in annual emissions growth rates. Three arguments explaining these results are outlined.

First, these countries may be different from the early adopters in various characteristics, which affects the effectiveness of carbon pricing. For example, although carbon-efficient technologies have improved over the past decade, they are often more expensive. The capital needed for carbon-efficient investments may be lacking in these countries, or only supplied at a higher interest rate.

Second, the lower effectiveness can be an effect of the low carbon price level. Three of the six countries in the restricted sample have average carbon prices below two dollars. This may be too cheap to impose substantial emissions reduction. This is supported New Zealand Ministry for the Environment (2016) in a report on the ETS after 5 years of implementation. The report, which was based on surveys and interviews of stakeholders, indicated that the low carbon price was the main reason the ETS did not affect business decisions. The participants did indicate that now a carbon policy was put in place, the importance of the ETS on business decisions will only increase over time.

Third, the development and implementation of carbon pricing policies take a substantial time before emissions are reduced. This may be especially the case for emissions trade systems, as these are more difficult to organize from a government perspective. For example, the Kazakhstan ETS was implemented in 2014 but then froze its enforcement until 2016 to improve the policy. This argument is partially supported by Jun et al. (2021) as the first phase of the Korean ETS was only effective in the building and manufacturing sector, while for the electricity sector, too many free allowances were granted.

Like the sectoral regressions, no significant interaction effect is found for the carbon pricing variable. This may relate again to the low prices in general, or to the lack of variance in carbon prices within and among the limited number of countries.

7.1.4. Robustness tests

In the robustness controls a pattern is identified that the carbon policy effect is not significant when looking at the time period from 2010 to 2019. This can be seen in the regressions of the fossil fuel subsidy controls in columns (3) of Table 6.6 and Table A2, for the 3- and 1-year growth periods, respectively. The same occurs with the regulatory policy framework controls (see Table A4). Of course, these regressions have a much shorter time horizon and therefore a lower number of observations, which can explain the insignificance. However, the effect is also smaller, around a 1 percentage point growth rate reduction. Therefore, it must also be considered that the effect of carbon pricing overall has reduced, at least compared to other countries without carbon pricing. This may relate to the economic crisis in the world during the early years of the decade.

7.2. Implications

These results build on existing evidence of the effectiveness of carbon pricing. It is generally accepted in the literature (Green, 2021) that carbon pricing reduces emissions compared to business-as-usual scenarios but has not (yet) proven to lead to deep decarbonisation. While previous literature has focused on single-country policies, the result of this thesis demonstrates that the same conclusions are obtained in a study on many countries. However, policymakers and governments still see carbon pricing as a central pillar of environmental policy. More so, the recent findings of Best et al. (2020) and Rafaty et al. (2020) and this paper indicate a small effect on emissions of an increase in the carbon price, i.e. a low price elasticity. These results do not fit with the suggestions that carbon taxation can reduce CO2 emissions substantially within the observed price ranges. In addition, the results contribute to a clearer understanding of the relevance of time required before carbon pricing becomes effective. These results should be considered when considering how to reach carbon reductions set by governments effectively.

The implications of the results for practical policymaking can be shown with some rough calculations. These examples are provided to give the context of the (size of the) results, but should not be considered as in-depth scenario analysis.

The EU has set an emissions reduction goal of 55% compared to 1990 CO2 levels in 2030. To reach those goals, the EU should have a negative annual emissions growth rate of -4.0%, according to the European Environmental Agency (2022). Recent emissions trends are difficult to obtain due to the covid and energy crises. However, projections suggest an additional reduction of 2.0 percentage points would be needed to reach the 2030 goals beyond the measures already taken, which includes the lower ETS cap of 2.2% annually. With a coefficient on the carbon price of 0.11, this would imply an additional increase of around 17 euros in the ECP, which is double the price in 2019. Alternatively, the ETS base could be increased. The EU recently announced that road transport and energy use in buildings would also be subject to the ETS, which was not considered in the projections. However, the effects remain unclear as several countries already apply carbon pricing using national carbon or energy taxes.

In another scenario, all 45 current countries that apply carbon pricing are increased to an ECP of 30 dollars. In comparison, the average ECP worldwide in 2019 was 13 dollars (averaged by the number of countries). For each country, their emissions growth rate will reduce by 0.11 percentage points times the price increase. In total, this results in a decrease of 0.56 percentage point reduction of the worldwide emissions growth rate. The global emissions growth rate was around 1% in 2019, and even this measure would not suffice to reach ‘peak fossil fuels’, i.e. the maximum yearly emitted CO2 emissions.

On a worldwide scale, the goal to limit global warming to 1.5 degrees would require a 7.6 percentage point lower annual emissions growth between 2020 and 2030, according to the United Nations Environment Programme (2019). The implementation of carbon pricing worldwide will reduce emissions only by 1.5 percentage points, as the result indicated in Table 6.5. Thus, a gap of 6.1 percentage points is left. To reach the goals, an average global ECP of around 50$ would be required. Those price levels are currently only reached by Finland and Sweden. Moreover, these carbon prices would substantially increase the price of fossil fuels. For example, a barrel of oil averaged around 60 dollars over the last decade and contains roughly half a ton of CO2. A carbon tax of 25$ per barrel of oil would result in a (permanent) price increase of 40-50%. This has substantial economic and political effects.

To reach the political targets set out in the Paris Climate Accord, the EU fit-for-55 or other national goals require unprecedented levels of carbon pricing. These calculations, based on the findings of this research, indicate that radical decarbonisation can only be reached using extreme policies. However, the scenarios are hypothetical, the assumptions are extreme and the estimates of the effects are out-of-sample.

7.3. Limitations

7.3.1. Greenhouse gasses vs CO2

This research focuses on CO2 from fossil fuel burning, the largest source of CO2 emissions. However, land-use change, agriculture, and concrete production are key sources, covering between 20% per cent of emissions in 1990 and 10% in 2019 (Ritchie et al., 2020). Although concrete production is not part of the CO2 emissions in this research, it often falls under carbon pricing schemes. On the other hand, no large-scale CO2 pricing policies exist for agriculture and deforestation, although they could be essential policies towards carbon neutrality. Thus, the results must be used cautiously when addressing all countries' CO2 emissions.

Further, this research has been limited to the greenhouse gas CO2. However, many other (highly) polluting greenhouse gases exist in various forms. Together CO2 (79%), methane (11%) and nitrous oxide (7%) represent 97% of greenhouse gas emissions in the U.S. Methane and nitrous oxide are primarily by-products of fossil fuel extraction and burning. However, agriculture and livestock are the second most extensive sources of these emissions (Ritchie et al., 2020). In theory, the same mechanisms can be used to price these emissions, though this is much harder in practice. These gasses escape during production, transportation and burning or through livestock belching and flatulence. This implies that companies have no clear stock-taking on the input and output of these gasses, which is necessary for efficient taxation.

7.3.2. Carbon leakage

Carbon leakage is not directly considered, and therefore still a possible explanation for the reduction in growth rates in carbon pricing countries. Thus, although carbon pricing thus far possibly has not resulted in global emissions decreases, it implies that firms are sensitive to price signals. Therefore, one could argue that carbon pricing works but needs to be implemented by more countries.

7.3.3. Limited inclusion of relevant policy and regulatory indicators

Ideally, the thesis should include more relevant environmental policies, but due to data constraints, this was not possible. Including more variables on similar environmental policies may reduce the risk of omitted variable bias. Moreover, the general governmental position towards environmental policy could also be an interesting indicator, as this could influence both the carbon tax rate and support other policies that reduce emissions. However, such indicators are not available for all countries, which may lead to selection bias in larger or more developed countries.

7.3.4. ETS price volatility

ETS-free allowances are not considered in this database. However, the Worldwide Fund for Nature finds in a 2022 report that big polluters, subject to the EU-ETS, were given €100 billion in free allowances from 2013-2021 (WWF, 2022). This is higher than the auction revenue (€95.6 billion) of CO2 emissions rights. Thus, although the price variable is an emissions-weighted price, it might still be too high to account for the actual cost of emissions faced.

The robustness tests exclude this mechanism from the regression to address the incomplete data, especially by the EU-ETS. Nevertheless, the findings are similar in size, excluding E.U. countries, Iceland, and the U.K. Still, the estimates on price effects might be blurred and should be interpreted with caution. Therefore, improving the data quality on the European ETS can benefit future research enormously.

7.3.5. Specification of the model

The model used is based on a linear relationship between the carbon pricing policies and the annual emissions growth rate, with intercept α and slope β. However, in practice, this does not need to be the case. The model could also be specified in percentages, i.e. by taking the logarithm of the carbon price. Of course, a 1$ increase from $5 to $6 possibly has a different behavioural response than $30 to $31. However, such a specification might not reflect price-level effects that capture substitution possibilities. For example, coal plants switch to natural gas when the carbon tax difference in dollars is profitable.

Understanding the specification of the model also highlights the reliability of the results. The carbon price effect estimates are most reliable in the $0 to $25 range, as more than 90% of the price observations are in this range too. Beyond this range, the results should be used with caution, as the observed linear trend may not hold out-of-sample.

7.3.6. Identification strategy and model assumptions

As stated in the methodology section, the extent to which the results can be identified as causal depends on the assumption that the omitted variables do not correlate with the treatment or outcome variables. Despite the additional control variables, there could still be important differences between countries that are not included. Thus, the results should be used with caution when applied causally. Nevertheless, the special attention to the late adopter countries helps to find the most relevant estimates for countries assessing carbon pricing policies.

This paper finds correlational evidence of the ex-post effectiveness of carbon pricing. Though this is no guarantee of future effectiveness, it is still helpful to know which factors have contributed to carbon emissions reduction. In addition, the estimates are useful in calibrating ex-ante modelling assumptions.

7.3.7. Time and country heterogeneous treatment effects

In general, the effectiveness of a carbon policy can be different between countries and times. For cross-country comparison, some restrictions and averages have to be made. For instance, the emissions-weighted carbon price is a generalization where the policy-specific scope is effectively increased to 100% but at a lower price. Though this transformation is necessary to enable cross-country comparison; it reduces still information.

A similar tradeoff can be found in finding treatment effects that vary over time or vary between groups of countries. The research question one wants to answer is guiding the model specification. In this paper, one of the main research questions asked if there were differences in treatment effects for countries that only recently adopted carbon pricing. A model was specified such that these differences could be captured. Continent-specific effectiveness rates may be studied using dummies for geographical location. However, not all trends and differences can be included at the same time, as the model would have too many parameters and degrees of freedom. Nor can all research questions be answered using this (adapted) model, as data and trends are aggregated. Then, other methods may be better suited to capture the complex differences over time and between countries.

7.4. Recommendations

The main result of this thesis is that carbon pricing has significantly reduced the annual emissions growth rate. Yet, the estimate on the effects of the carbon price itself is rather small; this implies that price increases will only decrease emissions growth relatively little. Therefore, carbon pricing is an essential pillar of the carbon-neutral future but not the holy grail of decarbonisation. Still, carbon pricing is recommended to other countries as an effective method to reduce emissions.

Future research could build on this thesis to further study the impact of carbon taxation in late-adopter countries. For example, they could explore the legal framework and the coverage in more detail or look at specific sectors. Similarly to Lin and Li (2011), synthetic control methods studies could be used to study the causal effect of these policies in a Latin American context.

Further improving the World Carbon Pricing Dataset with updates on ETSs free allowances can substantially improve the accuracy of the price effects. Moreover, the effectiveness differences between emissions trade systems and carbon taxes can also be researched with more accurate ETS data.

Finally, research on reducing other greenhouse gasses can help stop climate change. For example, New Zealand is the first to propose a greenhouse gas tax on cows and other livestock in 2025. Studying such front-runners and establishing best practices can improve policy worldwide.

8. Conclusion

Carbon pricing policies have effectively reduced CO2 emissions over the last 30 years. This paper finds that countries with such policies have an average of three percentage points lower emissions growth rates. However, the effect of the carbon price level on the emissions growth rate has been limited. The results suggest that a 1$ increase in the emissions-weighted carbon price only has resulted in an additional 0.12 percentage point lower emissions growth rate. Moreover, the emissions reduction has also been smaller in countries that only recently implemented carbon pricing policies. These countries have seen a 1.5 percentage points reduction in CO2 growth rates.

The literature showed several gaps in assessing the effectiveness of carbon taxation. There are few cross-country comparisons, little attention was paid to carbon pricing outside the EU or North America, and the effect of the carbon price has not been studied. A cross-country comparison became possible using novel data that includes prices for an extended period of time. This methodology focuses on finding a general and comparable answer to the effectiveness of carbon taxes. It captures correlational differences between countries and within countries over time. In essence, the emissions growth rate is regressed on the carbon policy and other variables determining the level of emissions growth for periods of 1, 3 and 5 years. The regression controls for the primary drivers of carbon emissions through including controls related to the Kaya identity. Moreover, several different policies are included to separate the effects of carbon pricing. The results align with the hypotheses, although the effect of the carbon price varies between model specifications.

The findings of this paper can be used to inform the policy debate on carbon pricing. In conclusion, carbon pricing policies have reduced carbon emissions compared to a business-as-usual scenario. However, there is no evidence that these policies can fully decarbonise the economy and society in their current price ranges. Therefore, additional policies are required to substantially reduce emissions and reach the goals of the Paris climate agreement. Furthermore, based on the findings of this paper, the research could further investigate the differences between carbon taxation and emissions trade systems and how the effectiveness of these policies can be improved.

This research explicitly contributes to the effects of the carbon price concerning emissions reduction. The results indicate that the effect of a higher carbon price is low. Therefore, the effectiveness might be limited in the future when pricing are increased. Moreover, the findings indicate that carbon pricing policies have been less effective in reducing emissions in countries that implemented them after 2010. Thus, countries that have yet to start pricing carbon emissions could only see emissions reductions much later than is required to reach decarbonisation as stated in the Paris Climate Accord. Finally, the focus on differences between well-established carbon pricing policies and the newly introduced systems gives much insight into the importance of time before these policies become effective. In addition, these results are particularly interesting for countries that are currently considering carbon pricing.

9. Appendix

Table A1

Overview of carbon pricing mechanisms

Country	System	Mean Carbon price (2019 $)	Introduction year	Classified	Note
Argentina	Tax	2.60	2018		
Australia	Tax	9.70	2012		Ended 2014
Austria	ETS	5.40	2005		
Belgium	ETS	6.00	2005		
Bulgaria	ETS	10.00	2007		
Canada	Tax and ETS	3.20	2007		
Chile	Tax	2.60	2017		
China	ETS	0.31	2013	No	Regional only
Colombia	Tax	0.57	2017		
Croatia	ETS	4.50	2013		
Cyprus	ETS	8.20	2005		
Czech Republic	ETS	9.50	2005		
Denmark	Tax and ETS	15.00	1992		
Estonia	Tax and ETS	1.30	2000		
Finland	Tax and ETS	21.00	1990		
France	Tax and ETS	13.00	2005		
Germany	ETS	7.80	2005		
Greece	ETS	8.30	2005		
Hungary	ETS	7.20	2005		
Iceland	Tax and EU ETS	8.30	2009		
Ireland	Tax and ETS	14.00	2005		
Italy	ETS	6.40	2005		
Japan	Tax	1.40	2012		
Kazakhstan	ETS	0.58	2014		Not enforced 2016-2018
Korea, Rep.	ETS	12.00	2015		
Latvia	Tax and ETS	5.40	2005		
Lithuania	ETS	6.60	2005		
Luxembourg	ETS	2.70	2005		
Malta	ETS	11.00	2005		
Mexico	Tax	1.50	2014		
Netherlands	ETS	7.40	2005		
New Zealand	ETS	8.60	2010		
Norway	Tax and EU ETS	25.00	1991		
Poland	Tax and ETS	4.70	1993		
Portugal	Tax and ETS	9.00	2005		
Romania	ETS	8.50	2007		
Singapore	Tax	2.40	2019		
Slovak Republic	ETS	7.40	2005		
Slovenia	Tax and ETS	13.00	1997		
South Africa	Tax	7.20	2019		
Spain	ETS	6.60	2005		
Sweden	Tax and ETS	53.00	1991		
Switzerland	Tax and ETS	13.00	2008		
Ukraine	Tax	0.08	2011		No data available for 2015 - 2016
United Kingdom	Tax and EU ETS	8.50	2005		Was part of the EU ETS
United States	ETS	0.52	2009	No	State level only

Table A2

Total Emissions price signals controls - 1 year growth period

	Total emissions with control variables			
	(1)	(2)	(3)	(4)
VARIABLES	1 year	1 year	1 year	1 year
Time- period:	2003 - 2016	2003 - 2016	2010 - 2019	2010 - 2019
Policy	-0.0481***	-0.0482***	-0.0108*	-0.0102*
	(0.00945)	(0.00900)	(0.00583)	(0.00574)
Carbon price	0.000878	0.000908	0.000122	0.0000673
	(0.000703)	(0.000738)	(0.000822)	(0.000833)
Net gasoline tax		-0.0238		
		(0.0178)		
Fossil fuel subsidies				0.0000618
				(0.0000532)
Initial log CO_2			-0.267***	-0.264***
			(0.0351)	(0.0357)
Initial log GDP per capita	-0.185***	-0.197***	0.233***	0.231***
	(0.0502)	(0.0515)	(0.0620)	(0.0631)
Initial log population	0.147**	0.153**	0.288***	0.301***
	(0.0583)	(0.0594)	(0.0971)	(0.101)
Initial log energy intensity	0.250***	0.249***	0.0399	0.0387
	(0.0756)	(0.0783)	(0.0519)	(0.0520)
Initial coal share	-0.000625	-0.00847	0.169	0.148
	(0.0515)	(0.0521)	(0.200)	(0.193)
Initial oil share	-0.208	-0.0610	-0.00842	-0.0424
	(0.152)	(0.185)	(0.120)	(0.127)
Initial natural gas share	0.0574	0.0551	0.135	0.107
	(0.135)	(0.140)	(0.129)	(0.138)
GDP per capita growth	0.0944	0.118	0.497***	0.494***
	(0.124)	(0.127)	(0.0705)	(0.0696)
Population growth	0.540***	0.542***	0.0949	0.187
	(0.0746)	(0.0780)	(0.517)	(0.534)
Observations	1,599	1,552	1,152	1,152
R-squared	0.178	0.179	0.200	0.201
Number of countries	123	123	128	128
Fixed effects	Yes	Yes	Yes	Yes

Clustered robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table A3

Total emissions with both fossil fuel subsidies and gasoline taxes as controls

Total emissions with fossil fuel subsidies and gasoline taxes as controls		
	(1)	(2)
VARIABLES	1 year	1 year
Time- period:	2010 - 2016	2010 - 2016
Policy	-0.0432***	-0.0389***
	(0.0124)	(0.0130)
Carbon price	0.00494**	0.00446**
	(0.00202)	(0.00215)
Gasoline tax		-0.0300
		(0.0347)
Fossil fuel		0.0125
		(0.00764)
Initial log CO_2	-0.408***	-0.410***
	(0.0704)	(0.0744)
Initial log GDP per capita	0.348***	0.362***
	(0.0877)	(0.0932)
Initial log population	0.315	0.383*
	(0.202)	(0.215)
Initial log energy intensity	0.0875	0.0816
	(0.0767)	(0.0785)
Initial coal share	0.457	0.417
	(0.309)	(0.300)
Initial oil share	0.192	0.0888
	(0.163)	(0.200)
Initial natural gas share	0.410*	0.302
	(0.208)	(0.206)
GDP per capita growth	0.532***	0.529***
	(0.0767)	(0.0819)
Population growth	-0.294	-0.0423
	(1.112)	(1.148)
Observations	768	735
R-squared	0.249	0.266
Number of countries	128	124
Fixed effects	Yes	Yes

Clustered robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table A4

Total emissions with regulatory framework controls

Total emissions with regulatory framework controls				
	(1)	(2)	(3)	(4)
VARIABLES	1 year	1 year	3 year	3 year
Time- period:	2010 - 2019	2010 - 2019	2010 - 2019	2010 - 2019
Policy	-0.00819	0.000834	-0.0107	-0.00481
	(0.00590)	(0.00627)	(0.00756)	(0.00787)
Carbon price	-0.000634	-0.000405	0.000315	0.000506
	(0.000604)	(0.000622)	(0.000606)	(0.000578)
Renewable Energy Policies		-0.00103***		-0.000665**
		(0.000350)		(0.000274)
Energy Efficiency Policies		0.000596		0.000226
		(0.000424)		(0.000336)
Initial log CO_2	-0.282***	-0.282***	-0.202***	-0.209***
	(0.0374)	(0.0373)	(0.0357)	(0.0368)
Initial log GDP per capita	0.208***	0.186***	0.221***	0.215***
	(0.0687)	(0.0655)	(0.0592)	(0.0601)
Initial log population	0.419***	0.452***	0.274***	0.292***
	(0.112)	(0.109)	(0.0978)	(0.0936)
Initial log energy intensity	0.0429	0.0385	0.0412	0.0422
	(0.0514)	(0.0505)	(0.0438)	(0.0436)
Initial coal share	0.129	0.0923	0.270	0.262
	(0.209)	(0.201)	(0.235)	(0.232)
Initial oil share	0.00258	0.0254	0.0736	0.131
	(0.155)	(0.144)	(0.166)	(0.165)
Initial natural gas share	0.166	0.172	0.00864	0.0386
	(0.135)	(0.131)	(0.139)	(0.135)
GDP per capita growth	0.729***	0.707***	0.791***	0.792***
	(0.136)	(0.133)	(0.170)	(0.171)
Population growth	1.146**	1.195**	0.803*	0.827*
	(0.500)	(0.481)	(0.480)	(0.451)
Observations	990	990	330	330
R-squared	0.196	0.196	0.418	0.430
Number of countries	110	110	110	110
Fixed effects	Yes	Yes	Yes	Yes

Clustered robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table A5

Total Emissions growth rate without the EU ETS

Total emissions without EU ETS			
	(1)	(2)	(3)
VARIABLES	1 year	3 year	5 year
Time- period:	1990-2019	1992-2019	1994-2019
Policy	-0.0383***	-0.0309***	-0.0223***
	(0.00758)	(0.00639)	(0.00564)
Carbon price	-0.00116*	-0.00136**	-0.00103*
	(0.000666)	(0.000624)	(0.000528)
Initial log CO_2	-0.131***	-0.101***	-0.136***
	(0.0302)	(0.0146)	(0.0148)
Initial log GDP per capita	0.104***	0.0712***	0.123***
	(0.0377)	(0.0206)	(0.0202)
Initial log population	0.197***	0.151***	0.223***
	(0.0473)	(0.0260)	(0.0290)
Initial log energy intensity	0.00806	-0.0190	0.0203
	(0.0355)	(0.0182)	(0.0179)
Initial coal share	-0.0515	-0.0520	0.0785
	(0.153)	(0.0978)	(0.0927)
Initial oil share	0.108	0.0389	0.134***
	(0.0789)	(0.0704)	(0.0446)
Initial natural gas share	0.0739	0.00809	0.0933**
	(0.0724)	(0.0466)	(0.0407)
GDP per capita growth	0.526***	0.630***	0.536***
	(0.0801)	(0.0912)	(0.0969)
Population growth	1.034***	1.185***	1.125***
	(0.218)	(0.200)	(0.188)
Observations	3,623	1,132	625
R-squared	0.195	0.398	0.505
Number of countries	128	128	128
Fixed effects	Yes	Yes	Yes

Clustered robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table A6

Total Emissions growth rate without EU countries, Iceland and the United Kingdom

Total emissions without EU countries			
	(1)	(2)	(3)
VARIABLES	1 year	3 year	5 year
Time- period:	1990-2019	1992-2019	1994-2019
Policy	-0.0377***	-0.0439***	-0.0298***
	(0.00882)	(0.00877)	(0.00789)
Carbon price	0.000621	0.000728**	0.000411
	(0.000517)	(0.000353)	(0.000272)
Initial log CO_2	-0.137***	-0.104***	-0.140***
	(0.0330)	(0.0155)	(0.0150)
Initial log GDP per capita	0.105**	0.0530**	0.114***
	(0.0432)	(0.0245)	(0.0220)
Initial log population	0.191***	0.127***	0.216***
	(0.0522)	(0.0291)	(0.0312)
Initial log energy intensity	0.0101	-0.0287	0.0155
	(0.0394)	(0.0209)	(0.0198)
Initial coal share	-0.131	-0.105	0.0623
	(0.183)	(0.108)	(0.106)
Initial oil share	0.103	0.0229	0.127**
	(0.0829)	(0.0751)	(0.0485)
Initial natural gas share	0.0732	-0.00350	0.0926**
	(0.0798)	(0.0529)	(0.0454)
GDP per capita growth	0.518***	0.597***	0.494***
	(0.0868)	(0.100)	(0.106)
Population growth	1.233***	1.293***	1.252***
	(0.259)	(0.226)	(0.179)
Observations	2,815	877	486
R-squared	0.203	0.421	0.527
Number of countries	99	99	99
Fixed effects	Yes	Yes	Yes

Clustered robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table A7

Total Emissions growth rate including non-linear GDP

	Total emissions		
	(1)	(2)	(3)
VARIABLES	1 year	3 year	5 year
Time- period:	1990-2019	1992-2019	1994-2019
Policy	-0.0276***	-0.0265***	-0.0195***
	(0.00729)	(0.00693)	(0.00595)
Carbon price	-0.00100**	-0.00155***	-0.00101**
	(0.000447)	(0.000573)	(0.000447)
Initial log CO_2	-0.149***	-0.112***	-0.146***
	(0.0314)	(0.0141)	(0.0138)
Initial log GDP per capita	0.456***	0.288***	0.393***
	(0.125)	(0.0878)	(0.0814)
Initial (log GDP per capita)^2	-0.0192***	-0.0123**	-0.0158***
	(0.00613)	(0.00481)	(0.00449)
Initial log population	0.191***	0.140***	0.201***
	(0.0467)	(0.0262)	(0.0289)
Initial log energy intensity	0.0324	-0.00917	0.0266
	(0.0371)	(0.0176)	(0.0175)
Initial coal share	-0.0970	-0.0849	0.0549
	(0.147)	(0.0935)	(0.0821)
Initial oil share	0.104	0.0376	0.138***
	(0.0773)	(0.0681)	(0.0465)
Initial natural gas share	0.0766	0.00952	0.0951**
	(0.0734)	(0.0475)	(0.0421)
GDP per capita growth	0.502***	0.581***	0.467***
	(0.0765)	(0.0919)	(0.102)
Population growth	1.095***	1.198***	1.161***
	(0.228)	(0.199)	(0.174)
Observations	3,623	1,132	625
R-squared	0.202	0.410	0.529
Number of countries	128	128	128
Fixed effects	Yes	Yes	Yes

Clustered robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table A8

Total emissions growth rate excluding convergence factor

Total emissions growth rate excluding convergence factor			
	(1)	(2)	(3)
VARIABLES	1 year	3 year	5 year
Time- period:	1990-2019	1992-2019	1994-2019
Policy	-0.0359***	-0.0306***	-0.0225***
	(0.00761)	(0.00755)	(0.00694)
Carbon price	-0.00101**	-0.00154***	-0.00110***
	(0.000430)	(0.000532)	(0.000326)
Initial log CO_2			
Initial log GDP per capita	-0.0308	-0.0350*	-0.0147
	(0.0209)	(0.0188)	(0.0192)
Initial log population	0.0213	0.00946	0.0320
	(0.0206)	(0.0210)	(0.0220)
Initial log energy intensity	-0.114***	-0.117***	-0.109***
	(0.0192)	(0.0193)	(0.0196)
Initial coal share	-0.361***	-0.282***	-0.235**
	(0.127)	(0.0919)	(0.101)
Initial oil share	-0.134*	-0.148**	-0.140**
	(0.0705)	(0.0724)	(0.0647)
Initial natural gas share	-0.224***	-0.222***	-0.232***
	(0.0507)	(0.0524)	(0.0783)
GDP per capita growth	0.541***	0.647***	0.591***
	(0.0854)	(0.0944)	(0.114)
Population growth	1.138***	1.240***	1.137***
	(0.266)	(0.245)	(0.205)
Observations	3,623	1,132	625
R-squared	0.202	0.410	0.529
Number of countries	128	128	128
Fixed effects	Yes	Yes	Yes

Clustered robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table A9

Time periods relevance

3-year	**1990 - 2017**	**1990 – 2020**	**1991-2018**	**1992 - 2019**
dummy	-0.0275	-0.0270	-0.0307	-0.0293
Price	-0.00083	-0.00074	-0.00124	-0.00159

Table A10

Time periods relevance

5-year	**1990-2015**	**1990 – 2020**	**1991-2016**	**1992 -2017**	**1993-2018**	**1994-2019**
dummy	-0.0296	-0.0279	-0.0270	-0.0293	-0.0241	-0.02122
Price	.00037 N.S	-.00040 N.S.	-0.00133	-0.00165	-0.00105	-0.01087

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