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UNIVERSITY OF VAASA

Pekka Majanen

Economic incentives for environmentally sustainable growth

Carbon pricing in OECD countries

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UNIVERSITY OF VAASA**School of Accounting and Finance****Author:** Pekka Majanen**Title of the Thesis:** Economic incentives for environmentally sustainable growth: Carbon pricing in OECD countries**Degree:** Master of Science in Economics and Business Administration**Programme:** Master's degree Programme in Economics**Supervisor:** Stephen Onifade**Year:** 2024 **Pages:** 80

ABSTRACT:

The mitigation of greenhouse gas (GHG) emissions has become a common objective of environmental policies in many developed countries. The reason for this is the concern about the increase in the severity of damages caused by climate change which has been demonstrated in recent years. As the bulk of GHG emissions is made up of carbon dioxide (CO₂) emissions, one of the economic tools to incentivize emissions mitigation is called carbon pricing. This policy sets a price for CO₂ emissions which, in turn, encourages companies to abate emissions in an attempt to avoid additional costs.

The two mechanisms which are used for carbon pricing are carbon tax and emissions trading system (ETS). While the mechanisms are different in how the price for emissions is set, they both aim to achieve the same goal of emissions mitigation. However, the actual effectiveness and other effects on the economy have been under scrutiny as no consensus on whether carbon pricing abates emissions and whether it undermines economic growth has not been found. This is because while the literature on the topics is extensive, the results are conflicting. Therefore, this study aims to find consensus by building on the discussion about carbon pricing in regard to the environment and economic growth.

This study empirically analyzes the relationship between carbon pricing and CO₂ emissions, and carbon pricing and economic growth in OECD countries between 1997 and 2021. The framework for the analysis is constructed based on the previous literature and is executed by regressing variables in a panel regression with fixed-effects -model. Moreover, the literature overview covers the most recent annual climate report by the OECD which provides evidence that there is a decoupling between GHG emissions and economic growth. Lastly, the empirical analysis concludes with a brief causality analysis.

The results support the claim that with current carbon prices and carbon price coverage, neither the carbon tax nor ETS are sufficient enough to significantly abate aggregate emissions. However, the study also finds that carbon pricing does not undermine economic growth. Moreover, the results provide evidence that implementing a carbon price via an ETS might even enhance economic growth. Therefore, the findings of this study suggest that the emissions-weighted carbon prices should be higher, either by increasing the price rate or decreasing the amount of price exemptions, to achieve aggregate CO₂ emissions abatements. In addition, the more favorable carbon pricing mechanism seems to be implementing an ETS instead of carbon taxation.

KEYWORDS: Greenhouse gas emissions, Carbon dioxide emissions, Carbon pricing, Carbon tax, ETS, OECD, Emissions-weighted carbon price, Economic growth

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TIIVISTELMÄ:

Kasvihuonekaasupäästöjen vähentämisen tarve on noussut useiden kehittyneiden maiden yhteiseksi ympäristöpolitiikan tavoitteeksi. Syynä tähän on ilmastonmuutoksesta johtuneet vakavat tuhot, jotka ovat korostuneet etenkin viime vuosina. Koska suurin osa kasvihuonekaasupäästöistä on hiilidioksidipäästöjä (CO₂), eräs taloudellinen kannustin CO₂-päästöjen vähentämiseksi on hiilihinnoittelu. Tämä kannustin asettaa hinnan CO₂-päästöille, mikä kannustaa yrityksiä päästövähennyksiin kustannusleikkausten toivossa.

Hiilihinnoittelua voidaan tehdä pääasiassa kahden eri mekanismin kautta: hiiliverotuksen ja päästökaupan. Vaikka keinot määrittävät hinnan CO₂-päästöille eri tavoin, molemmat niistä pyrkivät päästöjen vähennykseen. Hiilihinnoittelun todellinen vaikuttavuus päästövähennyksiin sekä talouden muihin osa-alueisiin on kuitenkin ollut kritiikin kohteena, sillä aikaisemmat tutkimukset eivät ole päässeet yksimielisyyteen siitä vähentääkö hiilihinnoittelu CO₂-päästöjä ja onko sillä haittavaikutuksia talouskasvuun. Tämä yksimielisyyden puute johtuu siitä, että aihetta on tutkittu laajasti, mutta tulokset ovat ristiriitaisia. Tästä syystä tämä tutkimus pyrkii löytämään yksimielisyyden jatkamalla keskustelua hiilihinnoittelun vaikutuksista ympäristöön ja talouteen.

Tämä tutkimus analysoi empiirisesti hiilihinnoittelun ja CO₂-päästöjen sekä hiilihinnoittelun ja talouskasvun keskinäisiä suhteita OECD-maissa vuosien 1997 ja 2021 välillä. Analyysin viitekehys rakentuu perustuen aikaisempaan kirjallisuuteen ja toteutetaan vakiovaikutteisella paneeliregressiomallilla. Aikaisemmassa kirjallisuudessa huomioidaan myös viimeisin OECD:n vuosittainen ilmastoraportti, joka tarjoaa todisteita päästöjen ja taloudellisen kasvun erkaantumisesta. Empiiristä regressioanalyysia tuetaan laatimalla kausaalinen analyysi.

Tutkimuksen tulokset puoltavat väitettä, jonka mukaan hiiliveron sekä päästökaupan asettamat hiilihinnat ja niiden kattavuus eivät vähennä merkittävästi kokonaispäästöjä OECD maissa tutkimusperiodin aikana. Tulokset myös osoittavat, etteivät hiilihinnat kuitenkaan heikennä taloudellista kasvua. Tutkimus löysi todisteita siitä, että päästökaupalla asetetulla hiilihinnalla voi jopa olla positiivinen vaikutus talouskasvuun. Näin ollen tutkimuslöydökset osoittavat, että hiilihinnoitusten tulisi olla korkeampia tai tiettyjen toimialojen hiilihinnoitteluvapauksia tulisi vähentää merkitsevien päästövähennyksien saavuttamiseksi. Hiilihinnoittelumekanismeista päästökauppa näyttäytyy hiiliveroa parempana vaihtoehtona tutkimustulosten mukaan, sillä päästökaupalla saattaa olla jopa talouskasvua edistäviä vaikutuksia.

Avainsanat: Kasvihuonekaasupäästöt, Hiilidioksidipäästöt, Hiilihinnoittelu, Hiilivero, Päästökauppa, OECD, Talouskasvu

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Abbreviations

CAPMF	Climate Action Policies Measurement Framework
CO ₂	Carbon dioxide
COP	Conference of Parties
ETR	Environmental tax reform
ETS	Emission trading system
EU	European Union
FDI	Foreign direct investment
GCB	Global Carbon Budget
GCP	Global Carbon Project
GDP	Gross domestic product
GHG	Greenhouse gas
GNI	Gross national income
HPJ	Half-panel jackknife
ICAP	International Carbon Action Partnership
IEA	International Energy Agency
IPAC	International Programme for Action on Climate
NDC	Nationally determined contribution
OECD	Organization for Economic Co-operation and Development
OLS	Ordinary least squares
PHH	Pollution haven hypothesis
RD&D	Research development and demonstration

RGGI	Regional Greenhouse Gas Initiative
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention for Climate Change
VIF	Variance inflation factor

1 Introduction

The increase of greenhouse gases (GHG) in the atmosphere since the mid-1700s is caused by human activities (IPCC, 2023, p. 42). Guy Callendar (1938) first connected this increase to the rising global temperatures as he examined carbon dioxide (CO₂) data and its radiation absorption and compared this to the historical temperature data. Now, with more sophisticated measuring methods, it is stated that “It is undeniable that human activities have produced the atmospheric gases that trap Sun’s energy in the Earth system.” (NASA, n.d.) and that “This extra energy has warmed the atmosphere, ocean, and land, and widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere have occurred.” (NASA, n.d.).

During the 1990s, European countries, such as the Nordic countries, the United Kingdom, and the Netherlands, began to introduce early environmental policies for GHG emissions mitigation (Hoerner & Bosquet, 2001, p. 11–26). These policies revolve around environmental taxation, and thus, the transition for utilization of these taxes is called Environmental Tax Reform (ETR). In addition, in 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was founded which began the era of negotiations for intergovernmental climate change solutions (UNFCCC, n.d. a). The direct result of this was the Kyoto Protocol which was established in 1997 (UNFCCC, n.d. b).

In 2015, 196 countries signed the Paris Agreement, the successor of the Kyoto Protocol, in which participating countries agreed to limit the acceleration of global warming to 1.5 degrees Celsius by 2030 (UNFCCC, n.d. c). This was done because the effects of increasing global average temperatures have resulted in severe outcomes in terms of weather conditions which, in turn, leads to increased humanitarian crises (International Institute for Environment and Development, 2021). Most of the responsibility for emissions reduction is allocated to national governments through commitments called Nationally determined contributions (NDCs) (UNFCCC, n.d. d). The reason for this is that the UN recognizes the different economic states that the country parties are in, and thus, the

countries are not expected to reduce emissions at the same pace. Therefore, the task of choosing the right environmental policies plays a key role in national governments.

The motivation for this thesis originates from the need to abate carbon emissions and achieve economic growth simultaneously. This combination requires cost-effective environmental policies that incentivize emissions mitigation, energy transition, and energy efficiency improvements. By analyzing the country-specific data and policies that are currently implemented in the OECD, the aim is to examine the environmental and economic state of these countries, extend the literature on the effects of carbon pricing, and provide data-driven decision-making strategies for countries deciding on their environmental policies. Furthermore, the previous literature on carbon pricing has produced conflicting results, therefore beyond extending the literature, this thesis is a contribution to the effort being made to reconcile pertinent contrasting views on the topic.

Given this background and considering that carbon pricing is the main driver of the thesis's investigation, some of the inherent questions that this research addresses are quite important. Firstly, an enquiry is made on whether carbon pricing has reduced emissions in OECD countries. Peradventure, if it has, what is the magnitude of these possible abatements? In addition, the research examines whether this market-based climate policy has had any relevant impacts on income growth in the OECD bloc. To tackle these questions, regression models are built to isolate the performance and effect of the examined economic incentive. The regression models utilized in the study are panel regressions with fixed-effects which account for differences across years and countries. Furthermore, the regression analysis is supported by causal analysis which is conducted with Juodis, Karavias and Sarafidis (JKS) (2021) Granger non-causality test and pairwise Granger non-causality test.

The study continues as follows: chapter two presents the definition and overview of carbon pricing mechanics in OECD countries, chapter three builds a framework for the regression models based on previous literature, in chapter four, empirical analysis is

conducted, and in chapter five the results of the empirical analysis are discussed. The causality analysis is explained, conducted, and discussed in chapter six. Finally, the findings of the paper are presented in the conclusion chapter.

2 Carbon Pricing in OECD

The Organization for Economic Co-operation and Development (OECD) is an international organization that aims to shape policies and standards to tackle crucial problems regarding social, economic, and environmental well-being (OECD, n.d. a). As of now in 2024, the organization has 38 member countries. These are mostly high-income countries, but according to the World Bank (n.d. a) and their current classification for the 2024 fiscal year, four out of the 38 countries are considered upper-middle-income countries. The gross national income (GNI) per capita of 13846 US dollars is the current lower-bound for a high-income country in World Bank's (n.d. a) classification. Every continental region is represented in OECD member countries (excluding Antarctica) with Europe being the most represented with 26 countries (excluding Türkiye) of which 22 also belong to the European Union (EU).

Currently in 2024, there are two subgroups of carbon pricing mechanics. These are carbon tax and emission trading system (ETS). The latter is further divided into cap-and-trade systems and baseline-and-credit systems (OECD, n.d. b). Both mechanisms aim to reduce carbon emissions by putting a price on emissions, but they work in a slightly different way. In this section, both mechanisms are explained and an overview of their utilization in OECD countries is presented.

2.1 Carbon taxes: historical synopsis and theoretical foundation

A carbon tax is a tax rate set to charge a fee for producing CO₂ emissions. The actual tax rate, which is set by a national government, generally targets the carbon content of a certain product. The most common instance of a carbon tax is to tax the amount of carbon in fossil fuels (World Bank, n.d. b). Thus, the target of the tax is precisely on the emission that is released in the form of carbon dioxide from fossil fuel combustion.

The theoretical basis for corrective taxes can be traced to Arthur Pigou's (1920) book *The Economics of Welfare*. The book presents the concept of internalizing externalities by

taxing negative externalities and subsidizing positive externalities. Greenhouse gas emissions, and therefore CO₂ emissions, are considered as a negative externality because they inflict costs to third parties not involved in the process of producing said emissions. Thus, according to Pigou's theory on externalities, CO₂ emissions should be taxed. A tax, that is set to internalize an externality, is called a Pigouvian tax. Furthermore, Cadoret, Galli, and Padovano (2020) found empirical evidence on EU-28 countries that environmental taxes, of which carbon tax is a part, support the Pigouvian tax hypothesis.

There are currently 21 OECD countries that have implemented a carbon tax on a national level (World Bank, 2023a). To add to this, alongside their national carbon tax, Canada and Mexico have also introduced subnational carbon tax rates. According to World Bank's (2023a) Carbon Pricing Dashboard, the first OECD countries to adopt a carbon tax were Finland, Denmark, Sweden, Norway, and Poland, though Poland's nominal carbon tax rate, at the time of its implementation, was relatively low. In 2023, the nominal carbon tax rates vary significantly across OECD countries. As seen from Figure 1 Switzerland has the highest nominal carbon tax rate among OECD countries as it just surpasses Sweden at 130.81 US dollars per ton of CO₂ emissions (World Bank, 2023a).

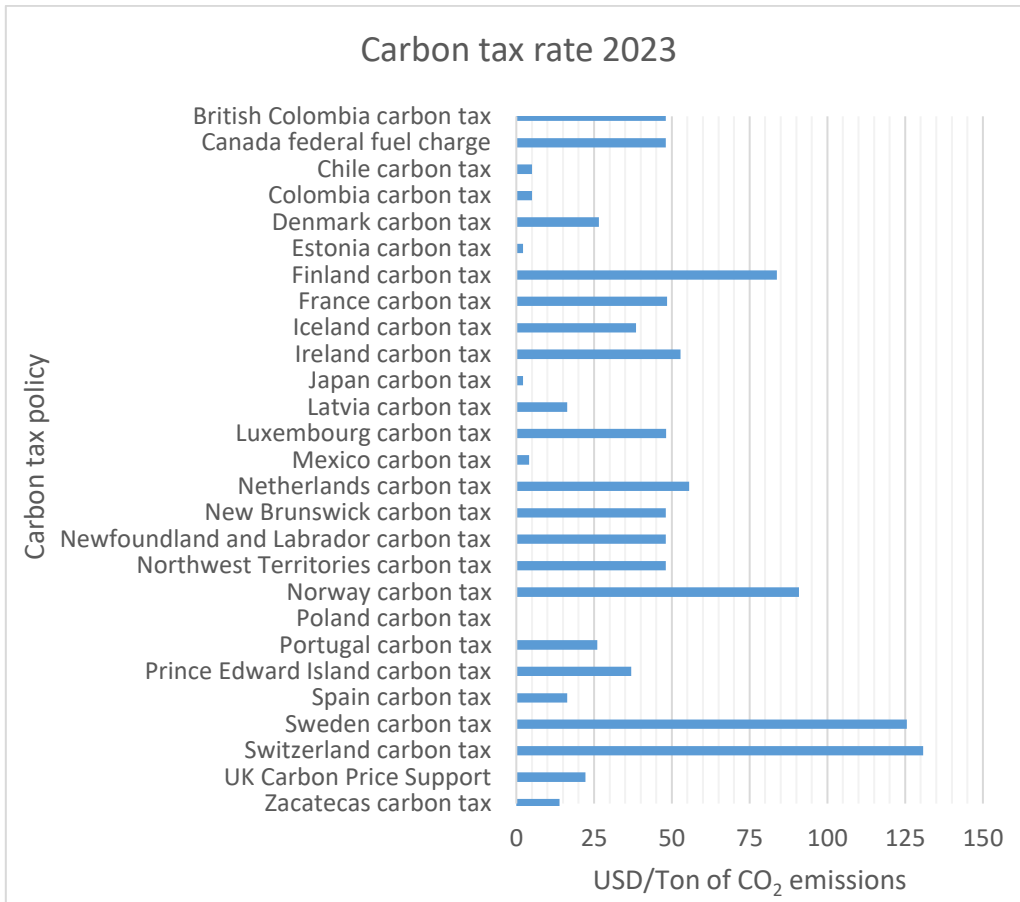


Figure 1. National and subnational carbon tax rates in OECD 2023 (World Bank, 2023a. Author's visualization)

2.2 Emission trading systems

Both types of emission trading systems work similarly as both cap-and-trade and base-line-and-credit systems create carbon markets where emission allowances or carbon credits are traded (UNDP, 2022). In these markets, companies and individuals are either mandatorily or voluntarily purchasing carbon credits to compensate for their emissions. Therefore, the buyers in these markets are emitters, and the sellers are entities that abate emissions. Moreover, the goal of these markets is to reduce emissions economically and efficiently. This is because, if working correctly, the emission abatements should occur in sectors where it is least costly to achieve them, and from these sectors, the carbon credits are sold to sectors where emission reductions are more costly (OECD, n.d. b). In the next subsection, the two types of ETS are presented in more detail.

The theoretical basis for ETSs can be viewed as a mixture of arguments provided by Pigou and Ronald Coase. Pigou is credited mainly for suggesting a corrective tax to internalize externalities, but the tax and the tax rate are levied by a government, suggesting a government intervention in the markets. Ronald Coase (1960) argued against Pigou's view by suggesting that with appropriately defined property rights and no transaction costs, economic entities will come to the overall most efficient outcome, in terms of externalities, by negotiating. Therefore, emission trading systems are a mix of both Pigou's and Coase's arguments since ETS is set and regulated by a central government, and thus is a government intervention. Then companies, which are included in the ETS, can "negotiate" by trading emission allowances with one another, which, in turn, supports the Coase Theorem. The framework of ETS is built on more research than just Pigou's and Coase's, but these can be seen as two of the most influential researchers in terms of tackling the problem of externalities.

2.2.1 Cap-and-trade and baseline-and-credit

In cap-and-trade systems, the governing entity sets an upper limit on emissions that the participating entities cannot exceed (OECD, n.d. b). In addition, emission allowances are either auctioned or distributed among the participants which can be used for trading with other participants in the system and within the set limit. In turn, baseline-and-credit systems set a baseline for the emissions, and if a participant emits less than the baseline amount, the participant is granted carbon credits (OECD, n.d. b). Now the participant can trade these credits in carbon markets to participants who want to emit more than the set baseline. Both systems stem from the objective of emission mitigation, and they act fairly similarly. The difference lies in the means of how these emission-reducing systems are enforced and operated. Cap-and-trade is more utilized as a national ETS in OECD countries as all of the national emission trading systems are in fact cap-and-trade systems (ICAP, 2023).

In 2024, the only OECD countries that have not implemented any kind of emission trading systems, either national or regional, are Australia, Chile, Colombia, Costa Rica, Israel, and Türkiye (ICAP, 2023). Australia has passed a legislation in March of 2023 to reform the country's Safeguard Mechanism, which would create an ETS for Australia (World Bank, 2023b, p. 59). In addition, Chile, Colombia, and Türkiye have reportedly emission trading systems under development or under consideration (ICAP, 2023). The most broadly utilized ETS is the EU ETS, which was adopted in 2005 making it the world's oldest emission trading system (European Commission, n.d. a). Along with the EU countries, the system operates in two other OECD countries: Iceland and Norway. According to the International Carbon Action Partnership (ICAP) (2023), the only country in the OECD that has only subnational ETSs is the United States. The country has several state-level ETSs, but these do not cover most of the states. In the EU, Germany and Austria have implemented national ETSs to accompany the EU ETS (ICAP, 2023).

2.3 Comparison

As seen in Figure 2, emission trading systems are more broadly implemented than a carbon tax. Furthermore, the only OECD countries that have implemented a carbon tax, but have not implemented any ETSs, are Chile and Colombia. Thus, it is observed that emission trading systems are viewed as a more favorable option between the two carbon pricing mechanisms by OECD countries' governments. The reason for this lies in either the political resistance to carbon taxation or in the differences between the two mechanisms.

Hsu (2012, p. 117–146) discussed the counterarguments that the implementation of a carbon tax faces, and it states the political resistance stems from concerns of both the voters and the policymakers. Based on a number of previous studies, Carattini et al. (2018, p. 2–4) presented these concerns in five stylized facts which argue that voters perceive the personal costs of a carbon tax to be too high and that it would affect people with low income the most. On top of that, voters and policymakers are concerned about the effectiveness of carbon taxation in incentivizing low-carbon activities, and the effect

that it would have on economic growth. Lastly, voters are suspicious of the government's intentions to collect revenues from its citizens. There is evidence of abandonment of carbon tax policies even in the later stages of decision-making processes across the OECD. This includes the renouncing of carbon tax policies in Australia (2014), France (2000), Switzerland (2000 and 2015), and the state of Washington (2016) in the United States (Carattini et al., 2018, p. 2). Of these countries, Australia and the United States at the federal level, have not implemented any carbon tax policies to this day (World Bank, 2023a).

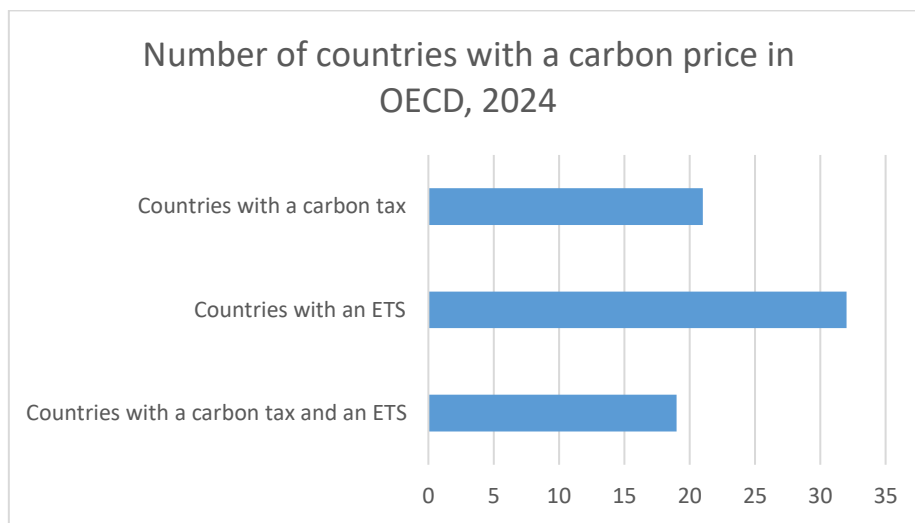


Figure 2. Carbon pricing mechanics in OECD in 2023 (World Bank, 2023a. Author's visualization)

Both carbon pricing mechanisms present similarities and differences. Similarities revolve around the motivation, efficiency, compliance obligation, and supervision of compliance (Center for Climate and Energy Solutions, 2009). The motivation for carbon pricing in general is to levy an additional cost to incentivize emission mitigation, and thus correct a market failure. The incentive derives from the competition in industries, as companies try to reduce costs in an attempt to create higher profits. Therefore, emissions are abated there, where it is least expensive to do so. Both carbon tax and ETS are set by a governing entity which requires compliance, which, in turn, requires reporting and monitoring of the climate actions taken by obligated entities.

However, the differences in current carbon pricing mechanisms narrow down to the revenue-generating nature of taxation, compliance flexibility, and known costs versus known emission levels (Taschini et al., 2014). In the case of carbon tax, the governing entity, most often a national government, can raise revenue with a carbon tax. In emission trading systems, however, the carbon allowances or credits are often “grandfathered”, which means that the emission permits are handed out to the entities taking part in the ETS, rather than auctioned. Handing out carbon allowances results in forgone revenue for the government, but, in turn, it leads to cheaper compliance for the industry. This is because companies have to pay extra only if they do not meet the set emission cap (Taschini et al., 2014).

According to Taschini et al. (2014), one of the key differences between carbon tax and ETS is the uncertainty about the costs and environmental damage. With a carbon tax, the costs for compliance are known since economic entities are obligated to pay the set tax rate under any circumstances whereas in ETS, if the emission permits are “grandfathered”, the costs to entities occur only when the emissions exceed the set cap. In contrast, in ETSs, the level of emissions is known as the emissions cap, which is set, whereas, with carbon tax, the level of emissions is unknown. Thus, in this context, the decision between the two mechanisms is dependent on the sensitivity of environmental damage to changes in emissions, and the sensitivity of companies’ costs of reducing pollution to changes in emissions (Taschini et al., 2014). It has to be noted, that in the long term, the rate of a carbon tax is also unknown, which can affect companies’ investment decisions (Haite, 2018, p. 963).

3 Literature review

By examining previous literature on carbon pricing, the framework for this thesis' empirical analysis is built. Since this paper presents two models in the empirical analysis section, the literature regarding the environmentally sustainable and economically sustainable models is examined. In addition, to understand the current state of OECD countries, the climate report from the International Programme for Action on Climate (IPAC) is also presented. The first part summarizes studies on the effects of carbon pricing on CO₂ emissions, the second part presents studies on how carbon pricing has affected income growth, and the third part concentrates on the IPAC climate report.

3.1 Carbon pricing and CO₂ emissions

The literature on carbon pricing's performance, namely in emissions reduction, is extensive. However, the results are conflicting which suggests that the region, methodology, and the examined time period is an important aspect while studying the effects of carbon pricing. Moreover, this suggests the need for a continuous study of the effects of carbon pricing as an emission-abating climate policy. This section provides an overview of the previous studies on the environmental impact of carbon tax and ETS.

3.1.1 Evidence on environmental effects of carbon tax

Some previous studies have found evidence for the effectiveness of a carbon tax at sub-national and national levels. Lin and Li (2011, p. 5142–5144) found that in Finland, carbon tax had resulted in reductions in per capita CO₂ emissions between 1990–2008. In addition, Andersson (2019, p. 11–20) provided evidence that carbon tax had contributed to a 6 % CO₂ emissions reduction in Sweden after its introduction in the early 1990s. Furthermore, Hájek et al. (2019, p. 6–7) argued that a slight increase in carbon tax rate could result in an 11.58 kg reduction in GHG emissions per capita. In the case of France, Dussaux (2020, p. 44–46) estimated that between 2014 and 2018 carbon tax had abated emissions between 1 % and 5 %. Rivers and Schaufele (2015, p. 29–33) found that over

2.4 million tons of CO₂ emissions reductions were the result of carbon taxation in British Columbia. Metclaf (2019, p. 428–432) validated this by estimating that carbon tax did, in fact, lead to at least a 5 % emissions reduction in British Columbia.

However, regarding the contradicting results, while Lin and Li (2011, p. 5142–5144) found that Finland had reduced its per capita CO₂ emissions with carbon tax, they also found that other countries in the study, namely Denmark, Sweden and Netherlands had abated emissions, but the results were statistically insignificant. In the case of Norway, the emission levels even rose (Lin & Li, 2011, p. 5142–5144). Similarly, Shmelev and Speck (2018, p. 975–978) found that carbon tax alone only reduced CO₂ emissions resulting from petrol consumption in Sweden from 1960 to 2010. However, they also found that in combination with other energy taxes, carbon taxation produces significant abatements for emissions produced by other energy sources as well. In the case of British Columbia, Pretis (2020, p. 125–128) declared that the previous findings by Metclaf (2019) were inaccurate as the aggregate emissions had not abated because of the introduction of a carbon tax. According to him, the only reductions in emissions caused by the carbon tax were in the transportation sector.

3.1.2 Evidence on the environmental effects of ETS

Compared to the literature on carbon taxes, the literature on ETSs is more comprehensive. However, similarly to carbon taxes, the existing literature on the implementation of ETSs has provided contradictory results in terms of emissions abatements across regions (Green, 2021, p. 6–9). While studying the EU ETS in phase 1 (2005–2007) and phase 2 (2008–2012), Gloaguen and Alberola (2013, p. 19–29) found that the carbon price set by said emission trading system did not have a significant effect in reducing CO₂ emissions in the sectors covered by the EU ETS. Rather, economic downturn, increased usage of renewable energy, and price substitution effects of fossil fuels were the main drivers of emissions reductions during the time period. Contradictory to this, Bayer and Aklin (2020, p. 8806–8809) found that the introduction of the EU ETS has abated carbon emissions

between 8.1 % and 11.5 % from 2008 to 2016 in comparison to a counterfactual situation where ETS was not implemented.

The finding by Gloaguen and Alberola (2013, p. 19–29) on the effect of an economic downturn on emissions development seems plausible. This is because it was observed that the economic crisis caused by the Covid-19 pandemic led to a global greenhouse gas emissions reduction in 2020 (IEA, 2022, p. 3). The abatement was soon followed by a rebound effect in which the global GHG emissions rose to a record-high level in 2021. Thus, there might be a correlation between economic crises and emissions reduction.

Wagner and Petrick (2014), and Wagner et al. (2014) studied the effects of the EU ETS in specific countries, specifically in Germany and France from 2005 to 2010. Petrick and Wagner (2014, p. 16–34) examined how the EU ETS affected the CO₂ emissions of manufacturing firms in Germany. They found that the emissions trading system led to firms optimizing their energy usage by improving efficiency in utilized technologies which abated emissions around 20 % more than firms that were not part of the EU ETS. Wagner et al. (2014, p. 9–12) found similar evidence from France as manufacturing firms, which are part of the EU ETS, reduced emissions 10 % more in phase 2 than unregulated firms.

Also, in the case of Tokyo, the results are mixed. Abe and Arimura (2019) studied the effectiveness of ETS on emissions, and electricity and energy consumption in regulated universities in Tokyo. This was chosen because universities were seen as least affected by the Fukushima disaster. They found that CO₂ emissions in regulated universities decreased by 3.6 % from 2009 to 2013 (Abe & Akimura, 2019, p. 110–113). To challenge this finding, Wakabayashi and Kimura (2018, p. 1031–1040) provided evidence that the ETS was not the main driver of emissions reduction in Tokyo, but rather the abatements should be attributed to the energy savings resulting from the aftermath of the Fukushima disaster and other energy conservation efforts. Nevertheless, based on these findings, Nguyen et al. (2019, p. 4–9) suggest that a well-constructed nation-wide ETS could reduce carbon emissions in Japan by as much as 42 %.

In the United States, the Regional Greenhouse Gas Initiative (RGGI), an ETS that includes 11 states, has been the scope of several studies since its inception in 2009 (RGGI, 2023). Murray and Maniloff (2015, p. 584–588) studied the data for 48 states from 1990 to 2012 and proved that the emissions in RGGI states would have been higher if the ETS was not introduced. They estimated that RGGI contributed to about half of the CO₂ emissions abatements, and the emissions were 19 % lower in the region. A few years later Chan and Morrow (2019, p. 415–420) further verified this finding while studying emissions abatements, carbon and other pollutants, in RGGI states between 2002 and 2016. They found almost identical results as Murray and Maniloff as the CO₂ emissions were reduced by roughly 20 % more in the RGGI regulated facilities during the examination period.

The literature on carbon pricing has provided conflicting results, and therefore the prediction based on the previous literature for the study conducted in this research is unclear. The reason for the difference in results is mainly due to the fact that the effect of carbon pricing is difficult to isolate from other emission mitigation policies and economic growth (Sumner et al., 2011, p. 936–937). Thus, these, or proxies of these, factors should be included in the model when assessing the effectiveness of carbon pricing in emission mitigation. To account for other variables affecting emission abatements, the studies presented utilize different methodologies which can be the reason behind contradictory results. Therefore, an accurate analysis of the environmental effects of carbon pricing requires econometric models built with robust statistical analysis methods. Furthermore, the results of these models should be carefully assessed when used in policy design decisions.

3.2 Carbon pricing and economic growth

As carbon pricing schemes create additional costs to firms, it is reasonable to assume that it has an impact on economic activity. The key question here is whether it has hindered economic growth in countries that have implemented it compared to countries that have not, or compared to situations in which the carbon pricing mechanism was not

implemented. In addition, the magnitude of possibly forgone economic growth is of interest in this research. This section reviews previous literature on the relationship between carbon pricing and economic growth.

Ko and Lee (2021, p. 662–668) studied the decoupling of greenhouse gas emissions and economic growth in 29 European countries from 1996 to 2014. They found that countries with an ETS are more likely to exhibit decoupling between economic growth and emissions when emissions intensity, which is GDP divided by aggregate emissions, is used as an indicator of the decoupling. Carbon taxes, however, did not support the decoupling which suggests that it might have adverse effects on economic growth. Furthermore, Ko and Lee (2021, p. 668) note that the decoupling across countries varies depending on unobserved socioeconomic conditions, economic structure, and energy efficiency.

Dechezleprêtre et al. (2018, p. 34–51) examined company-level data to assess whether the EU ETS had a negative effect on regulated firms' economic performance. From 2005 to 2012, it was observed that the EU ETS-regulated firms, contradictory to the expectations, outperformed the non-regulated companies by providing higher revenues and fixed assets. The increase in fixed assets was explained by companies investing in efficient and clean technologies to mitigate the costs of the carbon price. Moreover, there was no evidence of negative economic effects for regulated firms in comparison to non-regulated companies. This was found to be true for the across countries and across sectors analyses (Dechezleprêtre et al., 2018, p. 48–51).

Driscoll (2020, p. 2) examined the GDP of OECD countries between 1979 and 2018 and found that countries continued their economic growth after the introduction of carbon pricing. He found no significant relationship between carbon pricing and GDP, but the regression results are not included in the article. The most important part of the article is that Driscoll (2020, p. 2) presents two reasons for why carbon pricing does not affect economic growth. He argues that because of the tax exemptions of large, energy-

intensive companies, the largest emitters do not pay enough for their carbon dioxide emissions. Furthermore, Driscoll (2020, p. 2) claims that the nature of economic growth is misunderstood in the context of carbon pricing and that its complexity is often undermined by politicians advocating against carbon pricing.

While studying the economic impacts of environmental taxation in EU and OECD countries between 1995 and 2006, Abdoullah and Morley (2014, 28–32) found that environmental taxes might hinder growth in the short term, but in the long term, the level of environmental taxes does not have any effect on GDP. As environmental taxes include carbon taxes, the finding might suggest that carbon taxes do not have any significant effect on economic growth in the long term. Socci et al. (2023) add that carbon taxes could even enhance economic growth if income taxes are reduced simultaneously, and the revenues collected with the carbon tax are used to compensate for the lost revenue from income tax cuts. This effect is called the environmental double dividend (Pearce, 1991, p. 940).

Hassan et al. (2020, p. 6–13) also studied the effects of environmental taxes and economic growth in OECD countries. They found that between the years of 1994 and 2013, the environmental taxes had no significant effect on economic growth in the short and long term. However, they found that this relationship is dependent on the country's initial GDP per capita level. Moreover, in the study, higher income countries exhibited a positive relationship whereas lower income countries exhibited a negative relationship between environmental tax revenues and GDP in the short and long term. This indicates that high-income countries are more likely to increase economic growth while increasing environmental taxes. Hassan et al. (2020, p. 10–12) suggested that this is because high-income countries' economies are more service-based, and thus rely more on the productivity of human capital rather than physical capital. Also, high-income countries are more likely to be able to afford improvements in technologies, which reduce the adverse effects of environmental taxation. In addition, the paper argues that improvements in environmental quality can increase tourism which is a cornerstone of the service sector.

Lastly, it was found that there are differences in how environmental taxation affects economic growth depending on how the revenue of the tax is utilized (Hassan et al., 2020, p. 12–13).

Contradictory to the previous results, Tchapchet-Tchouto et al. (2022, p. 6–10) found that there is a statistically significant negative relationship between environmental taxes and economic growth in EU countries from 2009 to 2019. This result was driven by low-income countries, which are more adversely affected by environmental taxation than high-income countries. The latter finding supports the results presented by Hassan et al. (2020) and suggests that low-income countries need support from high-income countries in environmental preservation efforts.

Based on the previous literature, we can expect that while carbon taxes might have adverse effects on economic growth it is unlikely that the implementation of ETS will do so. Thus, an ETS could be a more favorable choice between the two carbon pricing mechanisms. Additionally, previous literature suggests that economic structure, energy efficiency, carbon price exemptions, revenue recycling, initial income, and unobserved socioeconomic conditions influence how economic growth is affected by carbon pricing. Therefore, these factors should be included when studying the relationship between carbon pricing and economic growth.

3.3 IPAC Climate Report 2023

IPAC provides regular tracking of the current state of climate in OECD countries, OECD partner countries which include Brazil, China, India, Indonesia, and South Africa, prospective OECD members which include Argentina, Bulgaria, Croatia, Peru, and Romania, other G20 country not included which is Saudi Arabia, and Malta (OECD, n.d. b; OECD, 2023a, p. 9). In addition, they perform policy evaluations and give feedback on implemented policies. This section covers the relevant aspects of the latest annual report by IPAC, titled *The Climate Action Monitor 2023 – Providing Information to Monitor*

Progress Towards Net-zero, to give an overview of the latest developments and the current state of climate and climate policies in the OECD.

3.3.1 Emissions developments

OECD countries, which emit a third of the global emissions, have decreased their emissions in aggregate since 2007 (OECD, 2023a, 17–22). Still, the abatements are not enough to achieve the goal of the Paris Agreement to limit the global average temperature increase to 1.5 Celsius, and OECD countries have, in fact, committed to larger emissions reductions. However, OECD (2023a, p. 21) recognizes even these commitments to greater emissions abatements are not sufficient enough to reach the temperature goal. Moreover, the policies that are implemented to abate emissions may not be adequate to achieve even these commitments. These gaps between the goal and the commitments, and between the commitments and mitigation efforts are called ambition and implementation gaps respectively.

Emissions per capita have decreased in the OECD but increased in OECD partner countries

CO₂ intensity , energy-related CO₂ emissions per capita, tonnes, 1990-2021

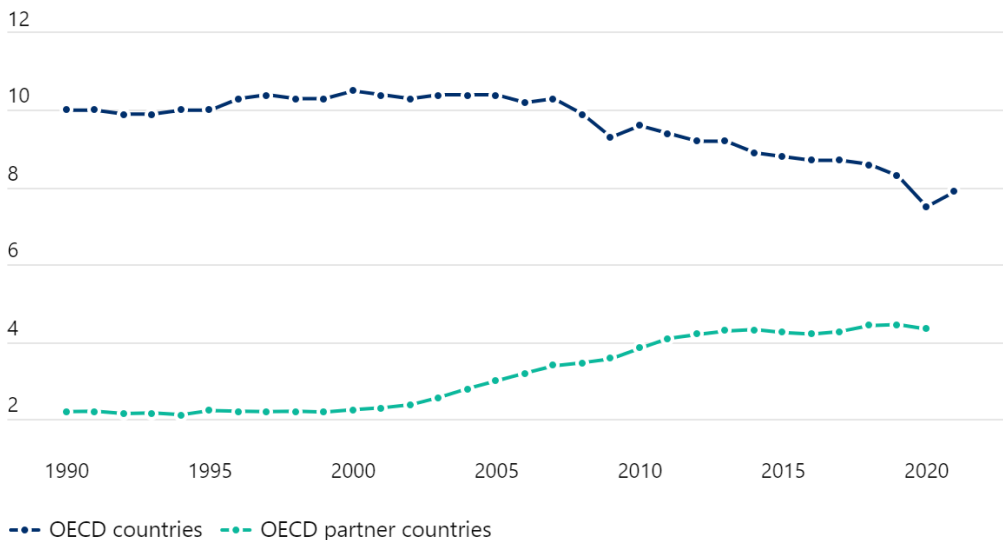


Figure 3. Energy-related CO₂ emissions per capita using data from OECD Environment Statistics (OECD, 2023a, p. 24; OECD, 2023b)

OECD countries have performed relatively well regard to abatements in per capita CO₂ emissions compared to their partner countries (OECD, 2023a, p. 23–24). Energy-related CO₂ emissions per capita have decreased, on average, in OECD countries since 2007 whereas the partner countries have increased their per capita emissions from the early 2000s onwards (Figure 3). However, OECD countries averaged 7.9 tons of energy-related CO₂ emissions per capita to partner countries 4.3 tons (OECD, 2023a, p. 24). In terms of GHG emissions intensity, OECD countries have decreased their emissions per unit of GDP since 1990, and the same can be said, with the exception of spikes in 1995 and 2004, for OECD partner countries (Figure 4). Contradictory to the energy-related CO₂ emissions, OECD countries' average GHG emissions intensity is less than half of what it is in OECD partner countries (OECD, 2023a, p. 25).

Emission intensities of both OECD and OECD partner countries have decreased

Total GHG (including LULUCF) intensity per unit of GDP, kilograms per USD, constant prices PPP, 1990-2020

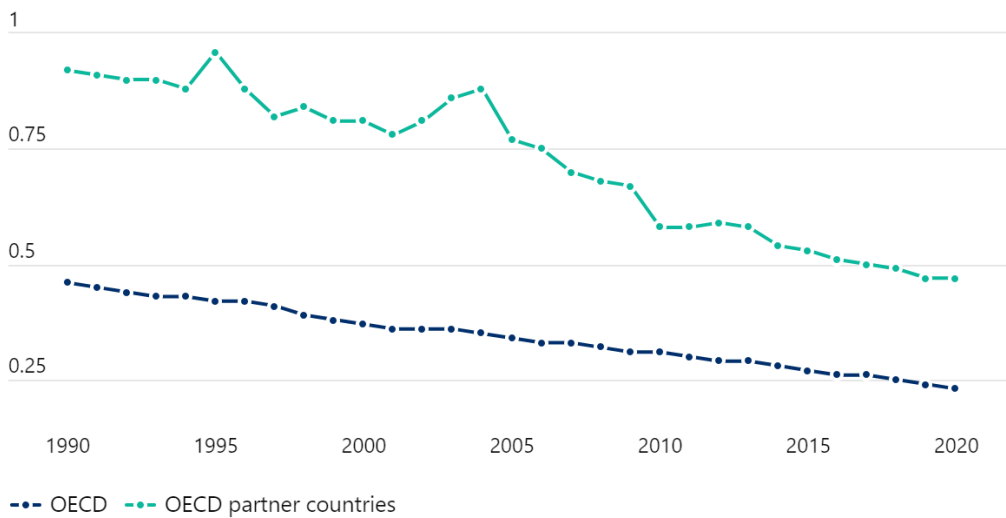


Figure 4. Emission intensities using data from OECD Environment Statistics (OECD, 2023a, p. 25; OECD, 2023b)

According to IPAC, there is evidence of carbon leakage from OECD countries to OECD partner countries (OECD, 2023a, p. 25–26). European Commission (n.d. b) defines carbon leakage as an occurrence of businesses transferring their production from high

carbon price countries to countries with more relaxed environmental policies, which can result in increasing emissions levels globally. This is evident in Figure 5 as OECD countries' production- and demand-based CO₂ emissions have abated from 2007 onwards whereas in OECD partner countries the production- and demand-based emissions have constantly increased (OECD, 2023a, p. 26). This suggests that a part of the carbon emissions previously emitted by OECD countries might be exported to other countries as carbon-intensive products are imported to OECD countries. Moreover, this would partly explain the decrease in GHG emissions intensity in OECD countries. To tackle this issue, carbon-related tariffs are being discussed in the EU (European Commission, n.d. c).

OECD countries export emissions partly to OECD partner countries through imported goods

Production- and demand-based CO₂ emissions, million tonnes

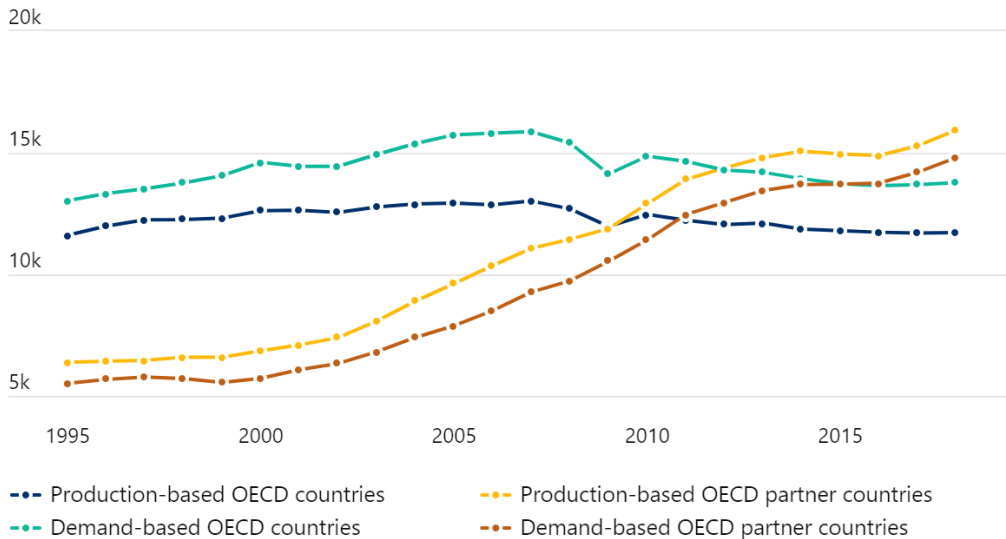


Figure 5. Production- and demand-based CO₂ emissions using data from OECD Environment Statistics and IEA (OECD, 2023a, p. 26; OECD, 2023b; IEA, 2023)

Carbon leakage is a part of a broader phenomenon called the Pollution Haven Hypothesis (PHH). Akbostanci (2007, p. 298) states that PHH expects environmental policies to affect the location decisions of emission-intensive industries, and thus, these industries increase in countries with more lax environmental regulations. This will also lead to a decrease in clean industries in the pollution haven and increase the amount of dirty

exports. Alongside the findings in the IPAC 2023 report, a number of other studies have found evidence for the PHH. Solarin et al. (2017, p. 712–717) provided empirical evidence for the PHH in Ghana as foreign direct investment (FDI) increased the amount of emissions in the country. Sapotka and Bastola (2017, p. 210–211) found similar results in South- and Latin America whereas Zheng and Shi (2016, p. 300–302), while studying the differences between providences in China, provided empirical evidence that the PHH could occur even domestically. They highlight that the PHH depends on the type of policy instrument and the industry features (Zheng & Shi, 2016, p. 301–302).

3.3.2 Emission sources

The most emitting sectors in OECD countries are energy including electricity and heat, transportation, manufacturing and construction, agriculture, and industrial processes (OECD, 2023a, p. 27). Across countries, however, the top emission sources vary significantly. Thus, IPAC recognizes that countries need to take into account their specific emissions structures and implement policies that abate emissions in the key sectors (OECD, 2023a, p. 31). Therefore, the policies should be designed to consider the global emission structure to avoid carbon leakage to or from other countries, and the domestic structure in order to reduce domestic emissions.

On average, the OECD countries' top emissions source is energy consumption either in the form of electricity and heat or other (OECD, 2023a, p. 27). The use of fossil fuels dominates this sector although OECD countries and OECD partner countries have increased the share of renewable sources in energy supply. From 1990 to 2020 OECD countries have reduced the share of fossil fuels in energy supply from 84 % to 78 % (OECD, 2023a, p. 28). Although this does not seem like a lot, compared to the global level it is since globally the share of fossil fuels in the energy supply has stayed at a constant level of around 80 % from 1990 to 2021. Still, considering that the OECD countries are mainly high-income countries, more could be expected from these countries.

In the OECD, GDP growth per capita is decoupled from GHG emissions per capita

1990-2020, OECD countries, index 1990=1

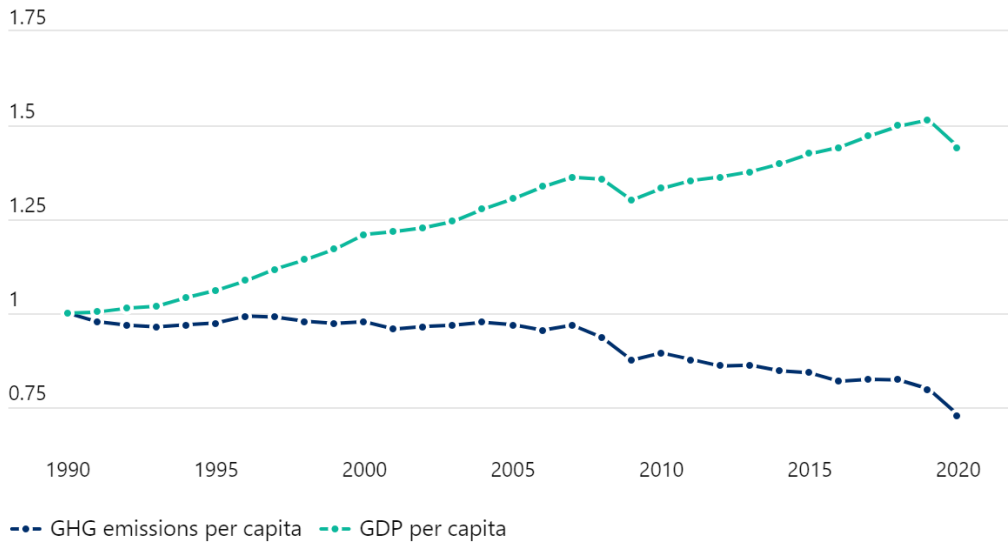


Figure 6. GDP growth and GHG emissions per capita decoupling in OECD countries using data from OECD Environment Statistics (OECD, 2023a, p. 33; OECD, 2023b)

Economic growth is not necessarily the main driver of emissions as evidence of decoupling between GHG emissions and GDP growth is found in OECD countries. From Figure 6 it is observed that between the years 1990 and 2020, the GDP per capita increased by 44 % and GHG emissions per capita decreased by 27 % on average in OECD countries (OECD, 2023a, p. 32). This suggests that economic growth and emissions abatements can be achieved simultaneously. However, emissions-reducing policies could slow down the growth as the OECD partner countries achieved 215 % GDP per capita growth and a 60 % increase in GHG emissions during the same time period (Figure 7). IPAC notes that improvements in energy efficiency are not sufficient alone and countries should invest in energy transition efforts, reduce material consumption, and increase circularity in economies (OECD, 2023a, p. 32). Moreover, if the decoupling of economic growth and carbon emissions in OECD countries is the result of carbon leakage, the level of global emissions offset the mitigation effects made in the OECD countries.

Both GDP and emissions per capita have increased in OECD partner countries but the trends show relative decoupling

1990-2020, OECD partner countries, index 1990=1

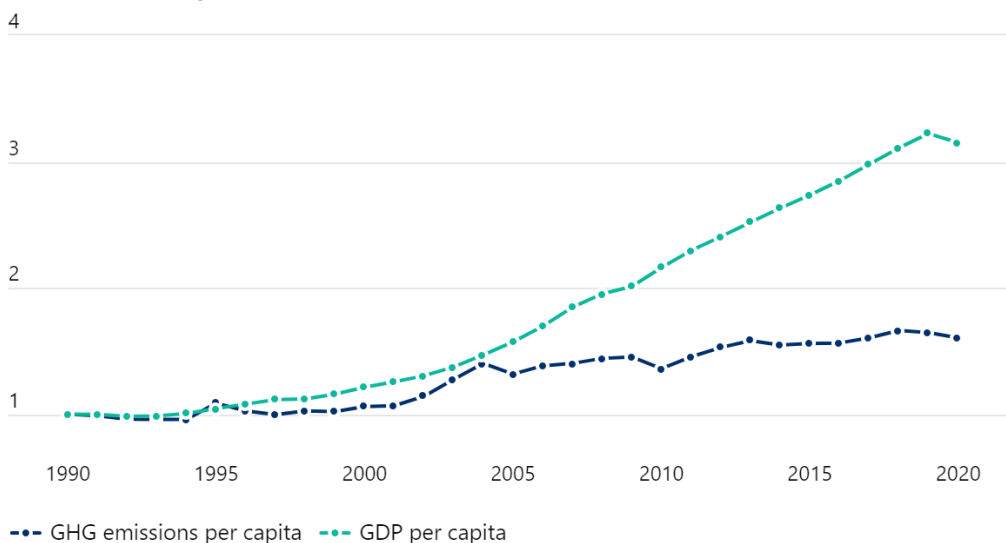


Figure 7. GDP growth and GHG emissions per capita decoupling in OECD partner countries using data from OECD Environment Statistics (OECD, 2023a, p. 34; OECD, 2023b)

3.3.3 Climate policy development

The 2000s have been the millennia of climate policy as, on average, OECD countries have increased their climate action, measured by the Climate Action Policies Measurement Framework (CAPMF), by 10 % annually (OECD, 2023a, p. 56). However, the year 2022 saw this trajectory slowing down, mainly due to geopolitical and macroeconomic shocks. This observation brings up an important aspect of climate policies which is its interconnectivity with other global events. For example, many countries backed out of their climate policy stringency and even increased fossil fuel support as the energy crisis, accelerated by the Russo-Ukrainian War, raised a question on energy security (OECD, 2023a, p. 56–63). However, this concern about energy security could impact the energy transition as renewable energy is often domestically produced.

Austria and Germany presented the most notable carbon pricing change in 2021 as they introduced a domestic ETS to include transportation and building sectors (OECD, 2023a, p. 62). This was because the EU ETS currently does not cover these sectors, although it

is planning to do so in 2026. Moreover, the EU ETS emission permit prices reached a new high in 2021 at 15.5 euros per ton of carbon dioxide (OECD, 2023a, p. 8). However, IPAC notes that even though a lot of countries have implemented carbon pricing, most of the countries placing a price on carbon have set the price level too low to reach the temperature goal of the Paris Agreement (OECD, 2023a, p. 62).

In 2022, fossil fuel subsidies across the globe rose to a new record high (OECD, 2023a, p. 63). Most of this increase can be attributed to the energy crisis, as consumers and companies were protected from the adverse effects of the sudden energy price hike. However, this subsidizing sends an incorrect price signal to energy-consuming agents who should decrease the use of fossil fuels. Energy prices should increase, especially if fossil fuels are utilized, but in this case, the governments did not let the prices rise. This is because if not dealt with, unexpected shocks in energy prices could lead to unexpectedly harsh results. Therefore, the increase in fossil fuel subsidies is understandable, and they are expected to decrease again as the energy prices normalize (OECD, 2023a, p. 63). In the case of other market-based instruments, support for research development and demonstration (RD&D) saw an increase as government expenditure on RD&D grew by 5 % from 2021.

OECD countries also use regulations and standards to ban and/or phase out certain assets and equipment that are deemed to be harmful to the environment (OECD, 2023a, p. 65). The increase of these bans and phase-outs have increased significantly from 2015 onwards, but from 2021 to 2022 the increase was only minimal. This is also because some countries had to cancel their previous commitments to more stringent policies to fight the adverse effects of the energy crisis. These cancellations of commitments included the extraction of more fossil fuels than previously planned in Austria, Germany, and the United Kingdom, postponing the banning of diesel and petrol passenger cars in the EU, and postponing of the phase-out of lignite power plant in Hungary (OECD, 2023a, p. 66). Nonetheless, these policy adaptations have affected the OECD and OECD partner countries in their emission mitigation efforts.

Overall, OECD countries are regarded as the global leaders in emissions mitigation. However, these countries have historically been the largest emitters and they still produce an ample size of global emissions. The development in reducing greenhouse gas emissions has been significant, but recently in the early 2020s, the emissions abatements and climate policy implementations have slowed down. This is mainly due to the current geopolitical conflict and the recent macroeconomic turbulence. Most importantly, there is evidence of decoupling between economic growth and emissions in OECD countries which suggests that economically and environmentally sustainable growth is possible. Nevertheless, the issues regarding the possible carbon leakage should be addressed to achieve abatements in global emissions levels which is the key factor in fighting climate change.

4 Data and methodology

In this section, the data utilized in analyzing the relationship between emissions and carbon pricing and income growth carbon pricing are presented. The examination period in this study is from 1997 to 2021 since for some countries relevant data is missing from before 1997. The original data set includes all 38 OECD countries, but the scope narrows down after dealing with missing data points in section 4.1.1. After introducing the data, sources, and descriptive statistics, the section continues to define the methodology for conducting the study.

4.1 Variables and data sources

The variables of interest for the initial analysis are carbon price which is denoted both in terms of carbon tax rate and ETS carbon price as well as CO₂ emissions. Because carbon tax and the ETS carbon price cover different emission sources in different countries, these variables are applied as emissions-weighted carbon prices. Fortunately, a database covering the emissions-weighted carbon prices has been created by Dolphin and Xiahou (2022), and as of now, the database covers the time period between 1989 and 2022. Weighting the carbon price with emissions makes the data more suitable for cross-country analysis as it accounts for the pricing exemptions for energy-intensive industries to express the real average price rate of carbon emissions instead of the nominal price rate stated by the countries' jurisdictions. The average carbon price across all sectors is then weighted by the aggregate emissions of the economy to distinguish the actual carbon price rate levied in the country. The data on carbon price rates and their weights against aggregate emissions is gathered by investigating the information stated in legislative acts on carbon pricing mechanisms and mapping the sectoral emission data¹ (Dolphin & Xiahou, 2022). The unit of measure for the carbon price rates is constant 2019 US dollars per ton of CO₂ emissions.

¹ Detailed information on the data set is provided in the article by Dolphin and Xiahou (2022).

Aggregate CO₂ emissions data utilized in this study is extracted from the Global Carbon Budget (GCB). The GCB is a report created by the Global Carbon Project (GCP) which provides annual assessments of the sources and sinks of CO₂ and other GHG emissions on a global scale (Global Carbon Budget, n.d.). Thus, among other things, the GCB produces data on territorial CO₂ emissions across countries which are used as the dependent variable for analyzing the carbon price as an emissions-abating policy tool in this study. Other databases, such as the World Bank, provide similar data on emissions but as the GCB reports are presented at the Conference of Parties (COP), the most influential climate decision-making body of the UNFCCC, GCP data is regarded as the most reliable one for this study. To account for differences in countries' populations, the emission data is presented in CO₂ emissions per capita. The population data is extracted from the World Bank's (2023c) World Development Indicators database. Therefore, the final variable is carbon dioxide emissions per capita in thousand tons.

To isolate the precise relationship between CO₂ emissions and carbon price, control variables are included in the regression. Based on the previous literature, economic growth and other environmental policies affect emissions developments, and their effect should be isolated when assessing the environmental effectiveness of carbon pricing. To account for these, GDP and renewable energy consumption are included in the initial model. More specifically, renewable energy consumption is included as a proxy for clean energy initiatives, and it is presented as a percentage of the whole economy's energy consumption. Moreover, GDP is presented in per capita terms to compare countries' income rather than just pure output, and to account for inflation, the unit of measure for GDP per capita is constant 2015 US dollars. The GDP data is extracted from the World Bank's (2023d) World Development Indicators database and the energy and renewable energy consumption data is extracted from the Energy Institute's (2023) Statistical Review of World Energy.

Other control variables included in the first model are energy consumption and industry size. Energy consumption and industry are assumed to be highly correlated with

emission developments as energy use (including electricity production and heating), as well as manufacturing, construction, and industrial processes are the main emissions sources in the OECD. Energy consumption data is extracted from the Energy Institute's (2023) Statistical Review of World Energy and is applied in gigajoules per capita for the analysis in this study. Industry size data is measured as the percentage of value added to the GDP and it is extracted from the World Bank's (2023e) World Development Indicators database.

For analyzing the effect of carbon price on economic growth, the variables of interest are carbon tax rate, ETS price rate, and GDP per capita growth. The data source for the carbon price remains the same as in the initial analysis, and the GDP per capita growth is calculated from the GDP per capita measured as constant 2015 US dollars which is utilized in the initial regression model. Thus, the data remains consistent, and the GDP per capita growth is presented in real terms.

According to the previous literature, the effect that carbon pricing has on economic growth depends on economic structure, energy efficiency, carbon price exemptions, initial income, and unobserved socioeconomic conditions. Consequently, variables, or proxies of these variables, representing these dimensions are incorporated into the regression model as control variables.

Economic structure is included in the model as the size of the industry sector and is measured as a percentage of value added to GDP. Energy intensity serves as an indicator for energy efficiency, measured as gigajoules per 1000 constant 2015 US dollars of GDP produced. Data sources for these variables remain consistent with those used in the initial model. Because of the nature of the emissions-weighted carbon price, the exemptions of carbon pricing are already included in the model. The initial income is measured as a GDP per capita similarly as in the first model and the unobserved socioeconomic factors are included in the panel regression with the fixed-effects. This will be further

explained in the methodology section. All of the variables, their units of measure, and sources are presented in Table 1.

Variable	Unit of measure	Source
Population	Residents	World Development Indicators
CO2	Thousand tons per capita	Global Carbon Budget
Carbon tax	Constant 2019 US dollars per ton of CO2 emissions	World Carbon Pricing Database
ETS	Constant 2019 US dollars per ton of CO2 emissions	World Carbon Pricing Database
Renewable energy	Percentage of total energy consumption	Author's calculation based on The 2023 Statistical Review Of World Energy
GDP	Constant 2015 US dollars per capita	World Development Indicators
Energy consumption	Gigajoules per capita	Author's calculation based on World Development Indicators and The 2023 Statistical Review of World Energy
Industry	Percentage of value added to GDP	World Development Indicators
GDP per capita growth	Percentage	Author's calculation based on World Development Indicators
Energy intensity	Gigajoules per 1000 constant 2015 US dollars of GDP	Author's calculation based on World Development Indicators and The 2023 Statistical Review of World Energy

Table 1. Variable definitions and sources

4.2 Missing values

The data for the outlined variables is, unfortunately, missing for some of the OECD countries during the examination period. Specifically, Costa Rica is missing energy consumption data altogether, and Canada and New Zealand are missing data points on industry sector's percentage of value added to GDP. Canada has missing values of this variable from the years 2020 and 2021, and New Zealand has missing values from the year 2021. Therefore, the scope of countries decreases from the original 38 OECD countries to 35 OECD countries which from now on are regarded as just OECD countries.

4.3 Descriptive statistics

The descriptive statistics of the data variables are presented in Table 2. The data set comprises 875 observations, encompassing data from 35 countries across 25 years. The other statistics present the mean of the data variable, standard deviation, minimum and maximum values, skewness, and kurtosis. From these statistics it is observed that there is high variation between the variables across countries and years and that for variables, excluding industry size and income growth, the distribution is skewed to the right, indicating that more data variables across countries and years have values above the mean. Moreover, other variables besides the industry size display a leptokurtic distribution. This means that both tails of the distribution are thicker than in a normal distribution. Understanding the differences across countries and years in the context of these variables explains the data variable distribution distortions as the countries included in the data set have different political and economic landscapes and developments during the examination period.

Variable	Obs.	Mean	Std. Dev.	Min	Max	Skewness	Kurtosis
Population	875	35323881.1	56572851.7	271128	332031554	3.291437	15.58326
CO2	875	8.538364	4.215631	1.310241	25.98652	1.178427	4.843407
Carbon tax	875	4.667086	12.17673	0	72.85665	3.406603	15.17813
ETS	875	3.690054	5.730006	0	38.77945	2.169258	8.997191
Renewable energy	875	15.4203	17.60513	0.025893	87.6173	2.040957	7.207221
GDP	875	33568.93	22340.33	3953.73	112417.9	1.035686	4.055103
Energy consumption	875	173.5739	103.0733	28.2041	678.3005	1.956576	8.589245
Industry	875	25.28178	5.456254	10.42672	40.81159	-0.022141	2.76062
GDP per capita growt	875	2.059309	3.581973	-14.4643	23.20087	-0.245549	7.049681
Energy intensity	875	6.297902	2.947601	1.414652	19.24339	1.210596	4.650638

Table 2. Descriptive statistics

4.4 Methodology

This section discusses the regression models utilized in the study and checks for multicollinearity and unit roots in the data set. These steps help ensure the reliability of our model and the accuracy of the estimation results for the effects of carbon pricing on emissions and economic growth.

4.4.1 Model specifications

The assumption for the data set is that country and year-specific data is affected by unobserved factors such as cultural differences and time trends. Therefore, the methodology utilized in this study is a panel regression with fixed-effects. This is done to take into account the differences across countries and years (Stock & Watson, 2020, p. 372–374). Moreover, robust standard errors are used to account for possible serial correlation and heteroskedasticity in the data. The models for estimating the effect of carbon price on emission abatements and on income growth are presented in equations (1), (2), (3), and (4) respectively.

$$CO2_{i,t} = \beta_0 + \beta_1 Carbon\ tax_{i,t} + \beta_2 Renewable\ energy_{i,t} + \beta_3 GDP_{i,t} + \beta_4 Energy\ Consumption_{i,t} + \beta_4 Industry_{i,t} + u_{i,t} + e_{i,t} \quad (1)$$

$$CO2_{i,t} = \beta_0 + \beta_1 ETS_{i,t} + \beta_2 Renewable\ energy_{i,t} + \beta_3 GDP_{i,t} + \beta_4 Energy\ Consumption_{i,t} + \beta_4 Industry_{i,t} + u_{i,t} + e_{i,t} \quad (2)$$

$$GDP\ per\ capita\ growth_{i,t} = \beta_0 + \beta_1 Carbon\ tax_{i,t} + \beta_2 Energy\ intensity_{i,t} + \beta_3 GDP_{i,t} + \beta_4 Industry_{i,t} + u_{i,t} + e_{i,t} \quad (3)$$

(4)

$$\begin{aligned} \text{GDP per capita growth}_{i,t} = & \beta_0 + \beta_1 \text{ETS}_{i,t} + \beta_2 \text{Energy intensity}_{i,t} \\ & + \beta_3 \text{GDP}_{i,t} + \beta_4 \text{Industry}_{i,t} + u_{i,t} + e_{i,t} \end{aligned}$$

In these equations, the subindices denote variables across countries (i) and across years (t). Moreover, the term β_0 stands for the regression line intercept and the term $u_{i,t}$ captures the fixed-effects and the term $e_{i,t}$ is the error term.

4.4.2 Estimation techniques

The estimation method for the variable coefficients is the Ordinary least squares (OLS) method. The OLS estimation technique provides estimations of the actual relationship between the dependent and independent variables by minimizing the difference of the observed data and the estimated data. The difference is measured by the sum of squared differences between the observed and the predicted values of the dependent variable (Stock & Watson, 2020, p. 148–149). By doing this, the OLS selects the estimators, also known as OLS estimators, that best fit the observed data. In comparison to other estimation techniques, the OLS method is simple and straightforward which has made it one of the most popular estimation techniques for economics data (Stock & Watson, 2020, p. 151).

4.4.3 Multicollinearity

To check whether further variable transformations are needed, the correlation matrices of the independent variables for all the models are displayed in Table 3. This is because Stock and Watson (2020, p. 375) state that for the panel regression with fixed-effects to produce non-biased coefficient estimators, the independent variables cannot exhibit perfect multicollinearity. In other words, the independent variables cannot be perfectly correlated with each other. Furthermore, imperfect correlation, which is high but not perfect correlation between independent variables, may lead to the estimation of coefficients for the independent variables to be imprecise (Stock & Watson, 2020, pp. 230–231).

Variable	Carbon tax	ETS	Renewable energy	GDP	Energy Consumption	Industry	Energy Intensity
Carbon tax	1						
ETS	0.0693	1					
Renewable energy	0.4838	0.038	1				
GDP	0.333	0.0156	0.304	1			
Energy Consumption	0.2749	-0.037	0.5205	0.6286	1		
Industry	0.0369	-0.0843	0.0578	-0.3376	-0.1464	1	
Energy Intensity	-0.1768	-0.1088	-0.0446	-0.5753	0.0626	0.3575	1

Table 3. Correlation matrix between independent variables

From Table 3 it is observed that the variables GDP and energy consumption (0.6286), renewable energy and energy consumption (0.5205), and GDP and energy intensity (-0.5753) have relatively high correlation which could affect the model's coefficient estimation results. To further examine the possible multicollinearity problem, the model's variance inflation factors (VIF) are analyzed. The VIF estimates how the variance of the estimated coefficient changes when the independent variables are correlated (Akinwande et al., 2015). A VIF value of over five suggests that the multicollinearity of the independent variables may induce issues when estimating regression coefficients, and thus, the target value for the model's independent variable VIFs is less than five. VIF values are presented in Table 4.

The VIF values in Table 4 denote multicollinearities for all models that could adversely affect the coefficient estimation. Moreover, it is observed that for the environmental models (Models 1 and 2) the multicollinearity arises from the high correlation between GDP and energy consumption variables, and for the economic models (Models 3 and 4) the multicollinearity problem is caused by the high negative correlation between GDP and energy intensity variables. To address the multicollinearity between GDP and energy

Model	Variable	VIF	1/VIF
Model 1	Energy consumption	7.93	0.126065
	GDP	5.39	0.185594
	Industry	3.23	0.333236
	Renewable energy	3	0.630307
	Carbon tax	1.59	0.630307
Model 2	Energy consumption	7.79	0.128302
	GDP	5.14	0.194379
	Industry	3.46	0.289403
	Renewable energy	2.44	0.409045
	ETS	1.38	0.723263
Model 3	Industry	11.26	0.088818
	Energy intensity	7.33	0.136494
	GDP	3.12	0.320218
	Carbon tax	1.29	0.772484
Model 4	Industry	11.48	0.087116
	Energy intensity	7.27	0.137531
	GDP	2.9	0.34436
	ETS	1.38	0.726025

Table 4. VIF values for models 1–4

consumption, the variation in CO₂ emissions caused by energy consumption which is not explained by the variation in GDP is captured by regressing energy consumption with GDP. Then, the residual from the beforementioned regression is saved and utilized in place of energy consumption in explaining the variation in CO₂ emissions. Thus, a variable called energy consumption residual replaces the energy consumption variable, and therefore, the model specifications in Equation (1) and Equation (2) take the form of Equation (5) and Equation (6).

(5)

$$\begin{aligned}
 CO2_{i,t} = & \beta_0 + \beta_1 Carbon\ tax_{i,t} + \beta_2 Renewable\ energy_{i,t} + \beta_3 GDP_{i,t} \\
 & + \beta_4 Energy\ Consumption\ Residual_{i,t} + \beta_4 Industry_{i,t} + u_{i,t} + e_{i,t}
 \end{aligned}$$

(6)

$$CO2_{i,t} = \beta_0 + \beta_1 ETS_{i,t} + \beta_2 Renewable\ energy_{i,t} + \beta_3 GDP_{i,t} \\ + \beta_4 Energy\ Consumption\ Residual_{i,t} + \beta_4 Industry_{i,t} + u_{i,t} + e_{i,t}$$

Regarding the multicollinearity problem with models 3 and 4, the variation in GDP growth explained by energy intensity which is not explained by the industry size is captured similarly with the environmental models. Moreover, to reduce the multicollinearity even further, the GDP variable is utilized in the model as a first-order lag. This means that the variation in GDP growth is controlled with the GDP per capita value of the previous year. Furthermore, this aligns better with the existing literature as the income from the previous year is more likely to display the initial income of the country better than the income level in the same year. Therefore, the model specifications in Equation 3 and Equation 4 are modified and presented in Equation 7 and Equation 8.

(7)

$$GDP\ per\ capita\ growth_{i,t} = \beta_0 + \beta_1 Carbon\ tax_{i,t} + \\ \beta_2 Energy\ intensity\ Residual_{i,t} + \beta_3 GDP\ Lag_{i,t} + \beta_4 Industry_{i,t} + u_{i,t} + e_{i,t}$$

(8)

$$GDP\ per\ capita\ growth_{i,t} = \beta_0 + \beta_1 ETS_{i,t} + \beta_2 Energy\ intensity\ Residual_{i,t} \\ + \beta_3 GDP\ Lag_{i,t} + \beta_4 Industry_{i,t} + u_{i,t} + e_{i,t}$$

From Table 5 it is observed that the VIF values no longer suggest multicollinearity issues as the VIF values are all below five. Therefore, the coefficient should be precisely estimated.

Model	Variable	VIF	1/VIF
Model 5	GDP	3.05	0.327579
	Renewable energy	3.02	0.33165
	Industry	2.81	0.356265
	Carbon tax	1.58	0.634905
	Energy consumption residual	1.26	0.793386
Model 6	GDP	2.98	0.335239
	Industry	2.93	0.340746
	Renewable energy	2.49	0.401532
	ETS	1.39	0.719491
	Energy consumption residual	1.25	0.797432
Model 7	GDP lag	3.25	0.307721
	Industry	2.77	0.361165
	Carbon tax	1.29	0.772369
	Energy intensity residual	1.22	0.818555
Model 8	GDP lag	3.03	0.329789
	Industry	3.03	0.330113
	ETS	1.4	0.713896
	Energy intensity residual	1.21	0.823112

Table 5. VIF values for models 5–8

4.4.4 Unit root testing

To produce reliable estimations with statistical modeling using time series, the variables in the data set are required to be stationary. This is because the time series might exhibit trends from the past that are not present in the future, and thus, the implications of the calculated coefficient estimations could be unreliable (Stock & Watson, 2020, p. 561–562). To test whether the variables are stationary, a unit root test for the utilized variables is conducted. A unit root test detects if the variables in the data set have a stochastic trend, which in turn indicates that the variables are non-stationary (Stock & Watson, 2020, p. 586). The unit root test utilized in this study is the Fisher-type Phillips-Perron test which utilizes multiple different test statistics to determine whether the variable exhibits a unit root (Choi, 2001, p. 253–256). The test is chosen for this study since works

for unbalanced data which might exhibit some heteroskedasticity across panels (Choi, 2001, p. 252–253).

The Fisher test statistics are calculated using the Phillips-Perron test, hence the name Fisher-type Phillips-Perron test. The null hypothesis for the test is that all panels have a unit root, and the alternative hypothesis is that at least one panel does not have a unit root. The null hypothesis is rejected if the p statistics of all Fisher statistics are less than 0.05. In Stata, the Fisher-type Phillips-Perron test produces four Fisher test statistics: inverse Chi-squared statistic P, inverse normal statistic Z, inverse logit statistic L*, and modified inverse Chi-squared statistic Pm. In this study, the modified inverse Chi-squared statistic can be ignored as it produces unreliable results if there are not enough panels in the data set (“xtunitroot”, n.d., p. 18). Table 6 presents the results of the Fisher-type Phillips-Perron test.

Variable	Fisher test statistics		
	P	Z	L*
CO2	28.5841 (1.000)	7.168 (1.0000)	7.2334 (1.0000)
Carbon tax	23.469 (1.0000)	3.1393 (0.9992)	3.2948 (0.9993)
ETS	32.6343 (1.0000)	3.762 (0.9999)	4.0597 (1.0000)
Renewable energy	34.4241 (0.9999)	7.163 (1.0000)	7.9605 (1.0000)
GDP	79.5067 (0.2045)	1.4626 (0.9282)	1.5351 (0.9367)
GDP lag	100.6158** (0.0097)	-0.9757 (0.1646)	-1.1841 (0.1190)
Energy consumption residual	67.8124 (0.5518)	0.2131 (0.5844)	0.1711 (0.5678)
Industry	104.8086** (0.0045)	-2.2985** (0.0108)	-2.594** (0.0051)
GDP per capita growth	584.0229*** (0.0000)	-20.0205*** (0.0000)	-27.2675*** (0.0000)
Energy intensity residual	67.8124 (0.5518)	0.2131 (0.5844)	0.1711 (0.5678)

p-values in parenthesis
*p < 0.05 **p < 0.01 ***p < 0.001

Table 6. Fisher-type Phillips-Perron test results

As seen from the results, most of the variables in the regression models exhibit a unit root in their current form. The only variables that have significant p-values for all test statistics, and thus, are stationary in their current form are industry size and GDP per capita growth. However, as the test is conducted again for the first-order difference of the same variable, the variables become stationary (Table 7). That is, at least one of the panels is stationary. Since the results of the test change when taking the first-order difference of the variable, it is assumed that all of the panels in the time series are stationary.² Because the variables are modified, Equations 5, 6, 7, and 8 take a new form in Equations 9, 10, 11, and 12.

Variable	Fisher test statistics		
	P	Z	L*
ΔCO2	845.2021*** (0.000)	-24.9441*** (0.0000)	-39.4847*** (0.0000)
ΔCarbon tax	346.0877*** (0.0000)	-14.3579*** (0.0000)	-21.81*** (0.0000)
ΔETS	627.3665*** (0.0000)	-21.6292*** (0.0000)	-32.7693*** (0.0000)
ΔRenewable energy	761.8972*** (0.0000)	-22.5148*** (0.0000)	-35.3759*** (0.0000)
ΔGDP	637.7858*** (0.0000)	-20.9401*** (0.0000)	-29.7724*** (0.0000)
ΔGDP lag	254.7721*** (0.0000)	-9.788*** (0.0000)	-11.2888*** (0.0000)
ΔEnergy consumption residual	1060.2728*** (0.0000)	-28.4081*** (0.0000)	-49.5372*** (0.0000)
ΔIndustry	639.2616*** (0.0000)	-20.72*** (0.0000)	-29.8235*** (0.0000)
ΔGDP per capita growth	1369.0578*** (0.0000)	-33.7686*** (0.0000)	-63.9718*** (0.0000)
ΔEnergy intensity residual	695.1424*** (0.0000)	-22.1714*** (0.0000)	-32.4692*** (0.0000)

p-values in parenthesis
*p < 0.05 **p < 0.01 ***p < 0.001

Table 7. Fisher-type Phillips-Perron test results after first-order differentiation

² To test whether this is actually true, the Fisher-type Phillips-Perron test should be conducted for all of the individual panels separately which is out of scope for this study.

(9)

$$\Delta CO2_{i,t} = \beta_0 + \beta_1 \Delta Carbon\ tax_{i,t} + \beta_2 \Delta Renewable\ energy_{i,t} + \beta_3 \Delta GDP_{i,t} \\ + \beta_4 \Delta Energy\ Consumption\ Residual_{i,t} + \beta_4 Industry_{i,t} + u_{i,t} + e_{i,t}$$

(10)

$$\Delta CO2_{i,t} = \beta_0 + \beta_1 \Delta ETS_{i,t} + \beta_2 \Delta Renewable\ energy_{i,t} + \beta_3 \Delta GDP_{i,t} \\ + \beta_4 \Delta Energy\ Consumption\ Residual_{i,t} + \beta_4 Industry_{i,t} + u_{i,t} + e_{i,t}$$

(11)

$$GDP\ per\ capita\ growth_{i,t} = \beta_0 + \beta_1 \Delta Carbon\ tax_{i,t} + \\ \beta_2 \Delta Energy\ intensity\ Residual_{i,t} + \beta_3 \Delta GDP\ Lag_{i,t} + \beta_4 Industry_{i,t} + u_{i,t} + e_{i,t}$$

(12)

$$GDP\ per\ capita\ growth_{i,t} = \beta_0 + \beta_1 \Delta ETS_{i,t} + \beta_2 \Delta Energy\ intensity\ Residual_{i,t} \\ + \beta_3 \Delta GDP\ Lag_{i,t} + \beta_4 Industry_{i,t} + u_{i,t} + e_{i,t}$$

5 Presentation of results and discussion

This chapter presents the results of the models outlined in the previous chapter. Furthermore, the results are discussed in general and with respect to the previous literature on the subject.

5.1 Results of the environmental models

The results of both environmental models are presented in Table 8. Interestingly, the first observation from the results is that the sign of the carbon tax and ETS variables align with intuition, such that an increase in both indicators suggests a reduction in emissions levels. However, neither of the observed emission-reduction impacts of these indicators is statistically significant. Hence, we reached a decision that there is no sufficient evidence in support of significant emission-abating impacts of both ETS and carbon tax among the OECD countries at least for the period studied. Contrary to apriori expectations, this finding is quite unconventional as one of the main objectives of carbon pricing is to reduce emissions. Nevertheless, the current findings are partly suggestive of the supportive arguments that both indicators have not been outrightly effective in emission abatement, or perhaps their emission mitigation roles have only been marginal.

Based on the results, there are possible reasons why carbon pricing has not yielded significant emission reduction effects in the OECD bloc. Firstly, the nature of the sample utilized in the study may have contributed to these observed results. Secondly, the findings could also be due to the fact that emission-weighted carbon prices are too low. The sample in this study utilizes geographically and economically diverse countries that have different levels of carbon pricing which could affect the results. Moreover, if the emission-weighted carbon price is too low, either because of the sheer tax rate or because of tax exemptions for emission-intensive industries, the carbon price rate might not be sufficient enough to alter the actions of emitters. Furthermore, if the carbon tax rate does not increase over time during the study period, the emissions abatements are likely to not increase either over time. In addition, as IPAC stated, fossil fuel subsidies have been

on the rise following the COVID-19 pandemic which could distort the emissions reduction efforts induced by carbon pricing.

The rest of the independent variables are almost identical for both models. The coefficient of the renewable energy consumption variables indicates that a one percentage point increase in renewable energy consumption as a share of total energy consumption is associated with a decrease of the CO₂ emissions per capita by 99.2 tons all else being equal. However, as we utilize the first-order difference of the variables, the interpretation changes slightly. Thus, the one percentage point increase in renewable energy consumption as a share of total energy consumption is related to an abatement of emissions per capita growth by said amount. The coefficient is highly statistically significant as the p-value of the coefficient is below 0.001. The result of renewable energy utilization's effect on CO₂ emission abatement is intuitive as most of the excess emissions are the result of fossil fuel combustion.

From Table 8 it is also observed that the GDP per capita variable is highly significant, and it implies that a one-dollar increase in income is linked to 0.166 tons rise in per capita emissions growth. The finding could arise from, for example, increased consuming and waste, and thus, the finding is quite evident. Lastly, the energy consumption per capita residual and the industry size are moderately statistically significant, and they both increase per capita emissions. The energy consumption residual suggests that a one-giga-joule increase in energy consumption per capita, not explained by the variation in GDP per capita, increases emissions per capita growth by 30.4 tons. Furthermore, if the industry increases its share in total GDP by one percentage point, it is associated with an 8.56 tons increase in per capita CO₂ emissions growth. All these findings are quite intuitive as energy production and corresponding utilization, and industry are the two main sources of emissions in OECD countries. Besides, industrial demands constitute a significant proportion of total energy utilization as the bloc hosts a cluster of some of the most highly industrialized nations of the world.

Moreover, Table 8 presents the R-squared values of the environmental models. The panel regression with fixed-effects produces three different R-squared values: R-squared within, R-squared between, and R-squared overall. The interpretation of the R-squared within indicates how much of the variance in the dependent variable, in this case first-order difference of emissions per capita, is explained by the dependent variables within a panel which, in this case, is the countries included (Stata, n.d., p. 12). In other words, R-squared within presents the variance in the dependent variable, induced by the independent variables, across years. R-squared between, in turn, indicates the magnitude of the variance in the dependent variable is explained by the independent variables across countries during the same year. Therefore, the R-squared between demonstrates the differences in the average value of the dependent variable between different countries. Lastly, the R-squared overall reveals the variance in the dependent variable induced by the independent variables throughout the data set.

Environmental model results		
	Model 1	Model 2
ΔCarbon tax	-0.00372 (0.222)	
ΔRenewable energy	-0.0992*** (0.000)	-0.0993*** (0.000)
ΔGDP	0.000116*** (0.000)	0.000117*** (0.000)
ΔEnergy consumption residual	0.0304** (0.007)	0.0304** (0.007)
Industry	0.00856* (0.038)	0.00868* (0.042)
ΔETS		-0.000611 (0.833)
Constant	-0.271* (0.010)	-0.275* (0.013)
N	840	840
R ² within	0.495	0.495
R ² between	0.569	0.566
R ² overall	0.496	0.496
Prob > F	0.000	0.000

p-values in parentheses
* *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001

Table 8. Regression results for environmental models

The difference in R-squared within and between for both environmental models implies that the models explain the variance in CO₂ emissions per capita in first-order difference better across countries than across years. However, for both variances, across years and countries, the R-squared shows a moderate level of fit as the R-squared within indicates that the independent variables explain 49.5 % of the variance in the dependent variable in both models through the study period, and the R-squared between reveals that the independent variables explain 56.9 % of the variance in the dependent variable between different countries in model 1 and 56.6 % in model 2. Furthermore, R-squared overall shows a moderate fit for the whole data set as the independent variables account for 49.6 % of the variance in the dependent variable in both environmental models. These

results demonstrate that there are some other omitted variables, which affect the per capita emissions development across years and countries.

Lastly, the F-test results are also included in Table 8. The F-test tests the joint significance of the independent variables against the null hypothesis that all of the coefficients of the model's independent variables are zero (Stock & Watson, 2020, p. 253–255). Table 8 presents the p-values of the F-test which are 0.000 for both models. Therefore, the null hypothesis can be rejected at the 0.1 % significance level, and it can be concluded that at least one of the independent variables is statistically significant in both models.

5.2 Results of the economic models

Regression results and goodness-of-fit statistics of the economic models are displayed in Table 9. In these models, Model 3 and Model 4, the dependent variable is in level form whereas the independent variables of interest are in the first-order difference form. This changes the interpretation of the coefficients produced by the model such that the coefficients of the independent variables in the first-order difference are associated with changes in the dependent variable for the following period.

As in the environmental model, the carbon tax variable is not statistically significant. However, the sign of the coefficient is positive which implies that an increase in carbon tax could have a positive effect on GDP growth for the subsequent period. Furthermore, the coefficient of the ETS variable is positive and highly statistically significant as the p-value of the coefficient is lower than 0.001. This demonstrates that the increased carbon price deriving from emission trading systems is associated with higher income growth for the subsequent period in the sample countries. More specifically, a one-dollar increase in ETS boosts income growth for the next period by 0.092 percentage points. This finding that carbon pricing, especially when enforced through an emissions trading system, could enhance economic growth could arise from increased efficiency or new technology adoption incentivized by the carbon price. Moreover, the increased economic

growth could result from the revenue generated by the carbon price and an efficient allocation of these revenues.

Similarly to the environmental models, the coefficients of the other independent variables are almost identical. The only control variable that is not statistically significant is the first-order difference of the GDP lag variable. Although the sign of the coefficient is negative, from this model it cannot be concluded that the income of the previous year has any effect on the GDP per capita growth for the next period. This seems likely for this sample as income growth is usually at its highest when a country is industrializing. However as most of the countries in the sample were already high-income economies at the beginning of the study period, it is intuitive that the previous income level does not have an effect on GDP per capita growth.

However, as the other control variables are highly statistically significant with p-values below 0.001, it can be concluded that the one unit increase in energy intensity, not explained by the size of the industry, is associated with a 2.57 percentage point lower GDP per capita growth rate for the subsequent year. This could be explained by the inefficiencies of the energy-intensive industries which usually require more capital, and thus produce lower returns than less energy-intensive industries. Furthermore, the model predicts that one percentage point growth in industry size as a share of GDP produced could have induced higher income growth by 0.47 percentage points in the across the sample countries and study period. This, again, could be the result of the fact that economic growth is at its highest when an economy is industrializing.

Economic model results		
	Model 3	Model 4
ΔCarbon tax	0.00257 (0.947)	
ΔEnergy intensity residual	-2.568*** (0.000)	-2.567*** (0.000)
ΔGDP lag	-0.000113 (0.402)	-0.0000709 (0.585)
Industry	0.472*** (0.000)	0.474*** (0.000)
ΔETS		0.0915*** (0.000)
Constant	-10.20*** (0.000)	-10.32*** (0.000)
N	805	805
R ² within	0.216	0.231
R ² between	0.179	0.179
R ² overall	0.126	0.135
Prob > F	0.000	0.000

p-values in parentheses
* *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001

Table 9. Regression results for the economic models

Regarding the fit of the models, results from Table 8 and Table 9 that there are bigger differences in R-squared within and R-squared overall in the economic models than in environmental models. Model 4 explains 23.1 % of the variance in the GDP per capita growth throughout the study period whereas model 3 explains 21.6 % of the variance. Moreover, model 4 also explains the variance in the income growth better for the complete data set than model 3 as the R-squared overall for model 4 is 13.5 % and for model 3 it is 12.6 %. Lastly, it is observed that across countries, both models explain the same amount, 17.9 %, of the variance in the dependent variable.

The difference in the goodness-of-fit between the two models is not large, but it is worth noticing that the carbon price induced by the ETS explains the variance in income growth

better than carbon price induced by the carbon tax. However, the relatively low R-squared values imply that there are other significant variables that affect income growth more than the independent variables included in the model. This comes as no surprise since the purpose of the models is to examine the effects of carbon price on income growth, not to examine which variables best explain the variance in GDP per capita growth.

As in the environmental models, the F-test results provide additional information about the goodness-of-fit of the economic models. The p-values of the F-tests are, for both models, below 0.000 which indicates high statistical significance, and therefore the rejection of the null hypothesis. Thus, in models 3 and 4 there is at least one independent variable that is statistically significant.

5.3 Comparative discussion with existing evidence

The findings of the environmental models and the economic models are contrasted with the existing literature in this subchapter. As the literature on both the environmental and economic effects of carbon pricing is conflicting, some studies support the findings of this study while some challenge them as well.

5.3.1 The environmental effects

The findings of this study point out that the carbon pricing efforts are not sufficient enough to significantly reduce per capita CO₂ emissions across OECD countries. Therefore, carbon prices measured as emission-weighted prices, should be higher either through increasing the carbon price rate or decreasing the exemptions for paying the carbon price in the emission-intensive industries. This finding aligns with the findings of Gloaguen and Alberola (2013), Shmelev and Speck (2018), Wakabayashi and Kimura (2018), Pretis (2020), and partially with Lin and Li (2011). These studies did not find significant emissions-abating effects arising from carbon pricing through taxation or implementing an emissions trading system for specific countries or sets of countries. Moreover,

Gloaguen and Alberola (2013), Shmelev and Speck (2018), and Pretis (2020) all suggest that the reason for these results is that the effective carbon price rates are too low for achieving significant emissions reductions. The same shortcoming of emissions reduction efforts was stated by IPAC in their 2023 climate report.

Lin and Li (2011) did find evidence in one out of the five countries to have significantly abated emissions through carbon taxes, but the other four did not. However, they also found that one in five countries in the study actually increased emissions despite implementing a carbon price. Therefore, the finding of insignificant emissions reductions across OECD countries could be the result of other countries increasing emissions regardless of carbon tax implementation while other countries decreased emissions. Thus, the country-specific aspects, displayed by the differences in R-squared values in this study, could play a large role in whether carbon tax reduces emissions or otherwise.

However, many studies presented in extant works also found evidence that carbon pricing did induce emissions reductions. Petrick and Wagner (2014), Wagner et al. (2014), Rivers and Schaufele (2015), Murray and Maniloff (2015), Andersson (2019), Hájek et al. (2019), Metclaf (2019), Abe and Arimura (2019), Chan and Morrow (2019), Dussaux (2020), and Bayer and Aklin (2020) all found that carbon pricing is associated with emissions abatement which contradicts the findings of this paper. The reason for these contradictions could arise from the fact that these studies examined emissions of certain sectors or industries, not aggregate emissions like the study conducted in this paper. Moreover, Murray and Maniloff (2015) did explain CO₂ emissions in aggregate terms in their model but not in per capita form, although the population variable was utilized as a control variable. Furthermore, the difference in results could also be affected by the difference in methodologies, utilization of different types of data for the carbon price, and the differences in the study periods. The study period might play a large role in the study conducted on this paper as the period of increasing fossil fuel subsidies in OECD countries post-COVID-19 is included.

To conclude, from the differences in the estimation results, it can be observed that the time period, countries, data, and methodologies significantly affect the estimated outcomes of the relationship between carbon price and carbon emissions abatement. Therefore, the policy adaptations made based on the results of these studies should be carefully assessed. Although this study does not support the idea that carbon pricing abates emissions significantly, the tools for carbon pricing could affect other aspects, for example, renewable energy consumption, which, in turn, significantly reduces CO₂ emissions. Moreover, the results are based on historical data, and thus the effects of considerably higher carbon prices or reduction in carbon price exemptions could produce different outcomes.

5.3.2 The economic effects

The presented findings of this study did not find that carbon pricing hinders economic growth. In contrast, the signs of the estimated coefficient for both carbon tax and ETS indicate that carbon pricing is associated with a higher level of growth in income. Moreover, the ETS's induced higher growth is statistically significant. The latter finding aligns with the findings of Dechezleprêtre et al. (2018) since they found that taking part in the EU ETS increased the revenues of these companies. To add to this, the findings of this paper support the findings of Driscoll (2020), and Ko and Lee (2021) to some extent. This is because Driscoll (2020) estimated that carbon pricing has no effect on economic growth whereas the study in this paper states that it might increase it. Ko and Lee (2021) stated that ETS is more likely to have no effect on economic growth whereas carbon taxation is likely to do this. Therefore, the findings of this study align with Ko and Lee (2021), but only partially. Lastly, Hassan et al. (2020) did not necessarily study the effects of carbon price, but they concluded that environmental taxes have no significant effect on economic growth, which also aligns with the outcomes of this study.

Regarding the contradicting results, Abdoullah and Morley (2014), and Tchapchet-Tchouto et al. (2022) provided evidence that environmental taxes have a negative impact on economic growth. Abdoullah and Morley (2014) stated that this negative effect fades

away in the long term, but as the results of the study conducted on this paper do not provide evidence that carbon pricing slows down economic growth even in the short term, the finding is viewed as contradictory. However, as Abdoullah and Morley (2014), and Tchatchet-Tchouto et al. (2022) studied the effects of the total environmental taxes, the conflicting outcomes might arise from the effects of other environmental taxes than carbon taxes. Furthermore, the contradictions in the findings could be the results of differences in methodologies, study period, and data.

Overall, the previous evidence and the evidence provided by the study conducted in this paper point to the conclusion that carbon pricing has no effect on economic growth. The only contradicting results study the overall effects of environmental taxation, which could have some short-term negative impact on the economic growth of a country. However, as the results of the environmental models suggest that the current carbon price levels are not high enough to achieve significant CO₂ emissions abatements across OECD countries, and therefore they should be higher, it would be interesting to see what the economic impact of these higher carbon prices is.

6 Causality analysis

In addition to the regression analysis of the environmental and economic models, a causality test is conducted to determine whether the independent variables are in fact causing the variance in the dependent variables. The causality, or specifically, non-causality test utilized in this study is the Juodis, Karavias and Sarafidis (JKS) (2021) Granger non-causality test which tests against the null hypothesis that the independent variables in the model are not jointly Granger-causing the variance in the dependent variable in any of the panels. This particular test is chosen since it can detect causation in panel data with robustness to cross-sectional dependence, heterogenous panels, and heteroskedasticity (Juodis et al., 2021, p. 101). These aspects are important for our non-causality analysis as the countries are different from each other and assumed to have unobserved factors that might affect the results of the causation estimation. Moreover, the emissions-weighted carbon price variables, CO2 and ETS, have a lot of zero values for certain years in certain countries which can create biased results for other causality or non-causality tests³.

More insight into the relationship between all of the variables included in the models is gained by executing a pairwise Granger non-causality test. The pairwise Granger causality test is done according to the traditional Granger (1969) non-causality test to examine the non-causality between every variable in their respective models. However, because of the heterogeneous nature of the panel data, the data does not perfectly fit the requirements of Granger (1969), and therefore the results should be examined with caution. Nevertheless, the pairwise causality test might still provide some important insight into the causal relationship between the variables of the models. In the Granger (1969) non-causality test, statistical significance is tested similarly as in the regression analysis with a F-test, and the null hypothesis is that there is no Granger causal relationship between the variables.

³ The Dumitrescu and Hurlin (2012) non-causality test was experimented with the data but it did not present results for emissions-weighted carbon price variables.

6.1 JKS Granger non-causality test

The interest of this study regarding the JKS Granger non-causality test is whether the independent variables Granger-cause the variance in the dependent variables. The null hypothesis that the independent variables are not jointly Granger-causing the variance in the dependent variable in any of the panels is tested with a half-panel jackknife (HPJ) Wald statistic. If the HPJ Wald statistic is sufficiently large, the null hypothesis is rejected, and thus the independent variables are jointly Granger-causing variance in the dependent variable in at least one panel. The HPJ Wald statistics and their p-values models 1 to 4 are presented in Table 10.

	Model 1	Model 2	Model 3	Model 4
HPJ Wald test statistic	541.1153	636.9591	220.6953	1100
	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***
p-values in parenthesis				
* p < 0.05, ** p < 0.01, *** p > 0.001				

Table 10. Results of the JKS Granger non-causality tests

The results in Table 10 point that the null hypothesis is rejected in all of the models. This indicates that the independent variables across models are, in fact, jointly Granger-causing the variance in the dependent variables. This finding validates the model specifications of the study and further gives insight into the causal relationship between the independent variables and the dependent variables.

6.2 Pairwise Granger non-causality test

As the pairwise Granger non-causality test tests Granger causal relationships between every variable in their respective models, it provides some outcomes that are not necessarily in the interest of this study. Therefore, the summarized results which include the key variables of interest are provided in Table 11 and for the results of all of the variables

see Appendix 1. The results were mainly intuitive with a couple of interesting exceptions which are discussed after Table 11.

Null Hypothesis:	F-Statistic	p-value
Δ Carbon tax does not Granger cause Δ CO ₂	0.43351	0.7291
Δ CO ₂ does not Granger cause Δ Carbon tax	1.43056	0.2326
Δ ETS does not Granger cause Δ CO ₂	9.24573	0.0000***
Δ CO ₂ does not Granger cause Δ ETS	7.48321	0.0000***
Δ Renewable energy does not Granger cause Δ CO ₂	0.53023	0.6617
Δ CO ₂ does not Granger cause Δ Renewable energy	3.41227	0.0172*
Δ GDP does not Granger cause Δ CO ₂	2.85324	0.0365*
Δ CO ₂ does not Granger cause Δ GDP	0.43949	0.7248
Δ Energy consumption residual does not Granger cause Δ CO ₂	0.52294	0.6666
Δ CO ₂ does not Granger cause Δ Energy consumption residual	2.43670	0.0636
Industry does not Granger cause Δ CO ₂	2.92184	0.0333*
Δ CO ₂ does not Granger cause Industry	1.00222	0.3913
Δ Carbon tax does not Granger cause GDP growth	0.03190	0.9923
GDP growth does not Granger cause Δ Carbon tax	0.71686	0.5421
Δ ETS does not Granger cause GDP growth	19.2713	0.0000***
GDP growth does not Granger cause Δ ETS	17.7686	0.0000***
Δ GDP Lag does not Granger cause GDP growth	2.56211	0.0538
GDP growth does not Granger cause Δ GDP	412.002	0.0000***
Industry does not Granger cause GDP growth	1.97849	0.1158
GDP growth does not Granger cause Industry	2.72158	0.0435*
Δ Energy intensity residual does not Granger cause GDP growth	3.60263	0.0133*
GDP growth does not Granger cause Δ Energy intensity residual	8.96317	0.0000***

* p < 0.05, ** p < 0.01, *** p > 0.001

Table 11. Results of the pairwise Granger non-causality test

Similarly to the regression analysis, the pairwise Granger non-causality test finds no significant Granger causal relationship between carbon tax emissions-weighted carbon price and CO₂ emissions as well as GDP growth. Thus, strong evidence is found that carbon tax does not significantly decrease emissions, but it does not significantly affect economic growth either.

The pairwise Granger causality test provides interesting outcomes regarding the ETS and Renewable energy variables. According to the test, there is dual Granger causality between both the dependent variables and the ETS variable. This indicates that ETS emissions-weighted carbon price does reduce emissions, as we established in the regression analysis, but also CO₂ emissions cause variance in ETS emissions-weighted carbon price in the dataset. This finding could be the result that countries in the dataset with high per capita emissions are more likely to introduce and raise the level of ETS emissions-weighted carbon price. Moreover, as there is a dual Granger causal relationship with the ETS and GDP growth variables, it seems that implementation and increasing ETS emissions-weighted carbon price does boost economic growth, but also that higher economic growth leads to variance in ETS carbon price in the dataset.

The Granger causal relationship between renewable energy and CO₂ emissions seems to be reversed which means that emissions cause variations in renewable energy consumption. This finding is particularly interesting as intuitively the Granger causal relationship would be the other way around. As the regression analysis provided the result that the relationship between the variables is negative, the finding arises from the fact that countries with low per capita CO₂ emissions are more likely to increase their renewable energy consumption. Therefore, the finding is not as surprising since for example, the US has high per capita emissions but relatively low renewable energy consumption whereas Sweden has the opposite. Still, it would seem unreasonable to undermine the positive environmental effects that renewable energy-promoting policies have, and thus further studies are needed to examine the real effects of renewable energy consumption.

Lastly, the residual variables of energy consumption and energy intensity have intriguing Granger causal relationships. Energy consumption per capita which is not explained by GDP does not significantly cause CO₂ emissions which contradicts the findings of the regression analysis. Moreover, the results suggest that there is a dual causality between energy intensity which is not explained by industry and GDP growth. The first finding

might arise from the fact that some omitted factor which is correlated with energy consumption is the real driver of the emissions growth and the contradiction with the regression analysis could arise from methodological differences. As the relationship is negative between energy intensity and GDP growth according to the regression analysis, the latter finding could be the result of energy intensity negatively affecting economic growth because of inefficiencies in the industry. Furthermore, as the economy grows, countries can afford to fix these energy inefficiencies by investing in better technology. Thus, the energy intensity decreases when the GDP growth is higher.

7 Conclusions

As the concentration of greenhouse gas emissions in the atmosphere has led to an increasing number of adverse weather conditions, this paper explored the environmental as well as economic effects of carbon pricing in OECD countries. This is because CO₂ emissions make up the largest part of all GHG emissions which are released to the atmosphere from the combustion of fossil fuels. The target of carbon price is to put a price rate on the CO₂ content of the fossil fuels which in turn should decrease the amount of aggregate carbon emissions. The second part of the analysis explores whether the implementation of the carbon price rate affects economic growth as business units need to pay a price extra for their emissions.

The scope of the study was OECD countries which are mainly developed high-income countries. The OECD countries were chosen for the examination as there is evidence of decoupling between emissions and economic growth. Besides, many of these countries have put a price on carbon in recent decades. Moreover, every continental region is represented in the OECD, and thus the analysis covers different geographical areas.

In OECD countries, the two main carbon pricing mechanisms are carbon tax and emissions trading systems. Both of the mechanisms aim to decrease CO₂ emissions by putting a price on carbon in a slightly different way. A carbon tax sets a fixed price rate for carbon content in fossil fuels, and thus the carbon price rate is known beforehand, but the amount of emissions is not. In turn, ETS, especially cap-and-trade systems, put a limit on CO₂ emissions, and then emission allowances are either distributed for free (“grandfathered”) or auctioned to market agents. These allowances are then traded in carbon markets which also determine the carbon price rate. Therefore, with ETS the amount of emissions is known beforehand, but the carbon price rate is not.

The literature on the relationship between carbon pricing, both in the form of carbon tax and ETS, and CO₂ emissions has not been able to find consensus. There are several studies that point out that carbon pricing is affiliated with significant emission

abatements, but there is also a considerable amount of studies that do not support these findings. The differences occur most likely because the studies focus on either different countries or countries' economic sectors, the studies are conducted for different time periods, and/or the studies have differences in the utilized data and methodologies. Therefore, the framework for properly analyzing the relationship between carbon pricing and CO₂ emissions demands continuous development and research.

Similarly to the relationship between carbon pricing and emissions, the literature on the relationship between carbon pricing and economic growth is conflicting. There are studies pointing to the possibility that carbon pricing could adversely affect economic growth, especially in the long term. However, some studies find evidence that carbon pricing does not have a significant effect on economic growth, but, some studies find that carbon pricing might have a positive effect on economic growth. The result implies that the analysis framework requires more consideration and studying to find consensus on the topic.

This study analyzed the relationship between carbon tax and aggregate CO₂ emissions per capita, and between ETS and aggregate CO₂ emissions per capita separately. The carbon price rates of both mechanisms were utilized as emissions-weighted carbon price which takes into account the tax exemptions for industries as well as the overall coverage of the carbon price in an economy. The analysis was done with a panel regression with fixed-effects while controlling for renewable energy consumption as a share of total energy consumption, GDP per capita, energy consumption per capita, and industry as a share of value added to the GDP. Although the signs of the carbon price variables' coefficients point to the possibility of emission-abating effects, the study did not find a statistically significant relationship between CO₂ emissions and carbon price rates of either carbon pricing mechanism. However, a strong and significant negative relationship was found between renewable energy consumption and carbon emissions, and a strong and significant positive relationship was found between GDP per capita and carbon emissions. Moreover, the sign of the energy consumption per capita was positive and

statistically significant, whereas the industry variable has a moderately statistically significant and positive relationship with CO₂ emissions. For both environmental models, the statistical significance and the magnitude of the variable coefficients were almost identical. However, the differences between R-squared within, R-squared between, and R-squared overall prove that there are, in fact, differences in how the independent variables explain the dependent variable across years and countries in the dataset.

The economic effect of the carbon price was studied similarly with separate panel regressions with fixed effects for carbon tax and ETS. Therefore, the relationship amongst emission-weighted carbon price and GDP per capita growth was the focus of the regressions while controlling for previous per capita growth, energy intensity, and the industry share of GDP. The results of the regression provide evidence for the argument that carbon pricing does not adversely affect economic growth in OECD countries. The sign of the carbon tax variable in the regression was positive, indicating that carbon taxation might enhance economic growth, but the variable coefficient was not statistically significant. On the other hand, the estimated regression coefficient for the ETS variable was positive and highly statistically significant which implies that the adoption of ETS might boost economic growth through an increase in economic efficiency and technology adoption. Regarding the control variables, the first lag of the GDP per capita variable had a negative sign but was not statistically significant, the energy intensity variable had negative sign and exhibited strong statistical significance, and the industry variable had a positive sign and was highly statistically significant. Again, the differences in R-squared values proved that there are unobserved factors affecting the variance in the dependent variable across years and countries.

The study included a non-causality test developed by Juodis, Karavias and Sarafidis (2021). The test proved that the independent variables included across the models were jointly Granger-causing the variance in the dependent variables. In other words, the variables of interest, the carbon tax and ETS variables as well as the control variables chosen, have a Granger-causal relationship with emissions development and economic growth.

Thus, the study supports the argument that the current carbon price rates, taking into account the tax exemptions and carbon price coverage, are not sufficient enough to abate aggregate CO₂ emissions.

Lastly, the pairwise Granger non-causality test provided us with more insight into the Granger causality between individual variables included in the regression models. The

7.1 Policy implications

The results of the study suggest that the carbon pricing in the OECD, measured as an emission-weighted carbon tax and ETS price rate, are not sufficient in reducing emissions across OECD countries. This finding arises most likely from the fact that the emission-weighted carbon price is too low either because the set carbon tax or the ETS market price is too low, or because the tax exemptions for emission-intensive industries are too high. Furthermore, the results suggest that carbon pricing does not adversely affect the economic growth of a country. Therefore, the study suggests an increase in the emission-weighted carbon price across the OECD as it seems to be too low for achieving emission reductions, and because the increase in emission-weighted carbon price does not seem to affect the economic growth negatively. However, as the industry variable in the economic models points to the fact that larger industry sector is affiliated with higher economic growth, it is difficult to estimate whether the tax exemptions of industries have an effect on economic growth as well. Moreover, it has to be noted that the analysis is based on historical data, and therefore the economic effects of a higher emission-weighted carbon price could be difficult to estimate. Thus, the careful assessment of gradual increase in emission-weighted carbon price is in order.

Additionally, the results suggest that policies that promote the usage of renewable energy should be encouraged. The strong negative relationship between emissions and renewable energy even offsets the environmentally adverse effects of the increase in energy consumption per capita, and therefore as the energy consumption increases in developing countries, the evidence points that this should be done by increasing the supply

of renewable energy. Furthermore, this study does not explore what is the role of carbon pricing in increasing renewable energy usage. Therefore, if carbon pricing incentivizes industries to invest in renewable energy, it is another argument for increasing emission-weighted carbon price rates.

7.2 Suggestions for further studies

Even though emission-weighted carbon price does not seem to directly abate aggregate CO₂ emissions, the OECD countries still exhibit a decoupling of carbon emissions and economic growth. Therefore, the reason for this decoupling should be studied further. The assessment of the effectiveness of other environmental policies seems crucial for achieving environmentally and economically sustainable growth in the future. Moreover, although carbon pricing does not have a significant direct effect on emission development, it could incentivize other activities that abate CO₂ emissions. In addition, the joint effect of different environmental policies could be the reason behind the decoupling of emissions and growth.

Lastly, the decoupling of carbon emissions and economic growth in the OECD could be the result of carbon leakage. Therefore, the carbon leakage in the OECD and the pollution haven hypothesis should be studied further to assess the remedies for the exportation of carbon emissions from developing countries into developed countries. Furthermore, the remedy that the European Commission suggests, carbon tariffs, should be studied further to tackle the possible carbon leakage problem.

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Appendices

Appendix 1. Pairwise Granger causality test

	<u>Null Hypothesis:</u>	<u>F-Statistic</u>	<u>p-value</u>
Models 1-2	Δ Carbon tax does not Granger cause Δ CO2	0.43351	0.7291
	Δ CO2 does not Granger cause Δ Carbon tax	1.43056	0.2326
	Δ ETS does not Granger cause Δ CO2	9.24573	0.0000***
	Δ CO2 does not Granger cause Δ ETS	7.48321	0.0000***
	Δ Renewable energy does not Granger cause Δ CO2	0.53023	0.6617
	Δ CO2 does not Granger cause Δ Renewable energy	3.41227	0.0172*
	Δ GDP does not Granger cause Δ CO2	2.85324	0.0365*
	Δ CO2 does not Granger cause Δ GDP	0.43949	0.7248
	Δ Energy consumption residual does not Granger cause Δ CO2	0.52294	0.6666
	Δ CO2 does not Granger cause Δ Energy consumption residual	2.43670	0.0636
	Industry does not Granger cause Δ CO2	2.92184	0.0333*
	Δ CO2 does not Granger cause Industry	1.00222	0.3913
	Δ Carbon tax does not Granger cause Δ ETS	0.04568	0.9870
	Δ ETS does not Granger cause Δ Carbon tax	2.16699	0.0906
	Δ Renewable energy does not Granger cause Δ ETS	6.65610	0.0002***
	Δ ETS does not Granger cause Δ Renewable energy	0.49557	0.6855
	Δ GDP does not Granger cause Δ ETS	12.5334	0.0000***
	Δ ETS does not Granger cause Δ GDP	12.2157	0.0000***
	Δ Energy consumption residual does not Granger cause Δ ETS	1.26980	0.2837
	Δ ETS does not Granger cause Δ Energy consumption residual	3.60249	0.0133*
	Industry does not Granger cause Δ ETS	0.39431	0.7571
	Δ ETS does not Granger cause Industry	5.39009	0.0011**
	Δ Renewable energy does not Granger cause Δ Carbon tax	5.36612	0.0012**
	Δ Carbon tax does not Granger cause Δ Renewable energy	1.29012	0.2767
	Δ GDP does not Granger cause Δ Carbon tax	1.27530	0.2818
	Δ Carbon tax does not Granger cause Δ GDP	0.30609	0.8210
	Δ Energy consumption residual does not Granger cause Δ Carbon tax	3.08391	0.0268*
	Δ Carbon tax does not Granger cause Δ Energy consumption residual	2.26634	0.0796
	Industry does not Granger cause Δ Carbon tax	0.66210	0.5756
	Δ Carbon tax does not Granger cause Industry	0.45737	0.7122
Δ GDP does not Granger cause Δ Renewable energy	0.86067	0.4612	
Δ Renewable energy does not Granger cause Δ GDP	0.25105	0.8606	

Δ GDP does not Granger cause Δ Renewable energy	0.86067	0.4612
Δ Renewable energy does not Granger cause Δ GDP	0.25105	0.8606
Δ Energy consumption residual does not Granger cause Δ Renewable energy	1.61905	0.1836
Δ Renewable energy does not Granger cause Δ Energy consumption residual	1.22769	0.2986
Industry does not Granger cause Δ Renewable energy	5.81036	0.0006***
Δ Renewable energy does not Granger cause Industry	1.17424	0.3187
Δ Energy consumption residual does not Granger cause Δ GDP	3.98414	0.0079**
Δ GDP does not Granger cause Δ Energy consumption residual	1.42490	0.2343
Industry does not Granger cause Δ GDP	0.23607	0.8712
Δ GDP does not Granger cause Industry	2.46230	0.0615
Industry does not Granger cause Δ Energy consumption residual	1.51251	0.2100
Δ Energy consumption residual does not Granger cause Industry	1.34710	0.2580

* $p < 0.05$, ** $p < 0.01$, *** $p > 0.001$

Models 3-4 Δ Carbon tax does not Granger cause GDP growth	0.06560	0.9781
GDP growth does not Granger cause Δ Carbon tax	0.55906	0.6422
Δ ETS does not Granger cause GDP growth	19.2713	0.0000***
GDP growth does not Granger cause Δ ETS	17.7686	0.0000***
Δ GDP Lag does not Granger cause GDP growth	2.56211	0.0538
GDP growth does not Granger cause Δ GDP	412.002	0.0000***
Industry does not Granger cause GDP growth	1.97849	0.1158
GDP growth does not Granger cause Industry	2.72158	0.0435*
Δ Energy intensity residual does not Granger cause GDP growth	3.60263	0.0133*
GDP growth does not Granger cause Δ Energy intensity residual	8.96317	0.0000***
Δ ETS does not Granger cause Δ Carbon tax	2.21101	0.0856
Δ Carbon tax does not Granger cause Δ ETS	0.03282	0.992
Δ ETS does not Granger cause Δ Carbon tax	2.21101	0.0856
Δ Carbon tax does not Granger cause Δ ETS	0.03282	0.992
Δ GDP Lag does not Granger cause Δ Carbon tax	0.09401	0.9633
Δ Carbon tax does not Granger cause Δ GDP Lag	0.39744	0.7549
Industry does not Granger cause Δ Carbon tax	0.76179	0.5157
Δ Carbon tax does not Granger cause Industry	0.41197	0.7445
Δ Energy intensity residual does not Granger cause Δ Carbon tax	1.09702	0.3496
Δ Carbon tax does not Granger cause Δ Energy intensity residual	0.53940	0.6554
Δ GDP Lag does not Granger cause Δ ETS	5.49831	0.001**
Δ ETS does not Granger cause Δ GDP Lag	10.9678	0.0000***
Industry does not Granger cause Δ ETS	0.43705	0.7266
Δ ETS does not Granger cause Industry	4.78724	0.0026**
Δ Energy intensity residual does not Granger cause Δ ETS	0.94262	0.4195
Δ ETS does not Granger cause Δ Energy intensity residual	6.39756	0.0003***

Industry does not Granger cause Δ GDP Lag	54.5470	0.0000***
Δ GDP Lag does not Granger cause Industry	1.57589	0.1939
Δ Energy intensity residual does not Granger cause Δ GDP Lag	29.0049	0.0000***
Δ GDP Lag does not Granger cause Δ Energy intensity residual	4.44495	0.0042**
Δ Energy intensity residual does not Granger cause Industry	0.26530	0.8504
Industry does not Granger cause Δ Energy intensity residual	1.64488	0.1777

* $p < 0.05$, ** $p < 0.01$, *** $p > 0.001$