The impact of environmental taxes on CO_2 emissions

An examination of the relationship between environmental taxes and CO_2 emissions in OECD countries from 1995 to 2020

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Abstract

Dette speciale undersøger effekten af miljøskatter på udledningen af CO_2e i 25 udvalgte OECD-lande i perioden 1995-2020. Miljøskatter sætter et prissignal på forurening og tilskynder anvendelse af mere bæredygtige produktionsteknologier. Uønskede effekter af miljøskatter kan dog også forekomme, hvis indførelsen af miljøskatter resulterer i adfærdsmæssige reaktioner, der fremmer miljøskadelig adfærd.

Miljøskatterne vægtes i forhold til den totale skattemæssige indkomst. Det udledes, at den gennemsnitlige effektive miljøskatterate og CO_2e per indbygger er faldet i perioden 1995-2020. Distributionen af de gennemsnitlige effektive skatterater viser, at de er centreret omkring 5-8%, mens CO_2e varierer mellem 5-11 metriske tons per indbygger. Et scatterplot viser, at visse lande med højere miljøskatterater har lavere CO_2e per indbygger. En uklar sammenhæng mellem de to variable findes dog ved et mellemhøjt niveau for miljøskatteraten.

Der foretages et 1%-point chok til den effektive miljøskatterate på CO_2e per indbygger i en lineær local projections model baseret på paneldata. Der findes en maksimal, negativ, vedvarende effekt på ca. -0,12 metriske tons per indbygger, hvilket blandet andet tilskrives tilskyndelsen til at skifte til renere produktionsteknikker. Et tilsvarende chok foretages til energimiljøskatter som andel af den totale skattemæssige indkomst, hvilket resulter i en stærkere reduktion på -0,15 metriske tons per capita. Yderligere chok foretages til carbon-skatterater og carbon-energi-skatterater, der udviser en væsentligt stærkere reduktion i CO_2e per indbygger end chok til effektive miljøskatterater. Chokkene udviser dog usikkerhed omkring en vedvarende effekt på længere sigt. Chok til energimiljøskatter målrettet bestemte miljømæssige problematikker, såsom tiltag til begrænsning af klimaforandringer, luftforurening, fossile brændstoffer, energieffektivitet og kemikaliehåndtering udviser også initiale, negative effekter på CO_2e per capita. Chokket til energieffektiviteten mindsker CO_2e per capita med -0,50 metriske tons ved maksimum, hvilket er den største reduktion påvist i local projections. Generelt findes det, at energimiljøskatter påsat bredere miljømæssige problematiske områder medfører en effekt på mellemlang sigt modsat specifikke områder.

Endeligt anvendes Green Sacrifice Ratio til at vurdere, hvor store økonomiske omkostninger en reduktion af CO_2e per indbygger medfører. De brede, effektive miljøskatterater medfører større omkostninger, hvorimod carbon-skatter påfører økonomien mindre omkostninger. Det udledes dog via impulsresponsfunktionerne for carbon-skatter, at der kun måles en negativ effekt på kort og

mellemlang sigt, hvorimod effektive skatterater medfører en længerevarende reduktion og niveauskifte.

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1. Introduction

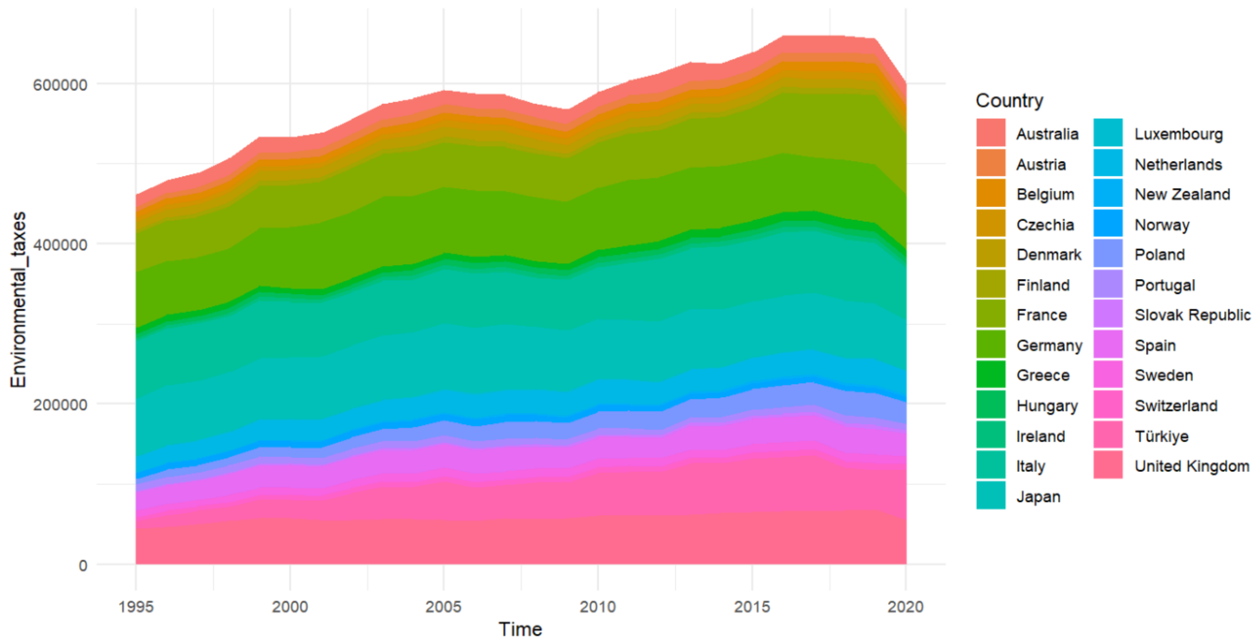
Global warming and the associated climate changes are central and critical challenges for the world's continents, nations and individuals (Zia, Yang, Masood, & Ahmed, 2024). Climate change has led to extreme weather events, temperature changes, loss of biodiversity, pollution, and poverty, which can, among other things, be attributed to greenhouse gas emissions resulting from economic activity and the burning of fossil fuels. The Earth is approaching tipping points, which define the points, where a complex system crosses a threshold, shifting from a relatively stable state into a new state with possible catastrophic consequences, as rolling back the shift can be very difficult and possibly irreversible is done. (Valdecantos, 2023a, p. 3). Therefore, a green transition is essential to prevent irreparable damage (United Nations, 2024, p. 7). Consequently, climate change and its consequences are critical challenges that societies face. More attention has been drawn towards economic policies in ensuring the alignment with goals and objectives to combat climate change.

Several seminal agreements have launched a global endeavor to curb environmental degradation. The 1997 Kyoto Protocol operationalizes the framework established by the United Nations Framework Convention on Climate Change, compelling both industrialized and developing nations to pursue reductions in greenhouse gas emissions according to individually determined targets (United Nations Climate Change, n.d). Likewise, the 2015 Paris Agreement – a legally binding international treaty – commits its signatories to diminish global warming (United Nations Climate Change, n.d). Additionally, several of the United Nations' Sustainable Development Goals address climate change and energy challenges. Overall, numerous global agreements exist as well as targets concerning sustainability, reduction of greenhouse gas emissions and energy supply.

To enhance environmental quality, policymakers therefore consider a range of instruments. One such instrument is environmental taxation, which are incentive-based economic instruments. Environmental taxes are imposed on things that have been proved to affect the environment negatively (Eurostat, n.d). Thus, environmental taxes act as a price signal to polluters. Furthermore, research also shows that environmental taxes can raise revenue at lower costs than conventional taxes by supporting formal employment and not the shadow economy. Since environmental taxes are an incentive-based economic instrument, they have the ability to achieve behavioral changes across sectors, thereby encouraging cleaner consumption and production. On another note, environmental taxation also has the ability to contribute to the achievement of Sustainable Developing Goals (World Bank Group, n.d).

The importance of environmental taxes varies between countries, but throughout the years, countries spend more on environmental taxes as seen in figure 1.

Figure 1 – Environmental taxes in selected OECD countries



Note: Figure 1 displays environmental taxes in million US dollars, 2015 PPP converted. The figure is a stacked-area plot in which each country's environmental taxes from 1995 through 2020 are piled on top of one another. Each colored band represents one country's contribution to the total. The vertical thickness shows the environmental taxes of the country each year. The x-axis displays years, and the y-axis displays environmental taxes in million US dollars, PPP converted. Source: Own production based on data from the OECD database.

Figure 1 shows that the selected countries have been collecting more environmental revenue throughout the period 1995-2020. The total environmental revenue across all countries has increased from approximately 450000 US dollars to approximately 650000 US Dollars in 2015. Afterwards, a small dip occurs in 2020. Also, figure 1 displays the composition of the total tax revenue among the selected countries. Large economics such as Germany, France, the United Kingdom and Japan consistently account for larger shares of the total environmental revenue, whereas smaller countries as Luxembourg and New Zealand have maintained a relatively small fraction throughout 1995-2020.

The total environmental tax revenue displays an upward trend, which highlights the growing importance of environmental taxes as a policy instrument to combat climate change and impose a price signal on pollution. Thus, the purpose of this thesis is to analyze the relationship between environmental taxes and environmental degradation. Specifically, this thesis places its focus on CO_2 emissions, as it is a critical driver of climate change.

The thesis is organized the following way: section two clarifies the research question, while section three provides an introduction to existing literature in the field. Section four presents a theoretical perspective on environmental taxes as a policy instrument, advantages and disadvantages as well as appertaining economic incentives. Relevant theoretical perspectives of the possible outcomes as a result of imposing environmental taxes end section four. The following section, section 5, presents the econometric approach used to perform shocks on various specifications of environmental taxes throughout the analysis. Section six presents a detailed description of the main variables included in the analysis clarifying the choice of variables and their scope as well as their technical definition. Section seven introduces descriptive statistics exploring the trajectory of variables through time as well as their distribution. Section eight presents the outcome of the thesis, which includes a shock to the effective environmental tax rate and effective energy tax rate on per capita CO_2 emissions. Section 9 discusses the findings of the study and computes a Green Sacrifice Ratio to discuss the economic tradeoff of the environmental outcome of section eight. Section 10 summarizes the findings of this thesis.

2. Research question

The existing literature on environmental taxes and its impact on CO_2 emissions is limited. As further elaborated in section three, the literature mostly covers time periods ending in 2015-2018. Most literature also considers the impact of renewable energy as a variable due to its growing importance in the energy transition and thus, climate change. A variety of different econometric methods have been employed to examine the impact of environmental taxes on environmental outcomes, but no studies employ a local projection model. Additionally, most literature, except Aydin & Esen (2024), focusses on the broad scope of environmental taxes without examining specific tax categories. Thus, this thesis aims to fill the literature gap by examining the impact of environmental taxes on CO_2emissions per capita, measured by CO_2 equivalents in a local projection model. Moreover, the thesis also specifies a shock to environmental energy taxes to examine the effectiveness of specific environmental taxes.

Based on the literature gap and identified shortcomings of existing literature, and the importance of environmental taxes, the following research question is proposed:

- What is the relationship between environmental tax levels and CO_2e per capita across 25 OECD countries from 1995-2020?

- How do broad environmental taxes compare to environmental energy taxes in their impact on CO_2e per capita emissions?
- How does an implicit carbon tax affect CO_2e per capita?
- What is the magnitude of the associated economic sacrifice relative to an improvement in CO_2e per capita?

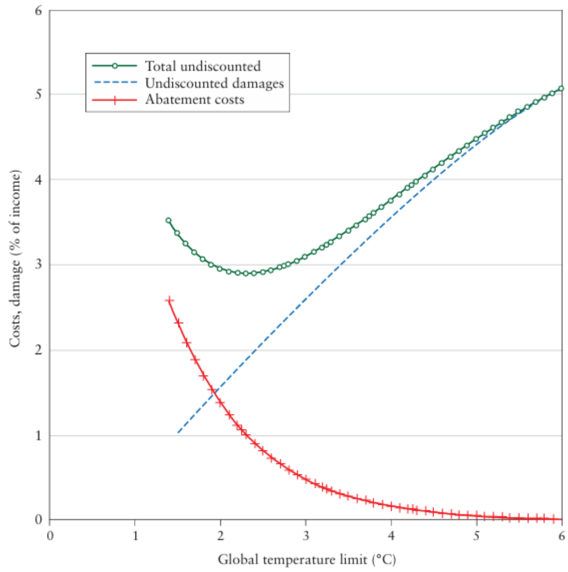
The research question aims to define the scope of the thesis and specifies the time frame while also maintaining tangibility. The abovementioned sub-questions clarify the research question and provide further insight into the scope of the thesis.

3. Literature Review

The following section conducts a literature review on environmental economics concerning the effect of environmental taxes on environmental outcomes. Therefore, the aim of the section is to present background knowledge within the abovementioned field of research.

A widely known contribution to the literature on environmental economics and climate changes is by Nordhaus (2013). Nordhaus (2013, p. 205) applies a cost-benefit analysis to analyze different climate scenarios to mitigate climate changes measured by a global temperature limit. Nordhaus (2013) shows that the optimal climate policy balances abatement costs and climate damages by identifying the temperature that minimizes their sum (Nordhaus, 2013, p. 206). Abatement costs denote the costs of greenhouse gas emissions-reduction as required by climate policy, whereas damage costs consist of monetary costs of damages resulting from climate change (Valdecantos, 2023b). Nordhaus (2013, pp. 206-211) illustrates the optimization problem by curves representing total costs, damages and abatement costs, respectively, as a share of global income. The results of the cost-benefit analysis vary across the different scenarios as different participation rates and discount rates among countries are used. Figure 1 presents an optimistic climate scenario with full participation and no discounting of costs resulting in the minimum of total costs being 2,3 degrees.

Figure 2 – Cost-benefit analysis applied to a climate scenario



Note: Figure 2 displays the global temperature on the x-axis and the costs on the y-axis, defined as a percentage of total income. Assumptions for all curves illustrated are 100 percent efficiency (participation of all countries) and no discounting of any costs. The downward-sloping red curve shows the abatement costs calculated for different global temperature limits, whereas the blue curve shows the undiscounted climate damage costs for different global temperature limits. The green curve illustrates the total undiscounted costs. Source: Nordhaus (2013, p. 207).

Savranlar et al. (2024) further contributes to the sparse literature examining the role of environmental taxes on climate variables. The study employs a panel vector autoregression (PVAR) econometric method to estimate the effect of environmental taxation, economic growth, renewable energy and urbanization on CO_2 emissions in metric tons per capita in EU-27 countries in the period 1995-2018. The study examines the environmental Kuznets curve (EKC) hypothesis[1] - which posits assumes a link between the by GDP per capita and environmental degradation – and finds a negative relationship between economic growth and CO_2 per capita. Also, the study finds that an increase in environmental taxes results in a decrease of 0,14% in CO_2 per capita, which reflects the importance of environmental taxes as a policy tool to combat CO_2 emissions (Savranlar, Ertas, & Aslan, 2024, p. 33776).

Rabhi et al. (2024) examine how environmental taxes and renewable energy consumption affect CO_2 emissions in 36 developing countries in the period 1994-2018 using cross-sectional autoregressive

[1] The EKC hypothesis suggests that emissions increase in early stages of economic growth resulting in declining environmental quality. However, beyond a certain level of income per capita, that depends on various indicators, the trend reverses, and higher levels of income per capita correspond to increasing environmental quality, highlighting an inverted U-shaped relationship between income per capita and environmental quality (Stern, 2017, p. 1).

distributed lag panel data. They estimate four log-linear models that vary in how environmental taxes are defined (as a share of total tax revenue vs. GDP) and how CO_2 emissions are measured (total vs. per capita). The first model regresses log environmental taxes as a share of total tax revenue, log renewable energy consumption of total final energy consumption, log energy consumption from fossil fuels, log GDP and log population on log CO_2 emissions. The second model resembles the first model, except it includes environmental taxes as a percentage of GDP instead of total taxes. The third model is identical to the first model, except the dependent variable is log CO_2 per capita. Finally, the fourth model is identical to the second model, except the dependent variable is log CO_2 per capita. The study finds that renewable energy consumption consistently reduces CO_2 emissions, whereas the environmental taxes do not result in significant reductions in CO_2 emissions due to economic and institutional constraints and a narrow tax base.

Morley (2012) has been leading the way of examining the nexus between environmental taxes and climate change by examining the effectiveness of environmental taxes on air pollution and renewable energy usage by using EU panel data from Eurostat in the period 1995 - 2006, since earlier work had focused on simulation exercises due to lack of useful macro-data.

Morley (2012) uses GMM to estimate two regressions on total GHG emissions as a pollution index, and energy consumption is measured as tons of oil equivalent. Morley (2012) performs a shock environmental tax revenue as a proportion of GDP, total tax revenue and population with real GDP per capita, squared real GDP per capita and capital formation per capita included as control variables. The study finds that an increase in environmental taxes significantly reduces air pollution, regardless of tax revenue definition. A shock to environmental tax revenue as a ratio of GDP has a larger effect on air pollution in comparison to environmental tax revenue as a ratio of tax revenue. The results also indicate a negligible effect of environmental taxes on energy consumption (Morley, 2012).

Ulucak et al. (2020) examine non-linear effects of environmental taxation on CO_2-emissions the in BRICS-countries excluding Russia in the period 1994-2015. The study employs a panel smooth transition that endogenously estimates a globalization threshold and captures shifts between low- and high-globalization regimes.

The model structure consists of the natural logarithm of CO_2 emissions as the dependent variable, with environmental taxation as the shock. Controls include GDP per capita, environmental-related technologies, and patents. Globalization at time t serves as a transition variable in the regression.

The study finds that globalization plays a critical role in negating the rebound effect and the green paradox in the BRICS countries. The rebound effect refers to the difference between expected and realized environmental improvements stemming from efficiency improvements after taking economic mechanisms into account. These environmental improvements are reduced due to behavioral responses. The green paradox describes a scenario, where climate policies aimed at reducing greenhouse gas emissions and improving environmental quality have the opposite result; greenhouse gas emissions can increase for a time period. Consequently, the study finds that environmental-related technologies and environmental-related taxes increase CO_2 emissions in a regime with a low level of globalization. Conversely, environmental-related technologies and environmental-related taxes decrease CO_2 emissions in regimes with high levels of globalization (Ulucak et al., 2020).

Wolde-Rufael and Mulat-Weldemeskel (2021) use an Augmented Mean Group estimator on 1994-2015 data from the following emerging economics: Czech Republic, Greece, Hungary, Korea, Poland, South Africa and Turkey to assess how environmental and energy taxes as shares of GDP, total tax revenue and per-capita tax as well as environmental policy stringency affect consumption-based CO_2 per capita controlling for real GDP per capita, squared real GDP per capita, policy stringency index, squared policy stringency index, fossil fuel and renewable energy consumption shares.

Wolde-Rufael and Mulat-Weldemeskel (2021) find that a unidirectional causality from environmental policy stringency to CO_2 emissions is present. Furthermore, the study finds that stringent environmental policies only induce a reduction in emissions after a certain CO_2-threshold due to an inverted relationship between environmental policy stringency and CO_2 emissions. The study also finds a negative relationship between CO_2 emissions and total environmental taxes. The causal relationship runs from total environmental taxes to CO_2 emissions. No causality is found between energy taxes to CO_2 emissions, however CO_2 emissions are negatively affected by energy taxes.

Aydin and Esen study the effects of environmental taxes on CO_2 emissions on 15 EU member states in the period 1995-2013 by using a dynamic panel threshold method that allows the researchers to endogenously identify nonlinearities and determine whether a threshold exists between environmental taxes and CO_2 emissions. The regression of the study includes the growth rate of CO_2 emissions per capita as the dependent variable, while environmental taxes, GDP per capita, gross domestic expenditure on research and development, industry structure, urbanization level, and energy prices are used as control variables. The tax variable is split into four individual tax categories: total environmental taxes, energy taxes, transport taxes, and pollution and resource taxes – each measured as a ratio of GDP. The study finds a nonlinear relationship: above estimated thresholds, all four categories significantly reduce CO_2 emissions, while below those thresholds they have no significant impact. Therefore, the study finds that environmental taxes serve as price signals that prompt polluters to account for environmental costs. The study identifies threshold rates of 3,02% (total environmental), 2,20% (energy), 0,88% (transport), and 0,28% (pollution/resource). Above these thresholds, each tax category significantly reduces CO_2 emissions, although transport taxes remain insignificant at all levels.

To sum up, the existing literature on both developing and developed nations mostly covers the period from 1994 to approximately 2013-2015. The presence of a common time frame is mostly driven by the availability of environmental tax data starting from 1994. A common denominator across abovementioned studies is the assessment of a causal direction from environmental taxes towards a measurement of environmental quality (Shahzad, 2020, p. 1). Additionally, the importance of renewable energy consumption has been addressed as a dependent and shock variable. Studies employ diverse econometric techniques and often test for the presence of cross-sectional dependence. The general consensus in the literature is that environmental taxes contribute to a reduction in environmental degradation, typically measured as CO_2 emissions, CO_2 per capita or greenhouse gas emissions.

4. Theory

This section outlines the theoretical framework of the project, which serves as a foundation for the analysis and discussion. It presents definitions, economic explanations, and mechanisms that are essential for understanding the implications of the analysis of environmental taxes on CO_2 per capita.

4.1 Environmental taxes as policy instrument

The foundation for the use of environmental taxes as a policy instrument to combat environmental degradation dates back to Pigou (1920), who recognized that market forces are not sufficient to solve environmental problems (Shahzad, 2020, p. 2). A Pigouvian tax is defined as a tax on negative market externalities that are not accounted for in the market and is a way of internalizing external costs (Cornes & Sandler, 1985, s. 1). Environmental taxes serve a dual purpose: they generate public revenue while simultaneously promoting behavioral changes among producers and consumers. Environmental taxes incentivize producers to adapt cleaner technologies and consumers to buy less environmentally harmful products. Therefore, environmental taxes together with strict regulations are important policy instruments to combat climate change (Wolde-Rufael & Mulat-Weldemeskel, 2021, p. 3).

Environmental taxes, quotas, charges, tradable permits, and other economic instruments are cost-effective controlling measures to combat greenhouse gas emissions (Fullerton et al., 2008, p. 1). Environmental taxes encourage cleaner production and consumption of energy-related products. It is also argued that environmental taxes have the potential to change the structure of production, favoring environmentally cleaner production (Wolde-Rufael & Mulat-Weldemeskel, 2021, p. 3).

The insufficiency of conventional environmental regulations has encouraged the use of economic instruments like environmental taxes and emissions trading to correct unsustainable practices. Environmental taxes – by internalizing pollution costs – offer incentive-based regulation that lowers the costs of shifting production and consumption patterns (Fullerton et al., 2008, p. 1). They encourage a sustainable energy transition (Shahzad, 2020, pp. 2-3). However, environmental taxes can influence individuals' perceptions and behavioral responses, which may either have beneficial or adverse consequences for the environmental quality, depending on whether environmental taxation is perceived as a 'green signal' or a permission to pollute (Fullteron et al., 2008, p. 6).

Environmental taxes are an efficient environmental policy tool. Environmental taxes can reduce the costs of achieving a given environmental quality or increase environmental benefits for a certain economic cost. Environmental taxes incentivize polluters to abate climate changes in the least expensive way which results in a certain level of abatement at a smaller total abatement cost. Environmental taxes also minimize the need for authorities to collect detailed information on the individual polluters' abatement costs highlighting the efficiency aspect of environmental taxes (Fullerton et al., 2008, p. 3).

Additionally, environmental taxes establish a continuous incentive to reduce greenhouse gas emissions. Polluters are also encouraged to reduce their emissions below the cost-effective level due to taxes being levied on residual emissions[2]. Thus, environmental taxes create an ongoing incentive for innovation in abatement technology by applying a cost to each unit of pollution. Under current technology, firms abate pollution up to the quantity, where marginal abatement costs equal the tax rate. Environmental taxes incentivize the innovation of techniques that reduce emissions at a marginal cost lower than the tax rate. A cheaper abatement technology that reduces emission for less than the

[2] Residual emissions are defined as emissions that are difficult to eliminate or evade due to financial, technological, or other limitations (European Commision, 2024).

tax rate allows firms to abate more pollution at lower cost, and environmental tax payments decrease. Ultimately, firms save money (Fullteron et al., 2008, p. 3).

Uniform environmental taxes are cost-effective regarding a wide distribution of abatement. Individual economic circumstances and individual negotiation are not considered when environmental taxes are uniform, and all polluters have limited possibilities in terms of negotiation of favorable terms (Fullteron et al., 2008, p. 3).

From a fiscal standpoint, environmental taxes based on energy, which is an inelastically-demanded commodity, are expected to be less sensitive to business cycles and behavioral changes compared to other tax bases (Fullerton, Leicester, & Smith, 2008, p. 3). Others argue that environmental taxes have asymmetrical effects on environmental quality as it depends on whether revenue stemming from these taxes is high or low. Consequently, tax levels influence the final effect on the environmental outcome (Aydin & Esen, 2018, s. 2400).

Ultimately, fully utilizing the potential gains from environmental taxes depends on effective targeting of incentives to pollute. Environmental taxes that are poorly targeted may exacerbate economic costs of taxation without offering sufficient environmental gains (Fullteron et al., 2008, pp. 8-9).

Implementation of environmental taxes does not rule out undesirable outcomes. The effectiveness of environmental taxes requires firms to weigh marginal cost against marginal savings from reduced tax payments when firms choose to abate more, which is not necessarily a priority within the firm as it could necessitate institutional adjustments. Such adjustments might be costly, and firms may exhibit limited or no behavioral response to low taxation levels. Although environmental taxes aim to internalize negative externalities, they can result in adverse outcomes, if the polluters' behavior offeset intended benefits. For instance, taxing toxic-waste disposal may incetivize illegal dumping (Fullteron et al., 2008, p. 5). Similarly, benefits from vehicle fuel efficiency can lower costs of driving and boost disposable income, which may be spent on additional driving or goods – ultimately raising overall energy use overall energy use. This phenomenon is known as the rebound effect (Vivanco et al., 2016, p. 60).

Additionally, environmental taxes are frequently regressive in nature, placing a disproportionately larger burden on low-income households. Benefits derived from environmental improvements are often accrued to high-income households, who exhibit a greater willingness to pay for improvements in environmental quality. Therefore, environmental quality can be seen as a luxury good, and the distributional consequences must be carefully handled in the construction of environmental taxes (Fullteron et al., 2008, p. 5). Furthermore, environmental taxes increase production costs for firms, which can affect their international competitiveness. Increased costs are often passed on to consumers, further exacerbating the financial burden of low-income households and strengthening the existing income inequality (Wolde-Rufael & Mulat-Weldemeskel, 2021, p. 4; Fremstad & Paul, 2019, p. 96).

Consequently, environmental taxes are a powerful tool for increasing the costs of pollution, and their full potential depends on the effective use of the revenue. Therefore, environmental taxes may result in additional economic benefits that increase welfare benefits while still cutting emissions. The next section explores the double dividend theory, which addresses this exact scenario.

4.2 Double dividend theory

The double dividend hypothesis states that environmental taxes serve a dual purpose: to improve the environmental quality, the "green" dividend, and to utilize the revenue generated from the environmental taxes to reduce overall economic costs of the tax system by reallocating the revenue to reducing distortionary taxes – such as taxes on labor supply, investment or consumption – that restrict economic growth, the "blue" dividend (European Environment Agency, n.d.). The green dividend occurs due to environmental taxes reducing the amount of greenhouse gas emissions. Simultaneously, the blue dividend defines a scenario, where the revenue generated from environmental taxes is used to lower existing taxes to obtain non-environmental benefits (Ciaschini et al., 2012, p. 273-274). The blue dividend is generally construed as an improvement in economic welfare resulting from the reduction of distortionary taxes on labor supply and investment that would otherwise discourage labor supply or investment due to adverse behavioral adjustments being induced (Ciaschini et al., 2012, p. 274).

Taxes impose an excess burden that reduces individual welfare. Fullerton et al. (2008, p. 11) argue that revenue from environmental taxes can reduce the income tax raising the net wage and possibly offsetting welfare costs. This increases the labor supply. When environmental taxes are passed on to consumers, the prices of taxed goods rise relative to the wage rate, reducing the real net wage – the goods one hour of labor can buy – and thus decrease labor supply. However, if tax revenue is used to cut income taxes, the real net wage increases, potentially boosting labor supply and lowering the excess burden of taxation (Fullerton et al., 2008, p. 12).

Although environmental taxes may result in less distortionary taxes from the blue dividend, unintended behavioral responses can possibly erode environmental and welfare gains. If future tax increases are anticipated, emissions are possibly expedited. The next section examines this phenomenon: the green paradox.

4.3 Green paradox

The green paradox refers to a scenario in which environmental policies, rather than achieving their intended target of reducing greenhouse gas emissions, result in unintended consequences leading to an increase in emissions. The term green paradox is generally used to define unintended consequences of climate policies (Jensen et al., 2015, p. 246).

A critical example, that is defined as the weak green paradox, is the energy tax policy, which can expedite the depletion of natural resources, e.g. fossil fuels, if the future energy prices are expected to rise more than current prices. Fossil fuels are nonrenewable resources, and the price reflects costs of production and scarcity rents. Profit-maximizing resource-owners may extract more resources sooner than later, when future net revenue is expected to decline. Consequently, the dynamic nature of the response from the supply side of the resource market creates a weak green paradox (Jensen et al., 2015, p. 246).

If resource-owners are still able to extract resources profitably, the forward shift in extraction could increase total damages. A strong green paradox refers to a scenario where climate policies result in an increase in environmental damage in the long run (Jensen et al., 2015, pp. 246-247, 252)

The green paradox, which describes a scenario, where tax signals can trigger immediate rises in extractions and thus emissions, highlights the importance of tracing dynamic responses to tax shocks. The following section presents the empirical aspects of the thesis, which employs local projections to a shock to environmental taxes on CO_2 emissions per capita. This approach provides a trajectory of the dynamic response of CO_2 emissions per capita, which makes it possible to identify whether CO_2 emissions per capita react as expected or not.

5. Econometric Approach

The following section presents the econometric approach applied in the thesis to analyze the relationship between environmental tax levels and CO_2 per capita. Employing local projections has several advantages. One advantage of local projections is that estimation can be done with simple least squares (Jordà, 2005, p. 162). Furthermore, local projections provide inference, which does not need delta methods or numerical techniques for calculation, and the method is robust to misspecification of the data generating process (DGP), due to each impulse response coefficient being estimated by a different regression (Jordà, 2005, p. 162; Jordà, 2023, p. 6). The sequential estimation of regressions also makes it possible to manage nonlinear specifications, which is useful when specifying the full system is difficult due to data limitations or model complexity (Jordà, 2023, p. 1). Local projections offer advantages that motivate the use of local projections compared to VAR models. A VAR model is a linear global approximation to the DGP and is ideal for one-period ahead forecasting. However, an impulse response function is a function of forecasts over longer horizons resulting in misspecification errors compounding with forecast horizons (Jordà, 2005, p. 162). Local projections, on the other hand, rely on different regressions estimated at each horizon, which results in a directly estimated impulse response coefficient at each horizon. This implies that small misspecifications do not compound when using local projections (Jordà & Taylor, 2024, p. 6).

5.1 Local projections

Local projections are an alternative econometric method for estimating impulse response functions to VARs (Jordà & Taylor, 2024, p. 1). Impulse response functions[3] illustrate the reaction of an outcome variable in response to an exogenous policy intervention or shock compared to a baseline scenario without any shocks (Jordà, 2023, p. 2). Fundamentally, local projections are used to characterize the structure of covariance matrix for a system of variables (Jordà & Taylor, 2024, p. 1).

A key feature of local projections is that the method involves a sequence of regressions of the endogenous variable, shifting forward each period. This econometric technique eliminates the need to estimate the underlying multivariate dynamic systems, as required in VAR models (Jorda, 2005, p.161). The endogenous variable is regressed onto the shock conditional on the control variables, meaning that a separate regression is estimated for each time horizon (Jordà & Taylor, 2024, p. 1). The collection of the h regressions is referred to as local projections (Jordà, 2005, p.163).

[3] Declaring y_t as the outcome variable of interest, x_t as a vector of control variables, s_t as lags of the outcome variable and of the policy intervention, s_0 as the baseline before intervention, and δ as the size of the shock, impulse response functions can be formally defined as: $R_{s \to y}(h, \delta) \equiv E[y_{t+h}|s_t = s_0 + \delta; \boldsymbol{x}_t] - E[y_{y+h}|s_t = s_0; \boldsymbol{x}_t]; h = 0,1 \ldots H,$where the subscript, $s \to y$ indicates, that the shock affects the outcome variable (Jordà & Taylor, 2024, p. 2).

Local projections can also be used to estimate impulse response functions for panel data. Assuming that there exists a sample of $i = 1, \dots, n$ observations over time period $t = 1, \dots, T$, the general functional form of panel local projections can be written as:

$$y_{i,t+h} = \alpha_{i,h} + \delta_t + \beta_h shock_{i,t} + \gamma_h x_{i,t} + \varepsilon_{i,t+h}, h = 0, 1 \dots . H - 1 \qquad (5.1.1)$$

(Adämmer, 2019, p. 4; Jordà, 2023, p. 26)

It follows from equation 5.1.1 that $y_{i,t+h}$ represents the endogenous variable, also denoted the outcome variable, $\alpha_{i,h}$ is a cross-section fixed effect, while δ_t represent a time-fixed effect. The shock represents an identified disturbance to the economy. $x_{i,t}$ refers to a vector of control variables, and $\varepsilon_{i,t+h}$ is the error term (Jorda, 2023, p. 26; Adämmer, 2019, p. 4).

5.2 Specification of local projections regression

The local projections panel data regression of this thesis has the following functional form:

$$y_{i,t+h} = \alpha_{i,h} + \delta_t + \beta_h shock_{i,t} + \gamma_h (L) x_{i,t-j} + \varepsilon_{i,t+h}, h = 0, 1 \dots . H - 1 \qquad (5.2.1)$$

The study conducts a local projections panel data regression with CO_2 per capita as the outcome variable, $y_{i,t+h}$. The baseline shock to the economy, $shock_{i,t}$, is a shock to the effective environmental tax rate. Various lagged control variables, $x_{i,t-j}$, are included to reduce omitted variable bias and capture the respective effects on the dependent variable. CO_2 per capita, GDP per capita, environmental domestic innovations as a percentage of total innovations, trade openness, renewable energy consumption as a percentage of total final energy consumption, petrol tax rate and OECD Environmental Policy Stringency Index constitute the control variables in the local projections panel data regression. $\alpha_{i,h}$ represents a cross-section fixed effect while δ_t represents a time-fixed effect. The choice of variables is further elaborated in section 6.

5.2.1 Twoways fixed effects

The linear local projection model uses a two-way fixed effects method to control for unobserved heterogeneity in terms of unit- and time-specific fixed effects. The unit-specific fixed effects are time-invariant, while the time-specific fixed effects are unit-invariant (Imai & Kim, 2020, p. 1). The unit-specific fixed effects work by removing the unit-specific time averages after which a pooled OLS is applied to the data. Thus, unit-specific fixed effects are unobserved differences between units that do not change over time. Time-specific fixed effects work by removing changes in the economic environment, such as global shocks, that have the same effect on all units over time (Woolridge, 2021, p. 2). Dummies for unit-and time-specific fixed effects are controlled for at each horizon, H. Consequently, this method targets cross-sectional dependence, which is a common occurrence in macroeconomic data (Driscoll & Kraay, 1998, p. 549).

5.2.2 Driscoll Kraay standard errors

The model employs Driscoll Kraay standard errors that are robust to general forms of cross-sectional dependence, since a weak cross-sectional dependence is present in the data[4]. Cross-sectional dependence is a common issue encountered in macroeconomic data, and it denotes the case where cross-sectional units were not randomly selected. Units are then subjected to observable and unobservable common disturbances (Driscoll & Kraay, 1998, p. 549).

Driscoll and Kraay (1998, p. 550) propose a modification of the standard nonparametric time series covariance matrix estimator, which is robust to cross-sectional dependence. Driscoll and Kraay standard errors for coefficient estimates are calculated as the square roots of the diagonal elements of the asymptotic covariance matrix. Therefore, the Driscoll and Kraay standard errors correspond to the Newey and West heteroscedasticity and autocorrelation consistent covariance matrix estimator applied to the cross-sectional averages instead of regression residuals (Hoechle, 2007, p. 8).

[4] Appendix A.2 presents technical tests for cross-sectional dependence.

6. Data description

This section provides a detailed description of the data utilized in the empirical model of the thesis. It clarifies the selection of variables, while also elucidating methods of measurement and data collection. To analyze the research question concerning the relationship of environmental taxes on CO_2 emissions, the local projection regression incorporates macroeconomic and environmental variables. The dataset is based on annual data in the period 1995-2020. Most countries began implementing environmental taxes in the years 1994 and 1995, and to broaden the scope of the study by including more countries, the study employs data from 1995, since the availability of data is greater in 1995. The study is based on 25 OECD countries from the western sphere. The following countries are included in the data: Australia, Austria, Belgium, Czechia, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Türkiye and the United Kingdom. The data sources of the variables are the OECD Database and the World Bank database.

6.1 Dependent variable - CO_2e per capita

The study examines the impact of environmental taxes on carbon dioxide emissions excluding LULUCF per capita (t $CO_2e/capita$) as the dependent variable. Carbon dioxide is measured as CO_2-equivalents in metric tons per capita. Higher concentrations of greenhouse gas emissions trap heat in the atmosphere – specifically carbon dioxide – driving climate change, which leads to natural disasters and globally rising temperatures.

Carbon dioxide is one of several greenhouse gas emissions included in the Kyoto Basket, which can be traced to the Kyoto Protocol, that operationalizes the United Nations Framework Convention on Climate change in which developed and developing nations commit to reduce greenhouse gas emissions (Eurostat, n.d.). The Kyoto basket consists of carbon dioxide, methane, nitrous oxide and F-gases (hydrofluorocarbons and perflurocarbons) and sulphur hexafluoride (Eurostat, n.d.). The gases are weighed according to their Global Warming Potential[5] (GWP) and aggregated to determine total greenhouse gas emissions, which are converted to carbon dioxide equivalents, CO_2e. The

[5] Greenhouse gases have different effects on climate change. Gases have various abilities to absorb energy and various lifetimes in the atmosphere. GWP measures the amount of energy that the emission of one ton of gas absorbs over a given time period compared to the emission of one ton of carbon dioxide (CO_2). Carbon dioxide, CO_2, is assigned a GWP of one by definition, irrespective of time period used, as it is the reference gas. A larger GWP means that a certain gas warms the Earth compared to CO_2 in a given time period (Eurostat, n.d).

conversion makes it possible to compare emissions of different gases, which makes it possible to identify emission reductions.

The variable is calculated as a measure of CO_2 from agriculture, energy, waste and industrial sectors, excluding LULUCF, and converted into a standardized measure of carbon dioxide equivalents. Finally, the measure is divided by the respective populations, which results in a weighted average (World Bank Group , n.d).

The measure excludes greenhouse gas emissions caused by land use, land-use change and forestry (LULUCF) due to large uncertainties in estimation. Notably, global greenhouse gas emissions cannot be directly measured; however, estimation approaches are used by scientific organizations, e.g EDGAR (Emissions Database for Global Atmospheric Research Community GHG Database, to generate the data (World Bank Group , n.d).

6.2 Shock variable – Effective Environmental tax rate

Environmentally related tax revenue as a ratio of the total tax base is the shock variable to the economy. Thus, this variable constitutes an effective environmental tax rate. It is important to note that the effective environmental tax rate does not specify the origin of the shock – whether the government raises the environmental taxes or exogenous events are the reason environmental revenue is increased. Environmentally related taxes have the ability to affect relative prices of goods and services, which make them an effective policy instrument to promote the green transition (OECD, 2024a, p. 1). Environmentally related taxes impose a price signal to polluters encouraging them to incorporate the costs of environmental degradation in consumption and production decisions (OECD, 2006, p. 10). Environmental taxes are frequently used and increasingly proven effective. Expressing environmentally related tax revenue as a ratio of the total tax revenue standardizes the measure across countries and years, allowing comparisons regardless of country size or economic scale. A higher ratio means that the country is collecting more environmental taxes relative to the total tax base, which indicates stronger environmental policies on pollution taxation. Environmentally related taxes can decrease if tax rates are lowered, or an erosion of the tax base occurs (OECD, 2024a, p. 1). Furthermore, the effective environmental tax rate captures the amount of resources to be spent on green innovation, investments and possible tax cuts.

The effective environmental tax rate can be considered a fiscal-like environmental policy instrument. The measure illustrates the budgetary weight of environmental taxation, which indicates the fiscal importance placed on the environment.

The effective environmental tax rate is calculated in billions in national currency to avoid translation issues. The environmentally related tax revenue is based on revenue from all tax categories and all domains. The total tax base is based on total tax revenue from the general government, which includes tax on income, profits, and capital gains of individuals and corporations, social security contributions, taxes on payroll and workforce, taxes on property, taxes on goods and services, and other taxes (OECD Data Explorer, n.d.).

6.2.1 OECD Definition of a tax

The OECD defines a tax identically to SNA and SEEA:

"Taxes are compulsory, unrequited payments, in cash or in kind, made by institutional units to government units" (OECD, 2023, p. 8)

Both SNA, OECD PINE Database and OECD Revenue Statistics and IMF Government Finance Statistics Manuals and Guides (IMF GFSM) comply with the abovementioned definition. All payments to the government that work the same way as taxes and tax-like fees and charges fall under the umbrella of a tax (OECD, 2023, p. 8).

6.2.1.1 Environmentally related taxes in the ERTR database

The OECD classifies taxes as environmentally related based on whether their tax base is deemed environmentally relevant, not on economic literature's marginal-cost criteria for internalizing externalities with the idea of decreasing environmentally harmful behavior. This approach of identifying environmentally related taxes is common ground among OECD, SNA, SEEA, IMF GFSM and Eurostat (OECD, 2023, p. 9).

OECD and Eurostat define environmentally related taxes the following way:

"Environmentally related taxes are taxes whose tax base is a physical unit (or a proxy of it) of something that has a proven, specific, negative impact on the environment." (Eurostat, 2001, p. 9)

Practical and administrative reasons result in taxation of input or output of activities closely connected to environmental pressures (i.e. emissions and pollutants), when physical units directly connected to environmental outcomes are not taxed for the reasons stated. Such taxes also define environmentally related taxes (OECD, 2023, p. 10).

Environmental tax revenue is extracted from the Environmental Related Tax Revenue Database (ERTR), which categorizes taxes based on their environmental relevance and filters them based on four tax base categories: energy taxes, pollution taxes, transport taxes and resource taxes – see Table 1. The tax base categories are mutually exclusive. Taxes are then organized into 22 environmental domains enabling empirical analyses of policy instruments. The ERTR database draws from the OECD Database 'Policy Instruments for the Environment (PINE)', which contains quantitative data on environmentally related taxes, fees, tradeable permits and more (OECD, 2024a, p. 1). The ERTR database is validated across and supplemented by OECD Revenue Statistics, Eurostat National Tax Lists, Global Revenue Statistics Databases and official national sources. Furthermore, ERTR database complies with the guidelines of System of Environmental Economic Accounting (SEEA)[6] and System of National Accounts (SNA)[7] in order to support harmonized, international ERTR accounts (OECD, 2023, p. 5).

6.2.2 Environmentally related tax categories

Environmentally related tax categories define what is being taxed. Consequently, taxes fall into one certain tax base. Table 1 summarizes examples of products and services taxes within each tax category.

Table 1 – Environmentally related tax bases

Tax base category	Detailed definition	Examples of Environmentally related tax bases (consumption, production and trade, including measured and estimated values)
Energy taxes Includes fuel for transportation	Energy products for transport purposes	Unleaded petrol, leaded petrol, diesel Other energy products for transport purposes (e.g. liquified petroleum gas, natural gas, kerosene, fuel oil

[6] The SEEA defines internationally accepted sets of standard concepts, definitions, classifications, accounting rules and tables to construct comparable statistics (System of Environmental Economic Accounting, n.d).

[7] SNA defines international accepted recommendations on how to compose measures of economic activity. It describes sets of macroeconomic accounts based on internationally agreed definitions, classifications, accounting rules and concepts (United Nations, n.d).

	Energy products for stationary purposes	Light and heavy fuel oil, natural gas, coal, coke, biofuels, electricity, district heat, other energy products for stationary use
	Energy-related GHG emissions	Energy related carbon content, energy related emissions of CO_2 emissions and other GHGs (including proceeds from permit schemes)
Transport taxes Excludes fuel for transport		Motor vehicles: production, trade or sale (one off taxes), registration or use (recurrent, annual taxes), vehicle insurance (excluding general insurance taxes) road: use of (e.g. motorway taxes), congestion (e.g congestion charges and city tolls), other means of transport: railways, waterways (e.g. taxes on ships), air (e.g. flight and flight tickets)
Pollution	Non-energy related GHG emissions	Non-energy related carbon content (e.g. peat), emissions of CO_2 and other GHG-emissions not related to energy (e.g. cattle-breeding, meat diets, rice cultivation, cement); including proceeds from permit schemes
	Pollutant emissions to air (excluding GHG emissions)	Nitrogen oxides emissions, sulphur oxides emissions, Other air pollutants (e.g. particulate matter, volatile organic compounds, ammonia, mercury), Products containing heavy metals (e.g. paint, solvents)
	Ozone depleting substances	Ozone depleting substances (e.g. chlorofluorocarbons, halons, hydrochlorofluorocarbons)
	Effluents to water	Effluents of oxidizable matter (biochemical oxygen demand, chemical oxygen demand), Other effluents to water, Wastewater collection and treatment (e.g. fixed annual taxes)
	Non-point sources of water pollution	Synthetic pesticides (taxes based on e.g. chemical content, price or volume), synthetic fertilizers

		(taxes based on e.g. phosphorus or nitrogen content or price), products containing chemicals or emerging concern (e.g. pharmaceuticals, personal care products), manure (taxes based on nitrogen released)
	Waste management	Waste collection, treatment or disposal, Individual products (e.g. batteries, electrical and electronic equipment, tyres, motor oil, lubricants), packaging (e.g. beverage containers, plastic bags, pallets)
	Noise	Noise (e.g. aircraft take-off and landings)
	Radiation	Radiation, radioactive substances
Resources	Resource extraction, abstraction, harvesting	Freshwater resources, Forest resources (e.g. timber), fisheries resources, Natural biological resources (e.g. wild plants and animals), Minerals (excluding oil and natural gas; including exploration activity), Landscape changes (e.g. cutting of trees)
MEMO ITEM 1	Certain land taxes	Land conversion taxes (e.g. from forest to agricultural land use), taxes on land or soil characteristics of environmental relevance (e.g. m^2 of soil sealing, soil quality), taxes on certain land uses (e.g. intensive agriculture and forestry, surface mining)
MEMO ITEM 2	Taxes on oil and natural gas extraction	Extraction of oil and natural gas
MEMO ITEM 3	Resource rent taxes (profit taxes only)	Profits related to the resource rent (e.g. from mining, fisheries)
MEMO ITEM 4	Elevated value-added taxes (VAT)	Elevated VAT on environmentally related tax bases

Note: Reconstruction of Table 1 from 'Methodological Guidelines for Environmentally Related Tax Revenue Accounts' (OECD, 2023, p. 11). The report employs Eurostat's statistical guide for compiling ERTR accounts; however, OECD has added additional refinements to the original framework due to revisitations of the conceptual foundation, and those are defined as MEMO ITEMs, *which are not included in the total. The table illustrates the tax bases in which environmentally related taxes are categorized. The list is dynamic and can be adjusted according to new approaches or definitions. Source: OECD (2023, p. 11).*

The energy tax category comprises tax revenue from energy products for both transport, stationary purposes, and from energy-related greenhouse gas emissions. The category also includes permit schemes, which fit the definition of a tax in national accounts and are based on energy-related greenhouse gas emissions (OECD, 2023, p. 12).

The transport tax category includes tax revenue linked to ownership, production, trade and use of motor vehicles and the use of transport services such as airplanes, ships, railways and more. Registrations of vehicles are also included in the transport tax base (OECD, 2023, p. 12).

The pollution tax category covers tax revenue from non-energy related greenhouse gas emissions, and tax revenue from all other sources of pollution not included in the energy and transport tax base. Tax revenue from non-energy related greenhouse gas emissions consists of taxes imposed on emissions linked to peat degradation, cattle breeding and synthetic fertilizer application. Specifically, pollutant emissions related to air and water, waste management and noise are included in the pollution tax base (OECD, 2023, p. 12).

The resource tax category encompasses tax revenue from resource-related tax bases of environmental relevance. Taxes imposed on extraction of natural resources, renewable and non-renewable. The category strictly includes tax revenue that is reported as such in the national accounts. Land taxes, which are included in MEMO 1, are not included in this tax category. Additionally, taxes on oil and natural gas extraction, which are included in MEMO 2, and taxes on resource rent, which are included in MEMO 3, are not included in this tax category (OECD, 2023, p. 12).

Accurate classification of the environmentally related taxes into the correct tax base category is critical. A tax imposed on mining operations could be identified as a resource tax, land tax, resource rent tax or pollution tax, depending on the tax base. In case the amount of mineral extraction (tons) is taxed, the tax is defined as a resource tax in the ERTR database. If the land utilized for extracting minerals (e.g. hectares) is taxed, the tax is identified as a land tax in MEMO 1 and is not included in the ERTR total. A tax imposed on the profits from mineral extraction would be defined as a resource rent tax in MEMO 3 (OECD, 2023, p. 12).

The ERTR database uses an accrual basis accounting method to report taxes on an annual basis. This method considers taxes when the obligation to pay occurs. In practice, this means that the ERTR is recorded when the taxable activity occurs. This does not necessarily correspond to the point at which the tax authorities are notified, a tax assessment is issued, the tax liability becomes due, or when the payment is ultimately made (OECD, 2023, p. 16).

6.2.3 Environmental domains

The ERTR database classifies environmental taxes into 22 environmental domains, each corresponding to a specific environmental externality, an environmental focal issue, that policy instruments address. Thus, the domains indicate the environmental motivation to impose a tax. While instruments can indirectly affect other domains, only the domains that policy instruments has a direct effect on are considered. As an example, a landfill tax directly affects domains solid waste and circular economy, but it may also affect climate change domains indirectly by reducing methane emissions. Consequently, only domains in which the policy instruments have a direct short-run impact are tagged (OECD, 2024b, p. 10). Contrary to environmentally related tax categories, environmental domains are not mutually exclusive, since multiple domains can be targeted by a policy instrument (OECD, 2024a, p. 3).

The domains can be divided into overall categories; environmental protection, natural resource management and cross-cutting domains. Domains that fall into the umbrella of environmental protection are air pollution, water pollution, soil pollution, solid waste, ozone layer, noise and radiation. Domains that define natural resource management are fisheries, forests, freshwater, renewable energy, fossil fuels and minerals. Finally, the cross-cutting domain includes climate change mitigation, climate change mitigation, climate change adaptation, land degradation, biodiversity, ocean, chemicals, energy efficiency, circular economy and mercury (OECD, 2024b, p. 8).

The study employs domains climate change mitigation, air pollution, fossil fuels, chemical management and energy efficiency in the analysis. Climate change exerts growing pressures on global ecosystems disrupting national economies and altering human livelihoods. Climate change mitigation aligns with Sustainable Development Goal 13 and supports the objectives established in the 2015 Paris agreement. Climate change mitigations policy instruments are targeted towards a reduction in greenhouse gas emissions as well as enhancements of nature-based or technology-based greenhouse gas sequestration (OECD, 2024b, p. 42).

Table 2 - Examples of climate change mitigation policy instruments

Taxes	Tradable permits
Tax on diesel and liquefied gas (Argentina)	Renewable Energy Certificates (Australia)
Contribution for intervention in economic domain (excise tax on fuels) (Brazil)	EU Emissions Trading Systems
National tax for diesel and petrol (Colombia)	Swiss CO_2 Emissions Trading Scheme
Domestic tax on electricity final consumption (France)	

Note: Reconstruction of Table 29 from 'Environmental domain tagging in the OECD PINE database' (OECD, 2024b, p. 43). The table proposes examples of different policy instruments that target climate change mitigation from various countries. Source: OECD (2024b, p.43)

Air pollution is considered a critical environmental health risk, since it causes diseases that lead to disabilities and deaths. Common strategies for combatting air pollution include reducing atmospheric emissions through fuel-efficient technologies and scrubbers for fuel combustion, monitoring and controlling emission levels, curbing or regulating air pollution-generating activities (e.g. road transportation), and the implementation of broader structural changes in the economy (OECD, 2024b, p. 15).

Table 3 – Examples of air pollution policy instruments

Taxes	Tradeable permits
SO_2 and NO_x pollution tax (Italy)	Clean Air Interstate Rule - SO_2 and NO_x allowance trading (United States)
Tax on emissions from stationary sources (Chile)	NO_x emissions trading (Netherlands)
Individual consumption tax on passenger vehicles (Korea)	Transferable consumption allowances for degreasing solvents (Canada
Excise tax on petroleum products (Seychelles)	

Note: Reconstruction of Table 2 from 'Environmental domain tagging in the OECD PINE database' (OECD, 2024b, p. 16). The table proposes examples of different policy instruments that target air pollution from various countries. Source: OECD (2024b, p.16)

Fossil fuels are contributing to climate change in an alarming way which makes reduction in the use of fossil fuels a priority. Measures are taken to redirect the support for non-renewable energy sources to comply with Sustainable Development Goal 12. Specifically, policy instruments tagged in the fossil fuels domain aim to minimize the extraction and use of fossil fuel as primary fuel, the transformation to secondary fuel productions or material goods (OECD, 2024b, p. 38).

Table 2 - Examples of fossil fuel policy instruments

Taxes	Tradable permits
Motive Fuel Taxes Unleaded gasoline (Newfoundland, Canada)	Transferable consumption allowances for degreasing solvents (Canada)
Liquified petroleum gas tax (Japan)	Energy Efficiency Certificates (TEE) for saving electricity, natural gas and/or other fuels (Italy)
Basic tax on mineral oil (Norway)	
Individual consumption tax on petroleum products, Kerosene (Korea)	

Note: Reconstruction of Table 25 from 'Environmental domain tagging in the OECD PINE database' (OECD, 2024b, p. 39). The table proposes examples of different policy instruments that target fossil fuels from various countries. Source: OECD (2024b, p. 39)

The energy sector plays a large role in emitting greenhouse gas emissions, which increases the focus on improvements in production, delivery and consumption of energy. However, energy also contributes to reducing global challenges like poverty, unemployment, insecurity and increasing access to basic services. This domain is in alignment with Sustainable Development Goal 7. Policy instruments consist of measures aimed at heat and energy savings, which reduce the energy intake from all energy sources. Thus, sectors affected by these instruments span from households, all economic sectors and value chain processes in both energy production, resource efficiency and technological development (OECD, 2024b, p. 55).

Table 5 - Examples of energy efficiency policy instruments

Taxes	Tradable permits
Tax on electricity (Sweden)	Energy efficiency certificate scheme (Victoria, Australia)
Duty on electricity for storage heaters (installed before April 1999) (Germany)	Perform Achieve and Trade - energy savings certificates (India)
Promotion of power-resources development tax (Japan)	Clean energy certificates (Mexico)
Federal contribution on electricity and natural gas (Belgium)	Energy Efficiency Certificates (TEE) (Italy)

Note: Reconstruction of Table 41 from 'Environmental domain tagging in the OECD PINE database' (OECD, 2024b, p. 56). The table proposes examples of different policy instruments that target energy efficiency from various countries. Source: OECD (2024b, p. 56)

Chemicals management policy instruments address environmental and health risks caused by production, consumption, usage and disposal of chemicals and products containing chemicals. The policy instruments support the innovation of safe and sustainable alternatives to harmful chemicals and the protection of individual consumers, workers and vulnerable populations, as well as protection of the environment. The instruments are in the nature of polluter-pays-principle (OECD, 2023, p. 53).

Table 6 - Examples of chemicals management policy instruments

Taxes	Tradeable permits
Tax on chemicals in certain electronic products (Sweden)	Ozone depleting substances (United States)
Hazardous chemicals inventory fee (Indiana, United States)	Tradable permits for lead in gasoline (United States)
Duty on pesticides (Italy)	Transferable consumption allowances for degreasing solvents (Canada)
Duty on PVC-fil (Denmark)	Tradable phosphorous discharge rights (Colorado, United States)

Note: Reconstruction of Table 39 from 'Environmental domain tagging in the OECD PINE database' (OECD, 2024b, p. 55). The table proposes examples of different policy instruments that target chemicals management from various countries. Source: OECD (2024b, p. 55)

6.2.4 Interpretation of the interaction between tax category and domain

The energy tax category is the only tax category used to further explore the pattern of the data. The choice of the energy tax category is based on the importance of the global energy transition and the growing demand for renewable energy to meet climate change commitments.

The analysis in section 8.7 is based on the energy tax category with abovementioned domains. Filtering the energy tax revenue by domains results in a specific interpretation of the data. One of the chosen domains is fossil fuels, and together with the energy tax category, the revenue should be interpreted as the sum of revenues from taxes on energy products that are classified to reduce the extraction and use of fossil fuels. Therefore, the tax category defines the types of activity, goods or services being taxed, and the domain states the environmental incentive behind the taxation. The same interpretation of the interaction between tax category and domain can be applied to the remaining domains used in the study, respectively.

6.3 GDP per capita

GDP per capita is included to control for the effect of per capita income on per capita CO_2 emissions. Controlling the relationship between greenhouse gas emissions and per capita income is linked to the Environmental Kuznets Curve hypothesis which states that in early stages of economic development, pollution and emissions increase due to the prioritization of economic expansion, however after a certain per capita income threshold, pollution and emissions decrease. Therefore, a clear linkage between emissions and per capita income level over time exists. This study does not consider economic development stages, since all countries included are developed countries, but the hypothesis stresses the relationship between income per capita and emissions over time, which may have explanatory power of the overall impact of the analysis. Furthermore, the economic development of a country also relates to the amount of energy used, which is depleting the environment by the emission of greenhouse gases. GDP per capita also indicates the level of wealth of an economy, meaning that the costs of abatement technologies and renewable energy are easier to finance. GDP per capita also accounts for the economic scale and consumption, which tend to increase emissions.

Empirically, the relationship between CO_2 per capita and GDP per capita has been tested by Fan et al. (2006, p. 390), who find that GDP per capita has the greatest impact on emissions, which supports the importance of controlling for GDP per capita on CO_2 emissions.

GDP per capita is based on purchasing power parity (PPP), which is the gross domestic product converted to international dollars on the basis of purchasing power parity rates[8]. International dollars are adjusted to reflect the same purchasing power over gross domestic product (GDP) as the U.S dollar has within the United States. GDP per capita PPP is expressed in constant 2021 international dollars. GDP is the sum of gross value added by all residents in all countries plus product taxes minus subsidies, respectively. Depreciation of fabricated assets and depletion of natural resources are not

[8] Purchasing power parity rates are the rates at which a currency is converted to equalize the purchasing power of different currencies. This mechanism eliminates any differences in price levels between countries. PPP rates are useful for conducting inter-country comparisons in real terms of gross domestic product, since a common currency is calculated (OECD, n.d).

considered. GDP is divided by midyear population to construct GDP per capita (World Bank Group, n.d).

6.4 Development of environment-related technologies, % of domestic inventions

Development of environment-related technologies as a percentage of domestic innovations is included in the panel local projections regression as a control variable. Green technology innovation is widely acknowledged as a critical driver of improvements in environmental quality by reducing energy intensity, optimizing production process efficiency, and promoting the development of sustainable products and services (Chang et al., 2023, p. 2). Controlling for environmental innovation isolates the effect of the price signal of environmental taxes on CO_2 per capita, since the variable captures the environmental innovation channel. It also reduces upward bias in the effect on CO_2 emissions due to some countries with higher environmental taxes investing more in green technology innovation. Finally, controlling for environmental innovation allows the model to separate higher pollution costs aimed at the demand-side from dynamic long-run shifts in technologies used. Consequently, the variable is regarded as proxy for green innovation, which is a structural factor.

The variable is calculated as environment-related inventions as a percentage of all domestic inventions covering all technologies making it possible to relate changes in environmental technological innovation to innovation in general. The measure is based on patent data across environment-related technological domains, which consists of environmental management, water-related adaptation, and climate change mitigation technologies. Patents included in the measure belong to patent family[9] two or higher, indicating higher-value inventions (OECD, 2024c, p. 49).

6.5 Trade openness

Trade openness is included as a control variable in the panel local projections regression due to international trade being considered determinants of energy consumption and greenhouse gas emissions (Shahzad, 2020, p. 11). The increase in trade openness can influence the amount of greenhouse gases emitted, especially the amount of carbon dioxide. Increasing trade may result in larger production, which results in higher energy consumption and thus higher pollution. Higher trade also implies a higher cross-border flows of intermediate goods, services and final products, which increase the environmental footprint. Thus, controlling for trade openness controls for this channel of emissions. However, emissions may also be ambiguously affected, since increased trade makes

[9] A patent family encompasses the set of all patent applications that protect the same priority (OECD, 2024c, p. 49).

specialization in certain products possible, which can lead to either higher or lower pollution depending on whether the products are energy-intensive or not. Finally, environmentally friendly production technique spillover flows from trade may lead to environmental improvements (Dogan & Seker, 2016, p. 2).

Empirically, studies find ambiguous effects of trade openness on emissions. Dogan & Seker (2016, p. 1) find that trade openness decreases carbon emissions. Conversely, Mahmood et al. (2019, p. 1) find that trade openness increases emissions.

Trade openness is calculated as the sum of export and import divided by GDP (World Bank Group, n.d). GDP, imports and exports are expressed in constant local currency to correct for inflation and currency translation issues. The definition for GDP is identical to the one stated in section 6.3 GDP per capita except it is not divided by the midyear population. Imports of goods and services are defined as the value of all goods and market services received from the rest of the world. Imports include the value of merchandise, freight, insurance, transport, travel, royalties, license fees, and services including communication, construction, financial, information, business, personal and government services (World Bank Group, n.d). Compensation for employees, investment income (factor services) and transfer payments are excluded. Exports include identical goods and services, except these are provided to the rest of the world (World Bank Group, n.d).

6.6 Renewable energy as a percentage of total final energy consumption

Renewable energy is included as a control variable in the panel local projections, since much literature highlights the importance of renewable energy in mitigating climate change. The ratio represents the strength of renewable energy policies; higher values indicate more effective sustainable energy policies, lower emissions per energy unit, and reduced energy carbon intensity. Countries with strict environmental policies may invest more in renewable energy, causing an upward bias. This is eliminated when including the variable. Additionally, renewable energy illustrates the energy structure of the countries, shedding light on the supply side of energy policy.

Renewable energy is regarded as a critical low-carbon and sustainable energy source (Li et al., 2023, p. 1). Innovation in renewable energy contributes to increased adoption of green energy, resulting in lower carbon emissions (Ulucak et al., 2020, p. 3). Renewable energy emits limited or no carbon dioxide emissions (CO_2) and other environmentally harming greenhouse gases, which is an advantage compared to fossil fuels. Consequently, renewable energy is an important factor in energy politics to ensure a low-carbon transition (Morris, 2023). Development of green technologies promotes sustainable development and decreases emissions (Wolde-Rufael & Mulat-Weldemeskel, 2021, p. 11).

Empirically, Rabhi et al. (2024) find that renewable energy consumption steadily and consistently reduces CO_2 emissions. Furthermore, Li et al. (2023) find that renewable energy consumption mitigates carbon emissions.

Renewable energy consumption is expressed the share of renewable energy in total final energy consumption. Data is collected from the World Bank, which draws from IEA, IRENA, UNSD and WHO (World Bank Group, n.d).

6.7 Petrol tax rate

The petrol tax rate is included as a control variable in the panel local projections regression, since the variable captures the transport-related policy effects. A higher petrol tax discourages petrol consumption and curbs emissions. The inclusion of petrol tax rate helps isolate the impact of the effective environmental tax rate on per capita CO_2 gas emissions, since this variable captures changes in petrol pricing policy.

The petrol tax is defined as the arithmetic average of household excise tax for unleaded premium 95, unleaded premium 98, and unleaded regular petrol. The tax rates are expressed per litre of petrol at constant 2015 US dollars PPP. Tax data are collected from datasets 'end-use energy prices and taxes' of the IEA World Energy Prices database (OECD, 2024c, p. 59).

6.8 OECD Environmental Policy Stringency Index

The OECD Environmental Policy Stringency Index (EPS) is included in the panel local projections regression as a control variable. The variable complements the model by controlling for instruments not relying on price mechanisms, which include command-and-control regulations (e.g. emission standards). Therefore, this variable also controls for the enforcement strength of environmental regulations, which can affect the ability of a change in the effective environmental tax to translate into emission reductions.

Environmental policy stringency is measured on a 0- 6 scale, with the higher values indicating stricter regulation (i.e. higher explicit or implicit pollution costs. The policy instruments considered in the EPS are classified into market-based instruments and non-market instruments. Market-based instruments include taxes and charges directly levied on the pollution source and on input or output in the production process, trading schemes, subsidies for environmentally friend activities and deposit-refund systems. Non-market instruments include command and control-regulations, technology support policies, and voluntary approaches. All instruments in each category are given equal weights (OECD, 2014, pp. 17,22).

7. Descriptive statistics

The following section presents descriptive statistics about the data of the panel local projections regression, which establishes an overview of the data set.

Table 3 – Key statistics of main variables

Variable	Obs	Mean	Median	Std	min	max	Main source[10]
CO_2e per capita	650	8,95	8,38	3,81	2,92	26,04	World Bank
Effective environmental tax rate	650	0,07	0,07	0,02	0,02	0,17	OECD Database
GDP per capita	650	49915,90	47622,02	21573,68	12900,58	137821,42	World Bank
Environmental innovations	650	10,70	10,29	3,78	1,76	26,66	OECD Database
Trade openness	650	0,90	0,69	0,59	0,20	3,71	World Bank
Renewable energy	650	16,19	11,40	13,95	0,80	60,90	World Bank
Petrol tax rate	650	0,82	0,77	0,32	0,26	2,60	OECD Database
OECD EPS	650	2,41	2,56	1,02	0,17	4,89	OECD Database

[10] The OECD and World Bank collect data from other data sources, which are specified in section 6. Data description.

Note: CO_2e per capita is expressed in metric tons. The effective environmental tax rate is a ratio, while GDP per capita is in constant 2021 international dollars. Environmental innovations, trade openness and renewable energy are also expressed as a ratio. Petrol tax rate is expressed in constant USD PPP, and OECD EPS is a number between 0 and 6. Source: Own production based on stated data sources.

Table 7 summarizes the key statistics of the variables included in the model. The average CO_2e per capita are 8,95 metric tons with a standard deviation of 3,81 metric tons. Notably, large cross-country differences in emission levels per capita are identified with a minimum of 2,92 metric tons per capita (Turkey in 1995) and 26,04 metric tons per capita (Luxembourg in 2005). This suggests diverse economic and carbon-intensive profiles.

Regarding the effective environmental tax rate, the average ratio is 7%. The standard deviation is 2 percentage points, which indicates a moderate spread over time across countries. The range of the effective environmental tax rate stretches from a minimum ratio of 2,2% (New Zealand in 1998) to a maximum of 17% (Türkiye in 2005). The wide range indicates substantial cross-country differences across countries and time in the emphasis on taxing pollution.

The average GDP per capita across countries and time is $49915,90. The standard deviation is $21573,68, which indicates a large spread. The minimum GDP per capita is $12900,58 (Türkiye in 1995), while the maximum GDP per capita is $137821,42 (Luxembourg in 2007). This indicates a large difference in income across countries.

Environmental innovations as a percentage of domestic innovations have an average ratio of 10,70%. The standard deviation is 3,87 percentage points, which is also considered a moderate spread. The minimum ratio is 1,76% of domestic innovations (Poland in 1995), while the maximum ratio is 26,66% (Denmark in 2010) indicating large differences in investment in green technology.

Trade openness has an average ratio of 0,90 (90%) meaning that on average, trade accounts for 90% of GDP. The standard deviation is 0,59 (59 percentage points) suggesting a large spread. The minimum ratio is 0,20 (Japan in 1995) and the maximum ratio is 3,71 (Luxembourg in 2020), which indicates large differences in trade-intensity across countries and time.

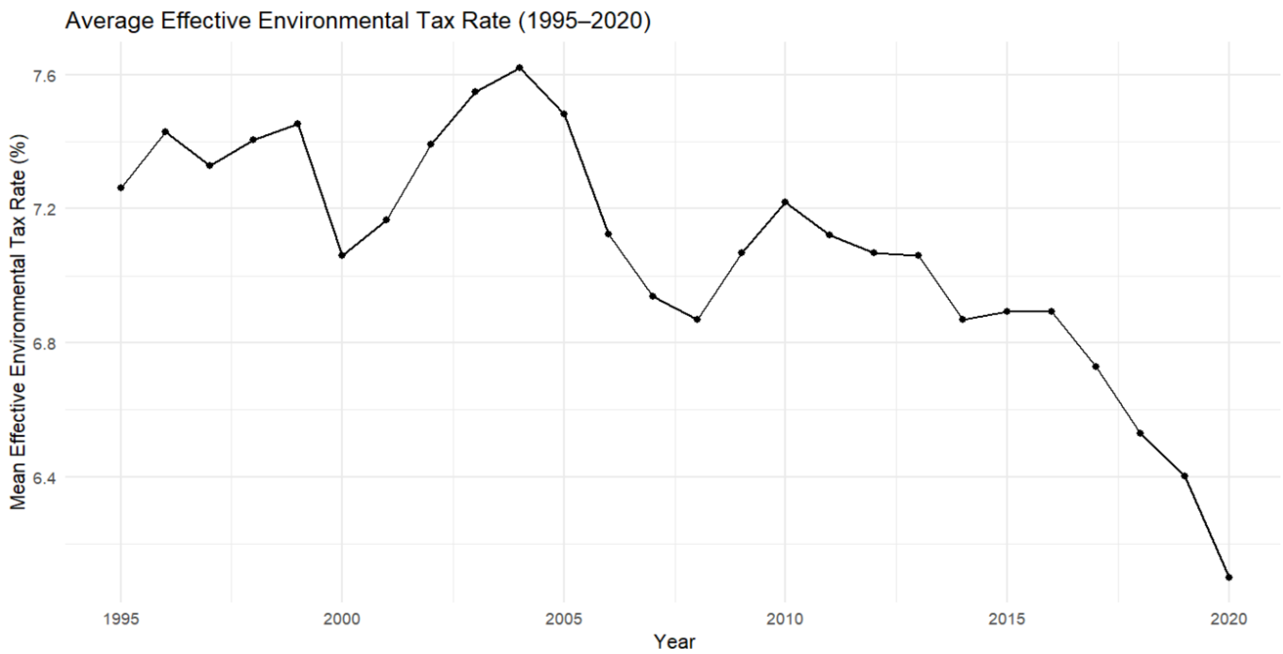
Renewable energy has an average ratio of 16,19% of total final energy across countries and time. The standard deviation is 13,95 percentage points, which indicates large differences in consumptions patterns of renewable energy. The difference between the minimum ratio at 0,80% (United Kingdom in 2001) and the maximum ratio of 60,90% (Norway in 2020) further enhances the differences in consumption of renewable energy.

The petrol tax rate has an average of $0,82 across time and countries. The standard deviation is $0,32 dollars illustrating a moderate spread. The minimum petrol tax is $0,26 per liter (Australia in 2014), while the maximum petrol tax is $2,60 per liter (Türkiye in 2005). This finding reflects different fuel tax regimes.

Finally, the OECD EPS has an average of 2,41 points with a standard deviation of 1,02 points. The standard deviation shows moderate differences in evaluations of stringency of environmental policies. The minimum score is 0,17 points (Australia in 1995), while the maximum score given is 4,89 (France in 2020). These findings illustrate differences in overall strictness of environmental policies across time and countries.

7.1 Environmental taxes and CO_2 emissions through time

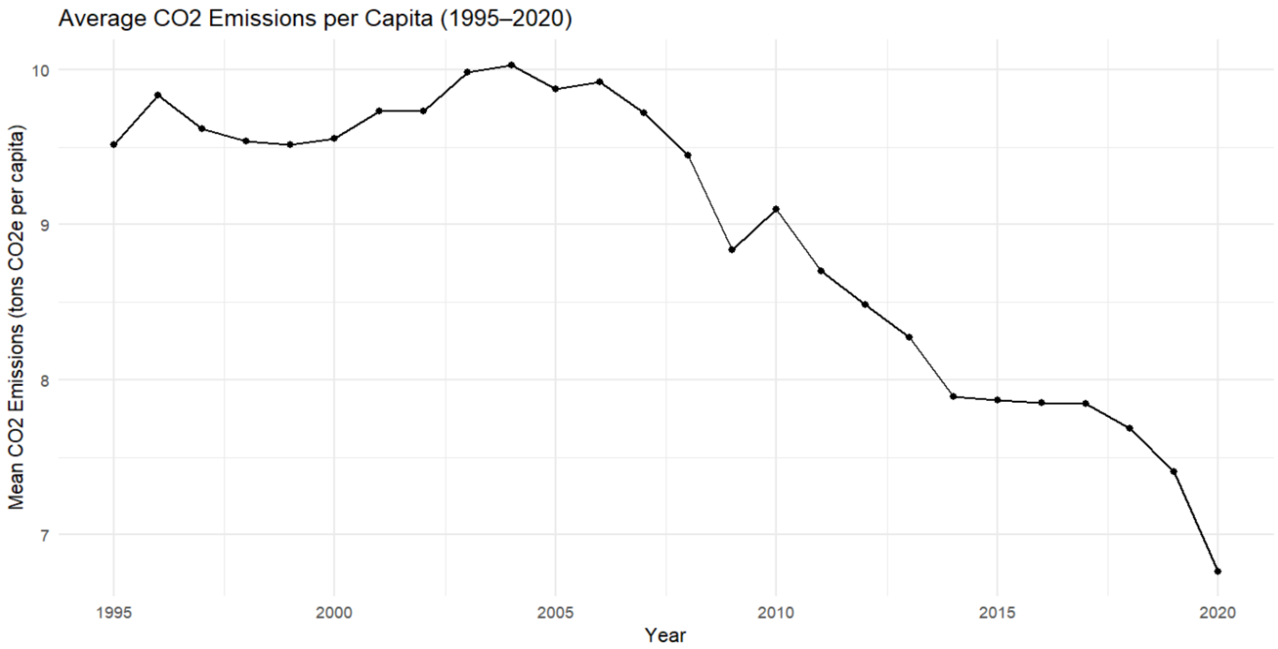
Figure 3 – Average effective environmental tax rate from 1995 to 2020



Note: The graph illustrates the average level of the effective environmental tax rate through time. The graph is based on the 25 countries included in the analysis. Each point represents the average effective environmental tax rate of the given year.

Figure 3 illustrates that the effective environmental tax rate has declined overall in the period 1995 to 2020 from approximately 7,3% in 1995 to 6.2% in 2020. In the mid-late 1990's, the rate fluctuates around 7,2-7,5% followed by a decline to 7.0% in 2000. The rate increases in the early 2000's, followed by another decline. The rate has been declining since 2010, indicating a declining reliance and focus on environmental taxes. The development of the average effective environmental tax rate implies a larger growth in the total tax revenue.

Figure 4 – Average CO_2 per capita in the period 1995-2020

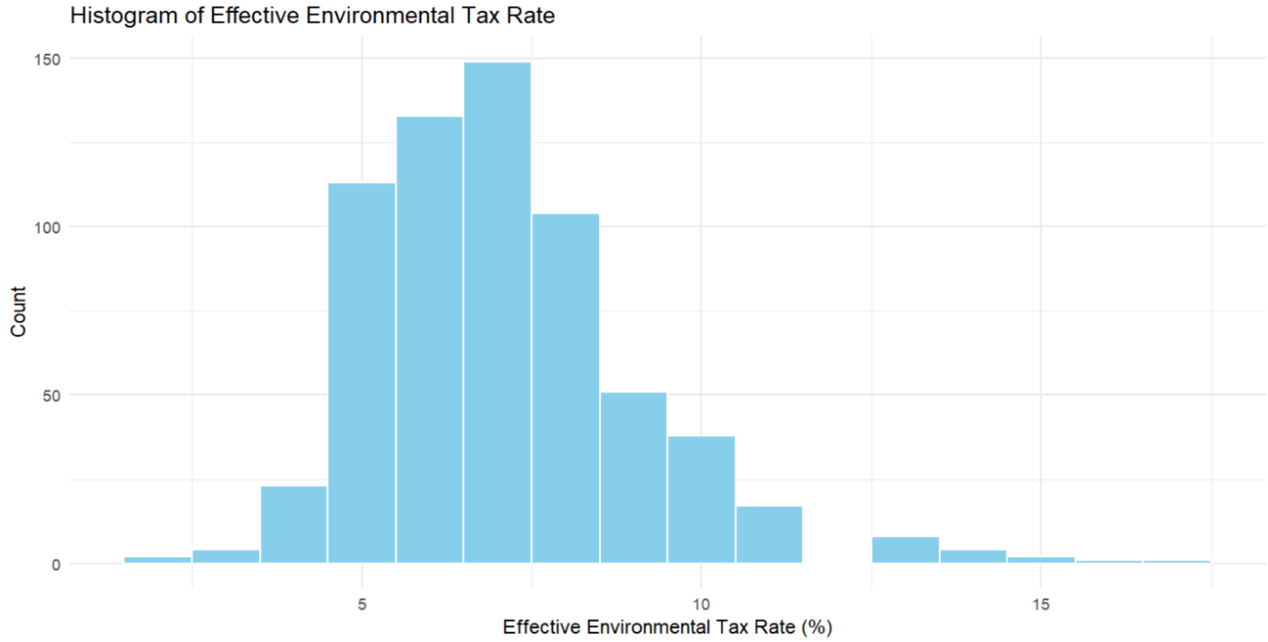


Note: The graph illustrates the average level of CO_2e per capita through time. The graph is based on the 25 countries included in the analysis. Each point represents the average CO_2e per capita of the given year.

Figure 4 shows a clear decline in average CO_2 emissions per capita in the period 1995-2020. The average CO_2 emissions per capita fluctuated around 9,5-10 metric tons per capita in 1995-2006. A steady downward trend shows from 2006-2020 with one upward spike in 2010. Average CO_2 emissions per capita have fallen from above 9,5 metric tons per capita to below 7 metric tons in the period 1995-2020. Figure 4 displays a large fall in average CO_2 emissions per capita around the global financial crisis, which corresponds with declining economic activity. The growing focus of renewable energy and cleaner technology could be factors explaining the further decline.

7.2 Distribution of environmental taxes and CO_2 emissions

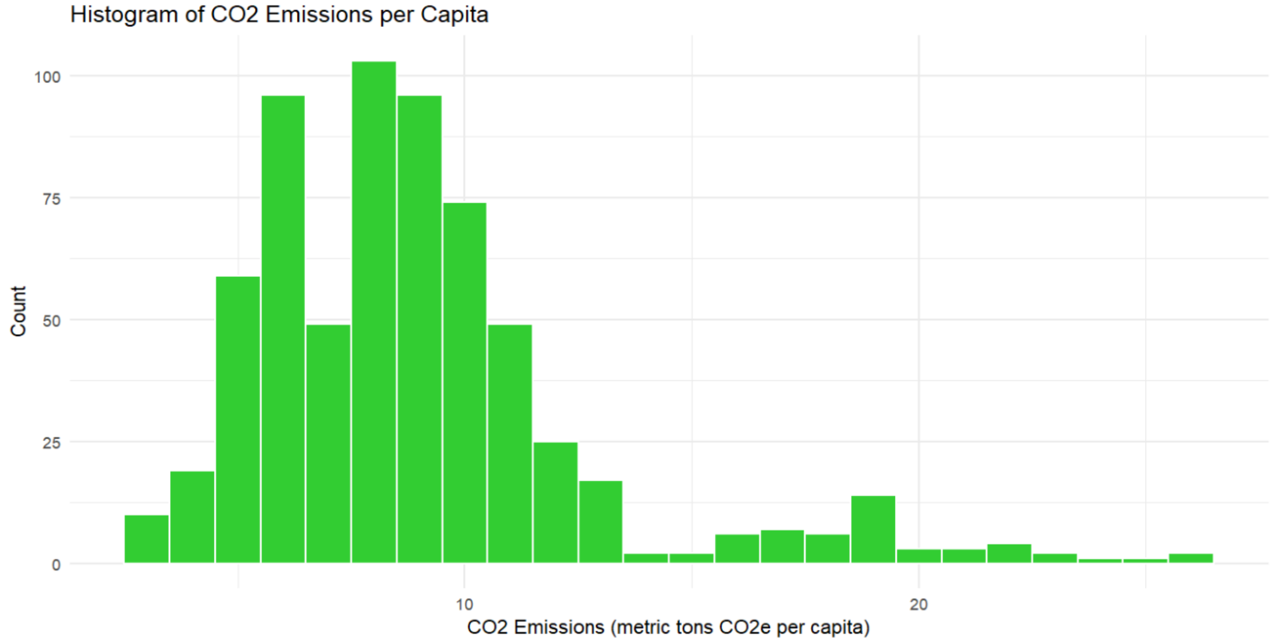
Figure 5 – Distribution of effective environmental tax rate for all 650 observations



Note: The histogram displays the distribution of the effective environmental tax rate. The x-axis is the effective environmental tax rate, whereas the y-axis is the count of observations based on country and time.

Figure 5 shows the distribution of effective environmental tax rates for all countries in all years. The distribution is centered around 5-8% range. The highest frequency is 7%, which also corresponds approximately to the average ratio and median as pointed out in table 7. The histogram is slightly skewed right, since the tail extends to higher values, 15%-17%. The distribution displays some outliers, but most countries devote 5-9% of their tax revenue to environmental taxes.

Figure 6 - Distribution of CO_2 emissions per capita for all 650 observations

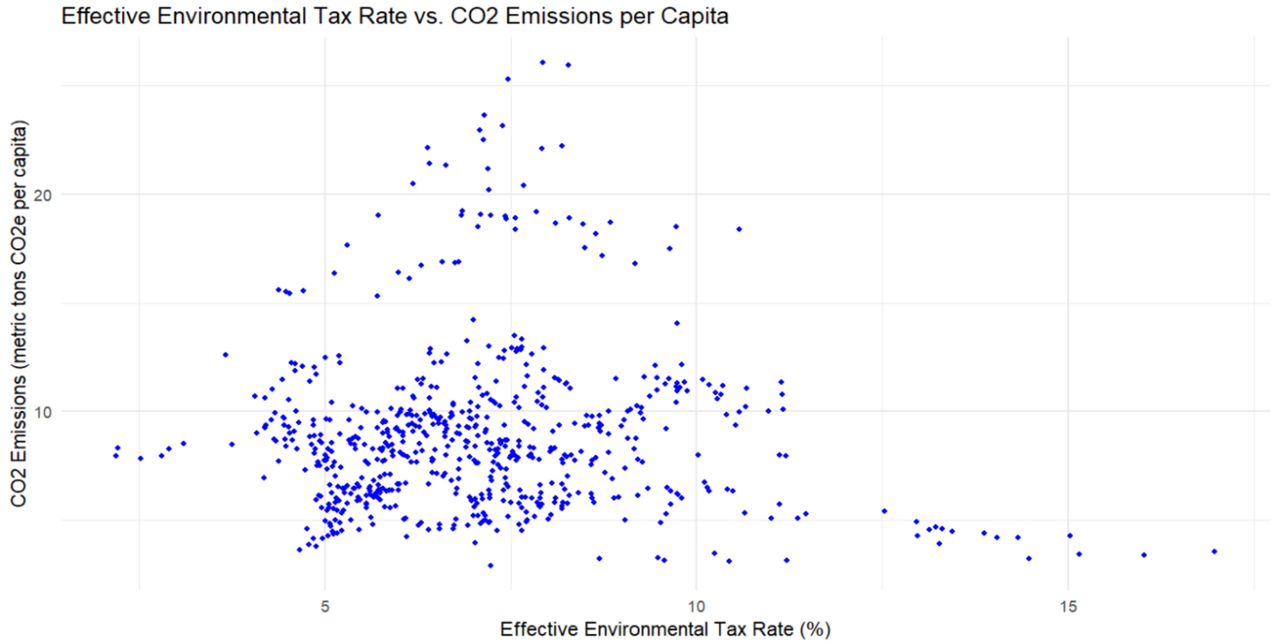


Note: The histogram displays the distribution of the effective environmental tax rate. The x-axis is CO_2e emissions per capita, whereas the y-axis is the count of observations based on country and time.

Figure 6 shows the distribution of CO_2 emissions per capita for all country-year observations. The distribution is notably wider and more rightly skewed than the effective environmental tax rate. The highest frequency of CO_2 emissions per capita is around 6-10 metric tons per capita, which includes the mean and median as calculated in table 7. Figure 6 is rightly skewed with some observations being noticeable in the range of 15-20 metric tons per capita. These outliers stem from carbon-intensive and trade-intensive countries like Australia and Luxembourg. Turkey and some European countries are in the smaller ranges from 3-5 tons per capita. The distribution illustrates the difference in economic, energy and trade profiles. Most observations are in the range of 5-11 metric tons per capita.

7.3 Relationship between environmental taxes and CO_2 emissions

Figure 7 – Scatterplot showing the relationship between effective environmental tax rate and CO_2 emissions per capita



Note: The graph shows the link between environmental taxes and CO_2 per capita. Each point the figure corresponds to a value for a single country in a certain year.

Figure 7 displays a weakly negative relationship – it is almost horizontal. Observations corresponding to higher effective environmental tax rate mostly have lower CO_2 emissions per capita. However, the relationship is quite unclear, since countries with higher effective environmental tax rates do not have significantly smaller CO_2 emissions per capita. Observations slightly to the left in the plot, the combination of lower to moderate taxes and high emissions per capita, are data belonging to Australia and Luxembourg among others. The middle cluster displays emissions in the range of 5-12 metric tons with corresponding effective environmental tax rate in the range 5-10%. This pattern is not clear, as countries with an average effective environmental tax rate (7%) can have CO_2 emissions per capita in the range of 5-12 metric tons per capita. Similarly, countries with average CO_2 emissions per capita, 8-9 metric tons, can have an effective environmental tax rate in the range of 5-10%. Finally, the bottom-right region displays the combination of low emissions per capita and high environmental taxes. Countries in this region of the plot include Türkiye and Sweden.

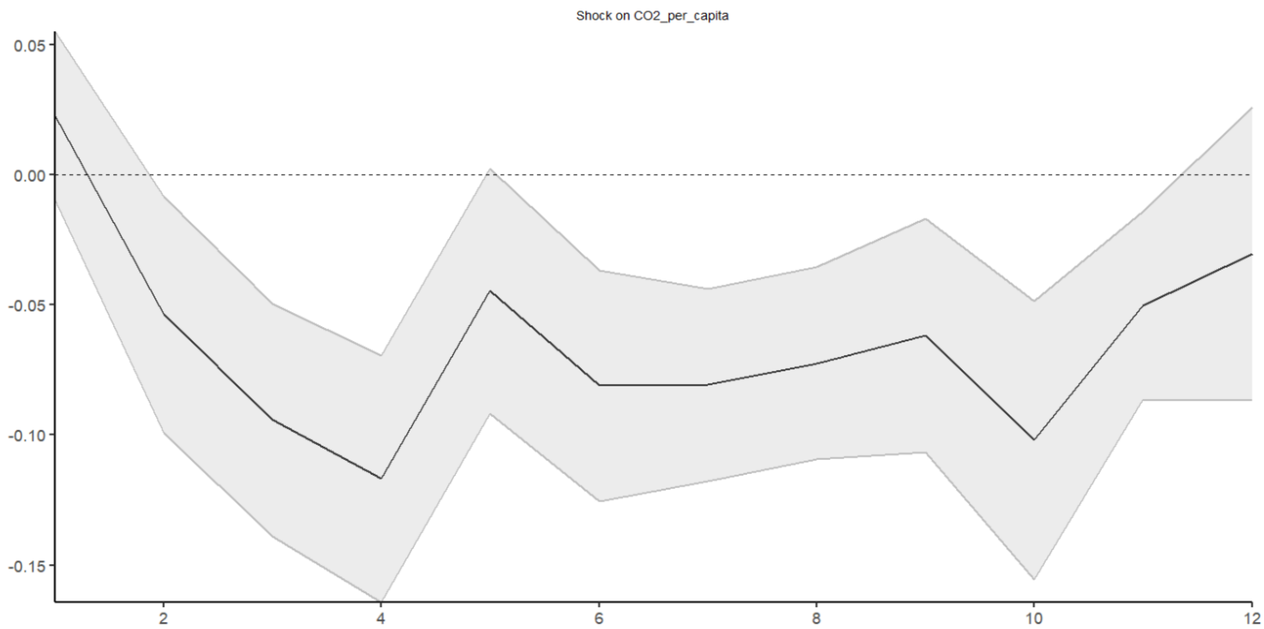
Overall, the correlation is slightly negative, but very small. This suggests that the effective environmental tax rate alone is not a reliant predictor of CO_2 emissions per capita. However, the plot does show a tendency of higher environmental tax rates being correlated with lower CO_2 emissions for a few countries. The plot suggests heterogeneity in the relationship between the effective environmental tax rate and CO_2 emissions per capita. Furthermore, the effectiveness of environmental policies, energy mix, green innovation and income play a role in determining the dynamic between the two variables.

8. Empirical results

The following section presents the empirical results from the panel local projection model constructed on the basis of 25 countries in the period 1995-2020. The panel local projection regression is a twoways fixed effect model, which accounts for differences across countries and time. An upward, exogenous one percentage point shock to the effective environmental tax rate is conducted, controlling for the variables in section 6 Data description using three lags each, t-1, t-2 and t-3. The confidence bands illustrate one standard deviation reflecting standard practice, which translates to 68% percent. The resulting impulse response function shows the average development in CO_2e emissions per capita based on a one percentage point shock to the effective environmental tax rate. Finally, the impulse response functions are displayed on a 12-year horizon, $H = 12$. The black line in figures 8-16 represents the impulse response function, and the shaded area corresponds to the confidence bands. The dynamic relationship between environmental taxes and per capita CO_2 emissions is further explored by conducting similar shocks to the energy tax revenue as well as in-depth analysis of domains on CO_2 per capita emissions. All impulse response functions represent the average impact of an environmental shock on CO_2e emissions per capita.

8.1 Environmental taxes on CO_2 emissions

Figure 8 – A one percentage point shock to the effective environmental tax rate on CO_2e emissions per capita



Note: Figure 8 illustrates an upward and exogenous one percentage point shock to the effective environmental tax rate on CO_2e per capita while controlling for three lags of CO_2e per capita, GDP per capita, trade openness, environmental innovations, renewable *energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents metric tons of CO_2 equivalents. Source: Own production.*

Figure 8 displays a significant, persistent reduction in CO_2e emissions per capita expressed as CO_2 equivalents per capita over 12 horizons. The magnitude of the reduction grows the fastest in the first years following the shock showcasing continuous adaptation to a higher effective environmental tax rate. CO_2 per capita reaches its largest reduction four years after the shock at 0,10-0,12 metric tons of CO_2 equivalents per capita, which implies gradual adaptation. Reductions of CO_2 emissions per capita also characterize the following years, although the emissions reductions shrink in magnitude, which can be attributed to some components of environmental taxes only being briefly impacted by the increase in the ratio. Therefore, this dampened reduction in the CO_2 emissions per capita indicates that some components subject to environmental taxation only exhibit a one-time behavioral change. Another downward movement, a dip, appears around the tenth horizon. The confidence bands are larger, which adds more uncertainty to the interpretation of the reasons for the dip. Reasons could include further adaptation in energy efficiency, such as long-term investments or technology changes as a result of the increasing environmental taxes, or estimation noise due to uncertainty about the distant future.

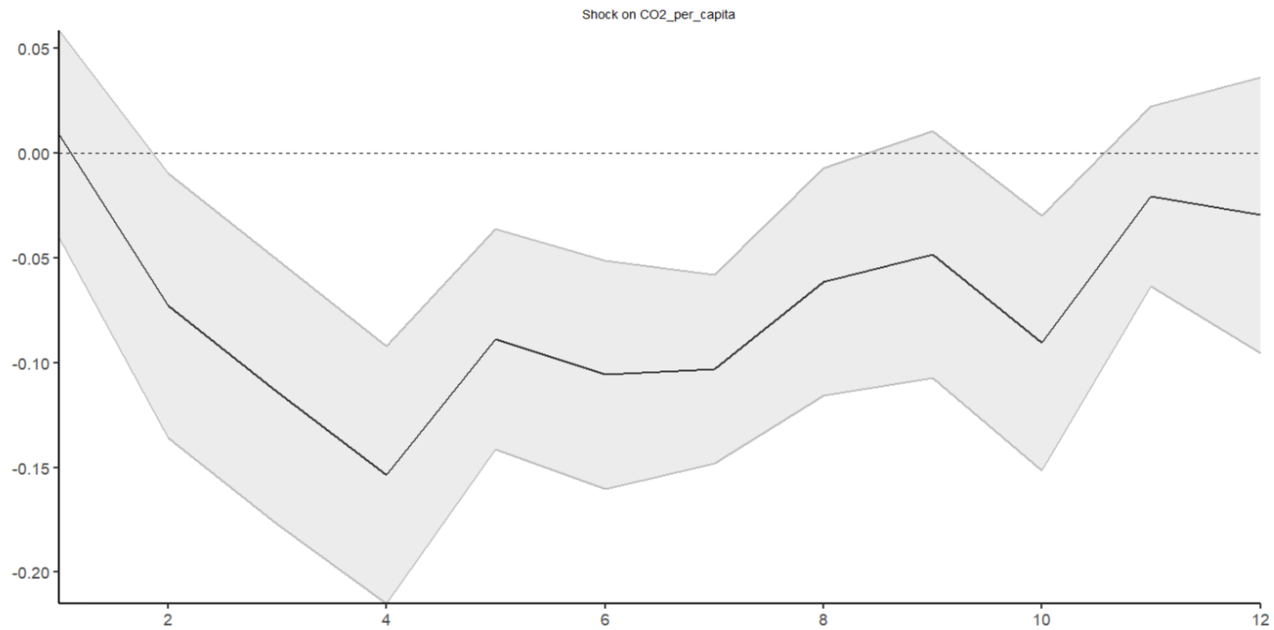
The impulse response function is significant at all horizons except the first, eleventh and twelfth horizons, confirming that a higher effective environmental tax rate reduces CO_2e emissions per capita. The impact is statistically different from zero except for in the abovementioned horizons. Wider confidence bands at longer horizons reflect greater uncertainty. CO_2 emissions per capita remain below pre-shock baseline level throughout, suggesting a lasting effect, which is likely driven by structural changes such as cleaner production technologies, green innovation and environmentally friendly consumption. The reduction is weaker in horizons the ten through twelve, indicating its strength varies over time.

Finally, figure 8 shows a delayed peak response to the shock, meaning that the effect builds over several years. The reason can be that firms and consumers are adjusting with a time lag, since adjusting production techniques, improving energy efficiency and consumption to the new economic conditions takes time. Additionally, the impulse response function does not show an increase in CO_2 emissions at any point in time, reflecting no rebound effect or green paradox, where emissions rise after implementation of environmental policies. Although, the dampened reduction around year five suggests that some components are only temporarily affected.

8.2 A shock to effective environmental energy tax rate

To explore how environmental taxes affect per capita CO_2e emissions, another shock is performed on CO_2 emissions per capita. The impact of one percentage point shock to the effective environmental energy tax rate on CO_2 emissions per capita is examined. The definition of the effective environmental energy tax rate is similar to the effective environmental tax rate; this shock variable is expressed as the environmental tax revenue from the energy tax category as a percentage of the total tax base. This shock illustrates the impact of environmental taxes targeted at energy on CO_2 emissions per capita, which establishes the importance of energy taxes in relation to reducing CO_2 emissions per capita. This shock allows a deeper understanding of the importance of taxation on energy-related taxes in order to encourage a clean energy transition and ultimately a low-carbon economy.

Figure 9 - A one percentage point shock to the effective environmental energy tax rate on CO_2e emissions per capita



Note: Figure 9 illustrates an upward and exogenous one percentage point shock to the effective environmental energy tax rate on CO_2e per capita while controlling for three lags of CO_2e emissions per capita, GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents metric tons of CO_2 equivalents. Source: Own production.

Figure 9 illustrates a persistent, negative reduction in the CO_2e per capita over 12 horizons following a shock to the effective environmental energy tax rate. Similar to figure 8, the magnitude of the reduction of CO_2e per capita peaks after four years. Emissions per capita drop 0,15 metric tons of CO_2 equivalents per capita at maximum magnitude in the fourth horizon, which also indicates gradual adaptation and a significant impact on CO_2 emissions. The pronounced decline in CO_2e emissions per capita indicates that the shock has important implications for combatting climate change. It prompts reductions in fossil fuel use and efficiency improvements that persist over a twelve-year horizon. Although a reduction in CO_2e per capita characterizes the trajectory of the impulse response function, a dampening of the reduction is also present in figure 9. The reduction is of much smaller magnitude compared to figure 8. The dampening of the reduction of CO_2 emissions per capita suggests that firms and individuals have adapted to the shock, but also that some energy taxes might only exercise a one-time behavioral change.

Similar to figure 8, a secondary increase in magnitude happens around ninth to tenth horizon dropping from a reduction of 0,05 metric tons of CO_2 equivalents to approximately 0,09 metrics tons of CO_2 equivalents. This dip may represent long-term investments and technology changes triggered by higher environmentally energy-related taxes or estimation noise, since confidence bands are increasing towards later horizons.

Overall, the negative effect persists across all horizons indicating that higher effective environmental energy taxes reduce CO_2e emissions per capita. Confidence bands exclude zero at most points except for the first and eleventh and twelfth horizons. Specifically, the effect is very significant at the highest magnitudes of the reduction three and four years after the shock. The confidence bands also include zero around the ninth horizon, but a significant horizon follows. Although the eleventh and twelfth horizons are not statistically significant, the impulse response function signals a lower level than the pre-shock baseline level. Therefore, an increase in energy-related environmental taxes causes a pronounced and sustained reduction in CO_2e emissions per capita, where the strongest impact occurs after three to four years. Finally, the impulse response function does not entail a rebound effect or green paradox, where emissions increase after a rise in energy-related taxes.

8.3 Comparison of the impact of environmental taxes and environmental energy-related taxes

Figure 8 and 9 both reduce CO_2e emissions per capita, but the trajectories, the strength and significance of the CO_2e emissions as a result of the shock differ. Environmental taxes and energy-related environmental taxes reach their largest impact after four years, which solidifies gradual adaptation. Furthermore, both impulse response functions experience a dip at the tenth lag, the reason to which it is difficult to correctly denote. The dip can be attributed to estimation noise, but the common occurrence across both figures also points to long-term investments. The statistical significance is higher at short-term horizons compared to long-term horizons in which uncertainty dominates as seen by larger confidence bands.

The figures differ in their 'rebound' after the fourth horizon. Figure 7 exhibits a relatively quick rise upwards, whereas figure 8 displays a slower upward trajectory, which points to the energy tax effect having a more sustained impact. The maximum magnitude of the impact of environmental taxes and energy-related environmental taxes is 0,12 metric tons per capita and 0,15 metric tons per capita, respectively. Consequently, the energy tax shock has a larger and longer-lasting maximum reduction in CO_2e emissions per capita.

Figure 8 and figure 9 highlight that the energy component of environmental taxes is a dominant, clear driver of the reductions in CO_2e emissions per capita exhibited. Energy taxes drive the shock due to carbon-intensive energy being directly targeted, whereas other environmental taxes may not be directly linked to carbon (e.g waste collection tax, noise tax) and only exhibit a one-time behavioral change. Consequently, not all environmental taxes are equal drivers of decarbonization, which shows that some components of environmental taxes are more effective policy measures for combating CO_2e emissions than others. This means that the design and composition of taxation is important to ensure a significant long-term impact on curbing emissions. Targeting energy taxes is a powerful tool to drive the low-carbon transition as it shows significant reductions, that are long-lasting.

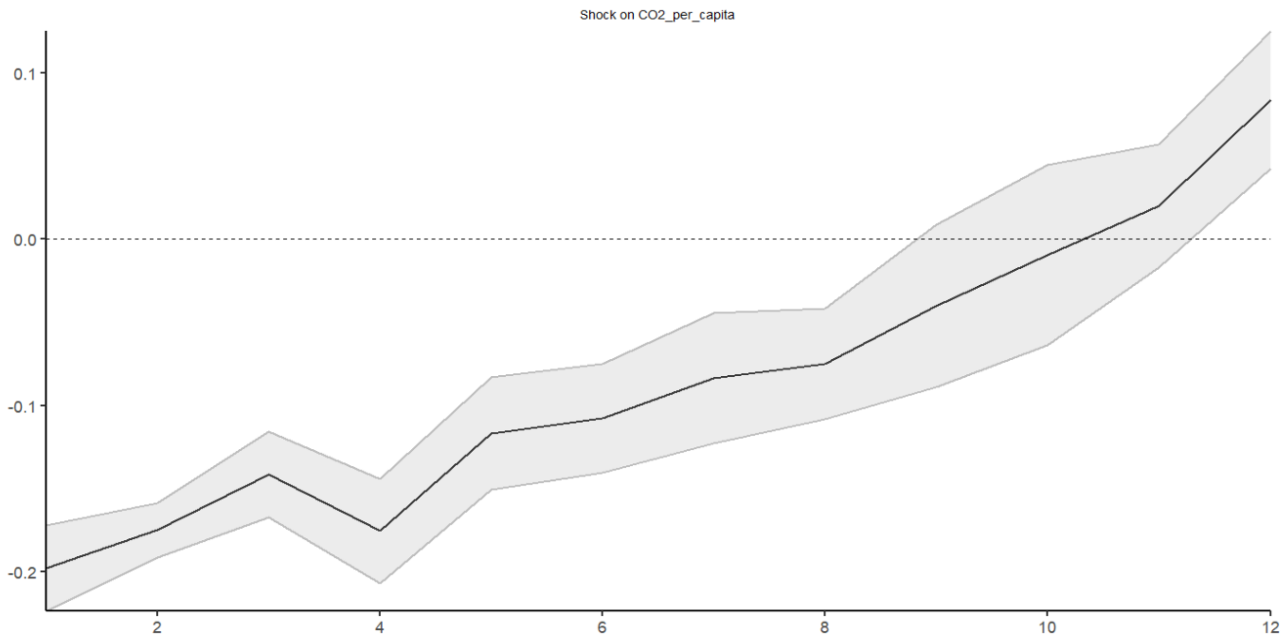
The results show that imposing higher energy taxes reduces CO_2e per capita more than targeting environmental taxes in a broad sense, which attests to the critical role of energy in the transition to a low-carbon trajectory.

8.4 A shock to the effective carbon tax rate

To further analyze the effect of imposing taxes on CO_2e emissions, this section presents a shock to the effective carbon tax rate. The effective carbon tax rate is defined as the ratio of environmental tax revenue to CO_2 emissions in metric tons. This ratio represents the average tax per metric ton of CO_2 emitted, which serves as a proxy for the carbon price. The ratio represents the average implicit carbon tax, since it captures how much tax is paid per unit of carbon emissions. Therefore, the effective carbon tax rate captures the overall tax burden on carbon emissions by including all environmental taxes – direct or indirect – making it a comprehensive measure. By expressing the shock as a ratio, taxes per metric ton of CO_2, it is normalized for the scale of emissions, and it is comparable across time and countries. A high value represents a strong price incentive to cut emissions, since polluters are paying more per unit of emissions. However, the interpretation of the shock should be done with caution, since the ratio can change due to other reasons than policy decisions. This happens if CO_2 emissions fall due to other circumstances, which then raises the ratio, and a biased estimate is produced. Furthermore, the results are interpreted with caution due to environmental taxes including some taxes, that are not targeted at carbon emissions at all. Additionally, it is important to note that the shock to the effective carbon tax only represents the average tax on carbon emissions, which is not the only GHG emitted.

Data on CO_2 emissions are collected from the World Bank Database, whereas the environmental tax revenue is the same data used for the other shock variables from the ERTR database within the OECD Pine Database.

Figure 10 - A one percentage point shock to the effective carbon tax rate on CO_2e emissions per capita



Note: Figure 10 illustrates an upward and exogenous one percentage point shock to the effective carbon tax rate on CO_2e emissions per capita while controlling for three lags of CO_2e emissions per capita, GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents metric tons of CO_2 equivalents. Source: Own production.

Figure 10 displays a shock to the effective carbon tax rate on CO_2e emissions per capita over a 12-year horizon. The impulse response function shows a significant, sharp decline in CO_2e emissions per capita in the short and medium term. Emissions drop significantly in the first year, approximately 0,20 metric tons per capita at maximum magnitude. The quick response of CO_2e emissions per capita to a shock to the effective carbon rate signals that firms and consumers quickly reduce emissions by cutting the use of fossil fuels, increasing energy efficiency, and switching to cleaner alternatives. Carbon-intensive activities are greatly discouraged as measured by the significantly large reduction in CO_2e emissions per capita. The magnitude of the reduction weakens over time. Also, the confidence bands widen though fifth to twelfth horizon. The reduction of the CO_2e emissions per capita is still significant through eight horizons, but the trajectory is upward sloping displaying a gradual convergence back to the baseline. At later horizons, the impact converges to the baseline scenario and exceeds the previous level of CO_2e emissions per capita. Therefore, the impact erodes over time, which could be due to a rebound effect, where the implementation of environmental policies results in a worse environmental outcome as explained in section 4.1. An industry could develop a production method that reduces taxes, and the emission level can be sustained or increased, which worsens the environmental outcome and offsets the initial gains. On the contrary, investments in green technology innovation from environmental tax revenue (blue dividend), might cause the economy to grow more than before with cleaner technology. This could erode some of the bases of environmental taxes thereby decreasing the average tax per unit of carbon emission.

A semi-temporary shock – driven by the statistically significant, initially strong tax per metric ton of CO_2 – causes the later rise of the rise in CO_2e emissions per capita. While this shock permanently lowers per-capita emissions in the short and medium term, over 12 horizons it mainly produces a large but temporary drop. Long-run increases remain uncertain due to wide confidence bands, though the impulse response function indicates the effect fades over time.

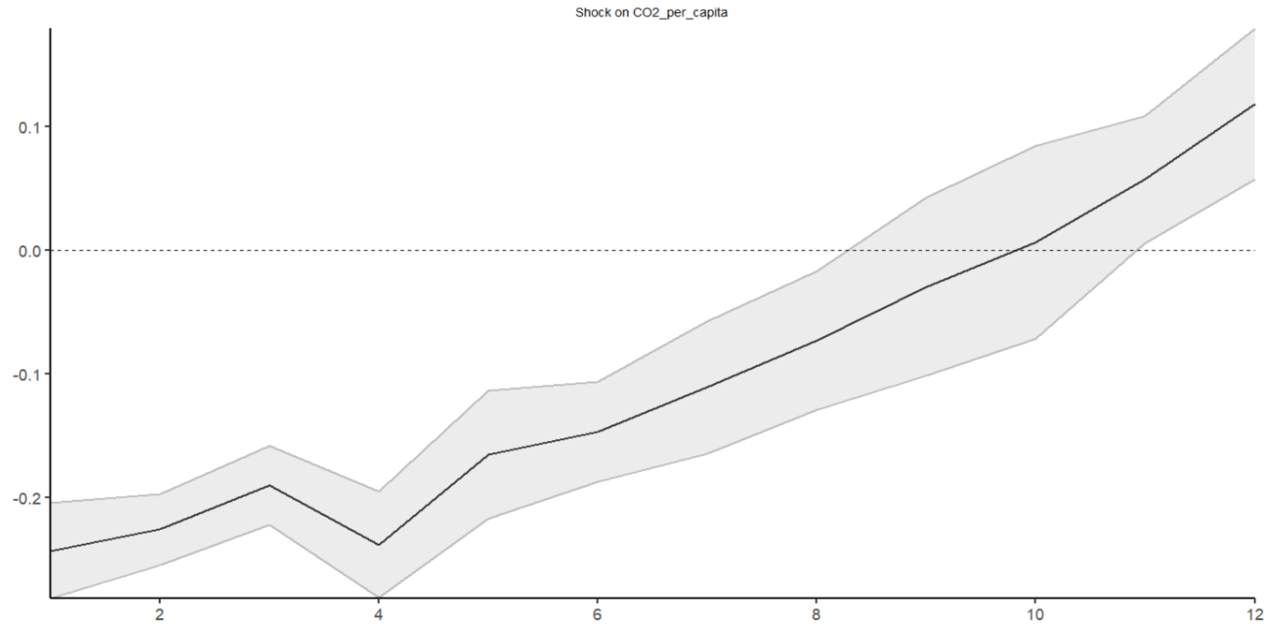
The negative impact of the effective carbon tax on CO_2e emissions is statistically significant through eight horizons. It is statistically insignificant around though the ninth to eleventh horizons since zero is included in the confidence bands. The significance is the strongest at the earlier horizons, which implies that increasing the implicit carbon tax is effective in the short and medium run, although strongest at earlier horizons, but the long-run effects are unclear and potentially environmentally worse off. Ultimately, the effective carbon tax is effective at curbing CO_2e emissions per capita in the short and medium run, but they must be continually strengthened or adjusted to improve the effectiveness and not be a one-time policy shock.

8.5 A shock to the effective energy carbon tax rate

As concluded in figure 9, the energy component of environmental taxes drives the downward trajectory. This section presents a shock to the effective energy carbon tax on CO_2e emissions per capita defined as a ratio of energy-related environmental taxes to CO_2 emissions in metric tons. This ratio represents the effective energy-related tax rate per unit of CO_2 emitted. By capturing the intensity of energy-related taxes per unit of CO_2, this measure reflects the stringency of carbon pricing faced by polluters. This ratio - average energy tax per metric ton of CO_2 emitted - serves as a proxy for the implicit carbon energy price, capturing the overall tax burden on carbon emissions from energy. Expressing the shock as taxes per metric ton of CO_2 normalizes for emission scale, enabling comparisons time and countries. High values signal strong incentives to cut emissions - polluters pay more per unit of emissions – and using energy-tax revenue makes this measure effective at targeting carbon emissions compared to general environmental tax revenue. However, the interpretation of the shock should be done with caution, since the ratio can change due to other reasons than policy decisions. This happens if CO_2 emissions fall due to other circumstances, which then raises the ratio, and a biased estimate is produced. Additionally, it is important to note that the shock to the effective energy carbon tax only represents the average energy-related tax on carbon emissions, which is not the only GHG emitted.

Data on CO_2 emissions are collected from the World Bank Database, whereas the energy-related environmental tax revenue is the same data used for the shock variable in figure 9. The revenue is extracted from the energy tax category from the ERTR database within the OECD Pine Database.

Figure 11 - A one percentage point shock to the effective energy carbon tax rate on CO_2e emissions per capita



Note: Figure 11 illustrates an upward and exogenous one percentage point shock to the effective energy carbon tax rate on CO_2e per capita while controlling for three lags of CO_2e per capita, GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents metric tons of CO_2 equivalents. Source: Own production.

Figure 11 shows the impulse response function of a shock to the effective energy carbon tax rate on CO_2 emissions over the period of 12 horizons. The impulse response function shows a significant, sharp decline in CO_2e emissions per capita in the short and medium term. Emissions drop significantly in the first year, approximately 0,22-0,23 metric tons per capita at maximum magnitude. The initial sharp decline in CO_2e emissions per capita after an effective energy carbon rate shock reflects that firms and consumers quickly reduce the use of fossil fuels, increase energy efficiency and switch to renewable energy. The magnitude of the reduction weakens over time, which begins eight to ten years after the shock. The reduction of CO_2e emissions per capita is still significant through eight horizons, but the trajectory is upward sloping displaying a gradual convergence back to the baseline. At later horizons, the impact converges to the baseline scenario and exceeds the previous level of CO_2e emissions per capita. Therefore, the impact erodes over time, which could be due to a rebound effect, where the implementation of environmental policies results in a worse environmental outcome as explained in section 4.1. An industry could develop a production method that reduces taxes, and the emission level can be sustained or increased, which worsens the environmental outcome and offsets the initial gains. On the contrary, investments in green technology innovation from environmental tax revenue (blue dividend), might cause the economy to grow more than before with cleaner technology. This could erode some of the bases of environmental taxes thereby decreasing the average energy tax per unit of carbon emission.

Similarly to figure 10, the shock is strong and significant initially but becomes statistically insignificant at the ninth to eleventh horizon. Therefore, the shock induces reductions in CO_2e per capita in short and medium term, but the effect disappears in the long run. The shock induces a persistent negative level shift in CO_2e emissions per capita in the short and medium term. Overall, the shock induces a permanent reduction in CO_2e emissions per capita in the short and medium term, but considering 12 horizons, the effect reflects a temporary large reduction. Whether emissions per capita actually increase in the long run is uncertain as the confidence bands are larger, but the impulse response function suggests a fading impact on CO_2e emissions per capita. Essentially, to curb long-term CO_2 emissions, carbon pricing benefit from a dynamic continuous policy effort.

The negative impact of the effective carbon tax on CO_2 emissions is statistically significant through eight horizons. It is statistically insignificant around though the ninth to eleventh horizons since zero is included in the confidence bands. The significance is the strongest at the earlier horizons, confirming the effectiveness of the policy in the short and medium term, but the long-run effects are unclear and potentially environmentally worse off.

8.6 Summary of the effectiveness of a carbon tax and energy carbon tax shock

Figure 10 and figure 11 display the effectiveness of a shock to the effective carbon tax rate and the effective energy carbon tax rate, respectively. Ultimately, both impulse response functions show that the shocks are particularly effective at curbing CO_2e emissions per capita in the short run and medium term. The impact is decreasing with time, showing an upward sloping trend at longer horizons. The magnitude of the reduction is the strongest for the shock to the effective energy carbon tax, which reaffirms that taxation of energy has a strong impact on polluters' incentive to reduce emissions.

Both impulse response functions exhibit a rebound by the twelfth horizon – signaling a fading long-term effect – but widening confidence bands thereafter introduce uncertainty, making long-term impacts unclear. Consequently, a single shock to the effective carbon tax rate and the effective energy carbon tax rate result in a reduction of CO_2e per capita emissions per capita in the short and medium term, but whether the impact remains persistent in the very long term is unclear.

8.7 Environmental tax rate and domains

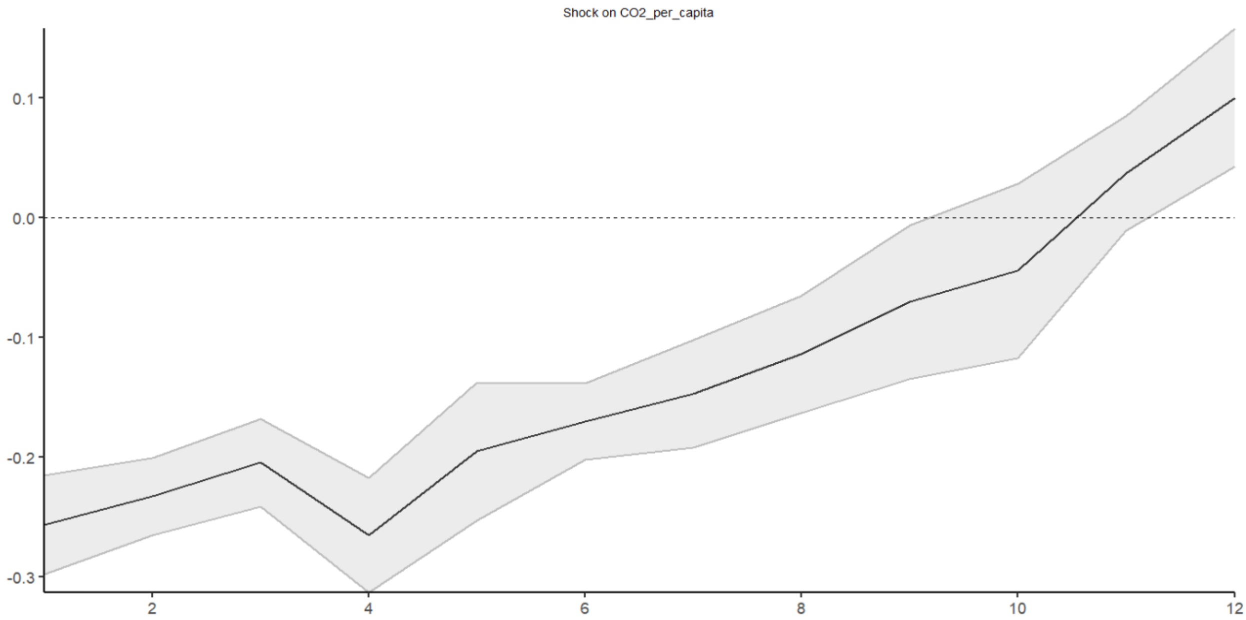
This section analyzes the effect of environmental tax revenue from the energy tax category of domains climate change, air pollution, fossil fuels, energy efficiency, and chemical management on CO_2e emissions per capita, respectively. The domains cover a broad scope of energy taxation. Not all countries included in the study have energy-related taxes that target all specific domains available, so the domains chosen are based on the number of countries targeting the specific focal issues. The shocks are defined as the ratio of energy-related tax revenue that targets the respective focal issues to CO_2 emissions. The measure represents the implicit carbon price imposed on each unit of CO_2 emitted, if all energy taxes targeting the specific domain is a carbon tax. A higher value means that the energy tax targeting a specific focal issue is higher, indicating a stronger green signal to polluters.

The revenue from the domains of the energy tax revenue is expressed in 2015 constant US dollars, that are PPP converted.

8.7.1 Climate change mitigation domain

The climate change domain represents energy taxes that are designed to reduce climate change. This is a broad category that includes instruments from electricity taxes to carbon taxes as mentioned in section 6.2.3. All countries included in the baseline shock have energy-related taxes that target climate change.

Figure 12 - A one percentage point shock to the climate change mitigation domain on CO_2e emissions per capita



Note: Figure 12 illustrates an upward and exogenous one percentage point shock to the climate change mitigation domain on CO_2e per capita while controlling for three lags of CO_2e emissions per capita, GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents metric tons of CO_2 equivalents. Source: Own production.

Figure 12 shows the impulse response function of a positive shock to the climate change mitigation domain on CO_2e emissions per capita, where the energy tax revenue targeting climate change mitigation increases relatively to CO_2 emissions. A notable decrease in CO_2e emissions per capita is present showing a clear initial negative reaction. The impulse response function reaches its maximum after three to four horizons obtaining an average reduction of 0,25 metric tons per capita. The maximum reduction being reached after three to four years shows an unfolding impact on CO_2e emissions. It takes time for firms to invest in cleaner technologies and for consumers to adjust their consumption and behavior.

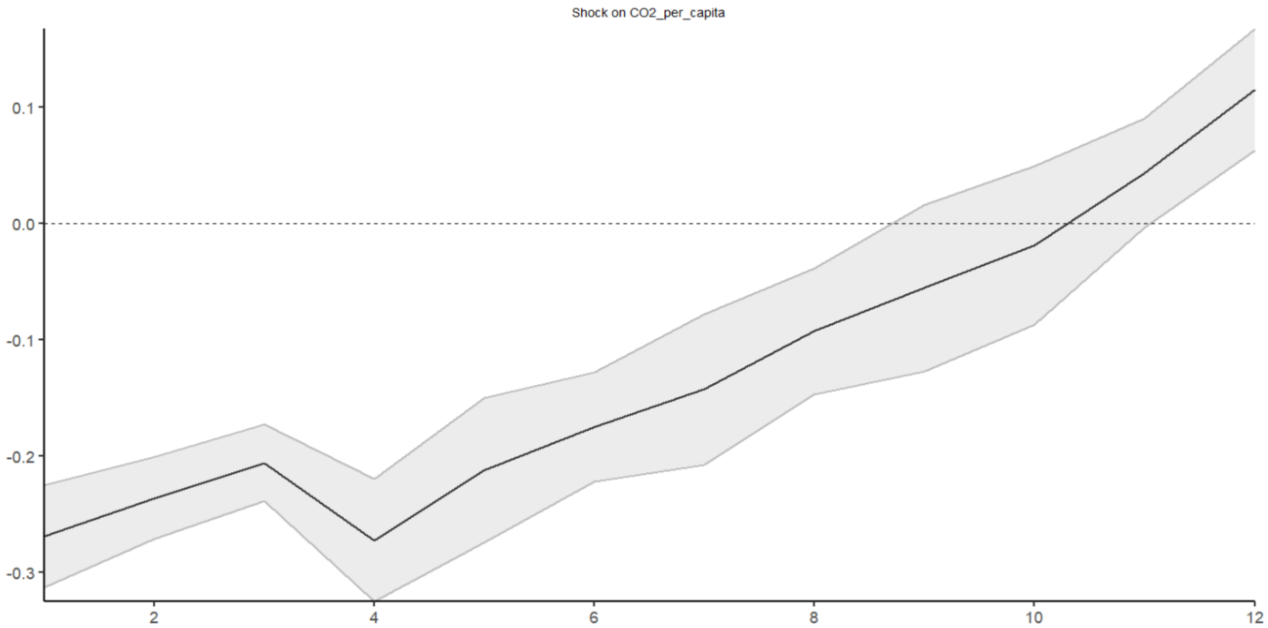
Higher pollution taxes encourage polluters to cut emissions and adopt cleaner technologies. The initial impact is large and negative but weakens over time. The emissions are converging back to the baseline level at later horizons. This indicates a gradual rebound effect as seen in figure 10 and 11, which shows that certainty about level impact of the shock is clearer in the short and medium term. Initial gains may be eroded in the long run, which is displayed at the twelfth horizon. The confidence bands widen after the fourth horizon increasing uncertainty about the size of reduction in CO_2 emissions. The statistical significance is the strongest at early horizons.

Overall, a shock to the climate change mitigation is effective at earlier horizons, since the expenses of polluting increase. Higher energy taxes targeted at climate change mitigation are associated with lower emissions levels in the short and medium term. However, uncertainty of persistence of the benefit of the one-time shock in the long run exists.

8.7.2 Air pollution domain

The air pollution domain represents energy taxes that are designed to reduce air pollution. This is a category that includes instruments from SO_2 and NO_x pollution tax to excise taxes on petroleum products as mentioned in section 6.2.3. All countries have except the United Kingdom have sufficient data on energy-related taxes that target air pollution.

Figure 13 – A one percentage point shock to the air pollution domain on CO_2e emissions per capita



Note: Figure 13 illustrates an upward and exogenous one percentage point shock to the air pollution domain on CO_2e per capita while controlling for three lags of CO_2e emissions per capita, GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents metric tons of CO_2 equivalents. Source: Own production.

Figure 13 illustrates the trajectory of the impulse response function of a one percentage point increase to the air pollution domain, where the energy tax revenue targeting climate change mitigation increases relatively to CO_2 emissions. The impulse response function depicts a similar trajectory to the climate change domain, showing the most significant impact in earlier horizons, where the statistical significance is the strongest. The maximum magnitude shows a reduction of 0,27 metric tons CO_2e per capita after four horizons. The delayed peak effect also indicates a gradual adaptation of firms and consumers, which takes time. Therefore, the maximum impact occurs with a time lag.

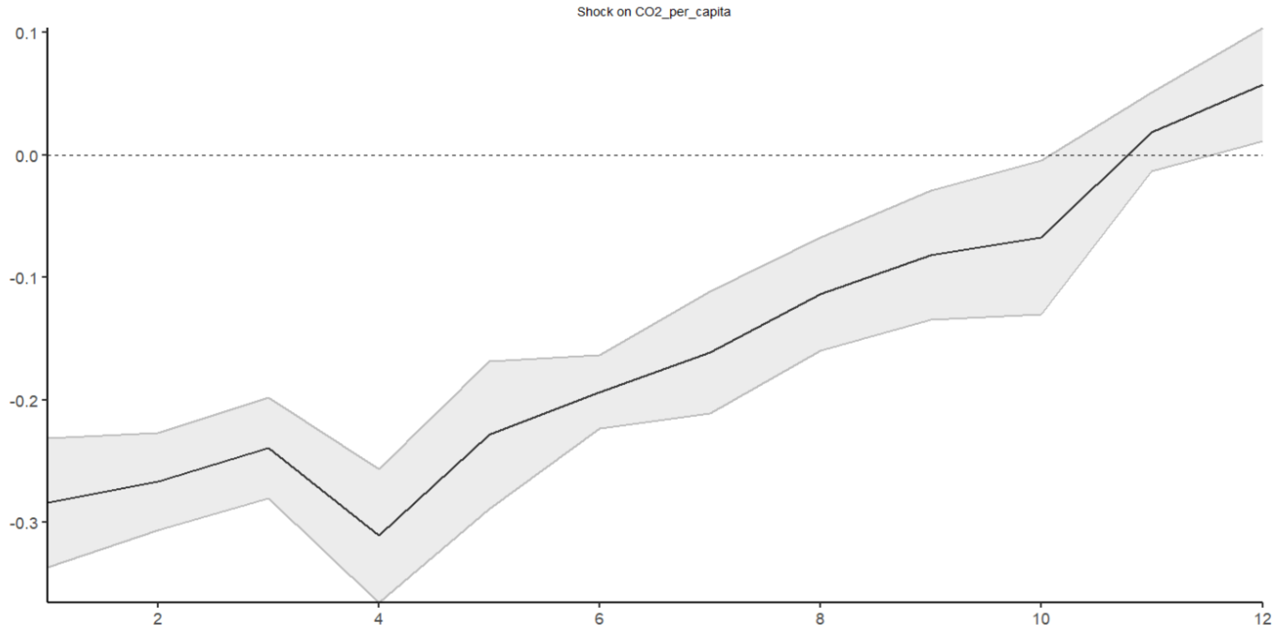
Figure 13 also shows a large negative reduction at earlier horizons, but the impact is fading out with time. The impact is still negative and significant in medium term, but the emissions per capita are converging back to the baseline level at later horizons. The confidence bands widen after the fourth horizon increasing uncertainty about the size of the reduction in CO_2 emissions. The later horizons indicate later rebound effect as a result of a one-time shock. Although a rebound appears at eleventh and twelfth horizons, high uncertainty precludes any definitive conclusion.

Overall, a shock to the air pollution domain is effective at earlier horizons, since the expenses of polluting increase. Higher energy taxes targeted at air pollution are associated with lower emissions levels in the short and medium term. A level effect shifting CO_2e emissions per capita appears persistent in spite of a rebound occurring at later horizons.

8.7.3 Fossil fuels domain

The fossil fuels domain represents energy taxes that are designed to reduce fossil fuel consumption. This is a category that includes instruments as basic taxes on mineral oil and individual consumption tax on petroleum products as mentioned in section 6.2.3. All countries have sufficient data on energy-related taxes that target fossil fuel consumption and extraction.

Figure 14 - A one percentage point shock to the fossil fuels domain on CO_2e emissions per capita



Note: Figure 14 illustrates an upward and exogenous one percentage point shock to the fossil fuels domain on CO_2e emissions per capita while controlling for three lags of CO_2e emissions per capita, GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents metric tons of CO_2 equivalents. Source: Own production.

Figure 14 depicts the impulse response function of CO_2e emissions per capita after a one percentage point shock to the fossil fuel domain over 12 horizons, where the energy taxes targeting fossil fuels increase relatively to CO_2 emissions. The trajectory of CO_2 emissions per capita in figure 14 resembles the trajectory of CO_2e emissions per capita shown in figures 12 and 13. The magnitude of the reduction of CO_2e emissions per capita occurs after four horizons at -0,31 metric tons of CO_2-equivalents, which shows a gradual adaptation of consumers and firms. Therefore, figure 14 also displays the peak reduction after a time lag. Firms and consumers reduce their consumption of fossil fuels and are encouraged to switch to cleaner alternatives.

The impulse response function is statistically significant through nine horizons and becomes insignificant at the tenth and eleventh horizons. The twelfth horizon shows inconsiderable statistical significance. The impact of an increase in energy taxes targeting the fossil fuel domain diminishes over time. The short- and medium-term horizons are significantly negative, which shows that the increase in an effective tool in curbing emissions per capita in the short and medium run. An insignificant rebound effect occurs at the twelfth horizon with which much uncertainty is associated.

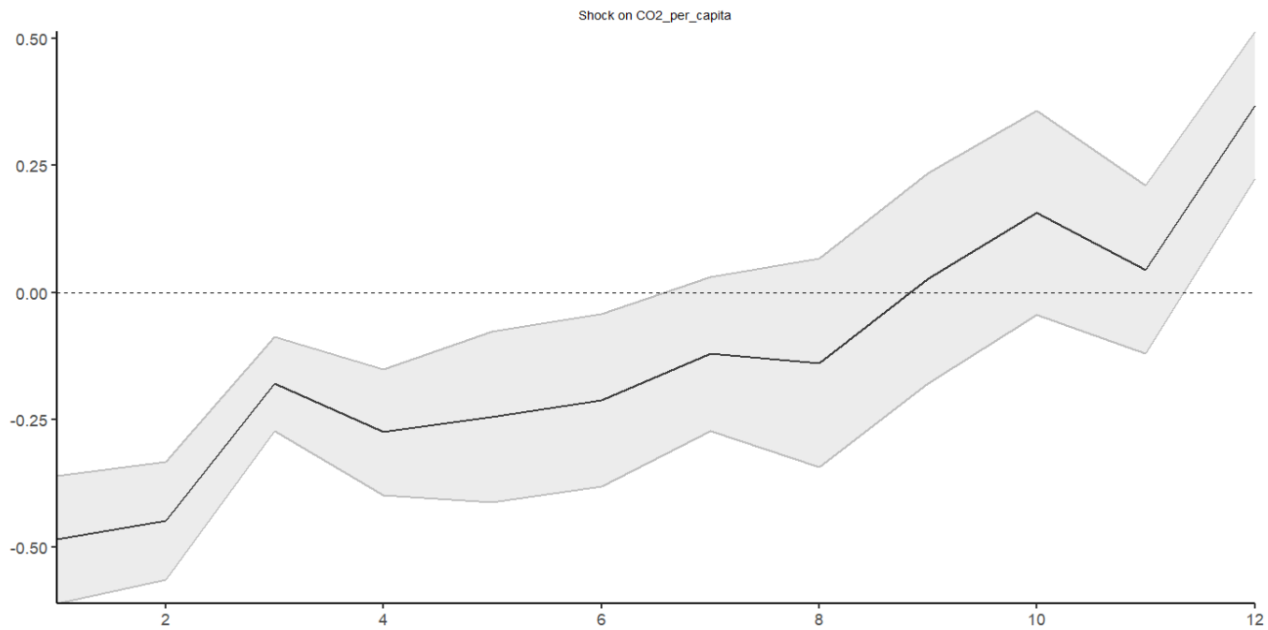
The trajectory suggests that the level shift in CO_2e per capita is stronger in the short and medium term. The size of the reduction in CO_2e per capita is uncertain in the long run.

Overall, a shock to the fossil fuel domain is effective at earlier horizons, since the expenses of polluting increase. Higher energy taxes targeted at fossil fuel consumption and extracted are associated with lower emissions levels in the short and medium term. A level effect shifting CO_2e emissions per capita appears persistent in spite of a rebound occurring at later horizons.

8.7.4 Energy efficiency domain

The energy efficiency domain represents energy taxes that are aimed at reducing the energy intake from all energy sources. This is a category that includes instruments such as electricity taxes and the promotion of power-resources development tax as mentioned in section 6.2.3. Countries included in this domain are Australia, Austria, Belgium, Czechia, Denmark, Finland, France, Italy, Japan, Luxembourg, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland and the United Kingdom. These countries have sufficient data on energy-related taxes that target energy efficiency.

Figure 15 - A one percentage point shock to the energy efficiency domain on CO_2e emissions per capita



Note: Figure 15 illustrates an upward and exogenous one percentage point shock to the energy efficiency domain on CO_2e emissions per capita while controlling for three lags of CO_2e emissions per capita, GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents metric tons of CO_2 equivalents. Source: Own production.

Figure 15 displays a one percentage point shock to the energy efficiency domain on CO_2e emissions per capita over 12 horizons. The ratio of energy taxes aimed at energy efficiency to CO_2 emissions increases, which results in an immediate reduction in CO_2e emissions per capita. The reduction is strong and immediate, since the magnitude is approximately -0,50 metric tons per capita. This shows that the shock translates quickly into behavioral or technological changes thereby reducing emissions. The quick response indicates a rapid reduction in energy use, and efficiency improvements, triggered by higher taxes.

The magnitude of the impulse response diminishes after the second horizon and maintains a level at a reduction of approximately -0,20 metric tons per capita from the second horizon through the sixth horizon. This trajectory implies that energy efficiency does not have a persistent effect on CO_2e per capita long term, since the one-time shock only results in a one-time drop in CO_2e per capita. In the long run, emissions per capita can be seen increasing to a level higher than the pre-shock baseline level. Since this impact is in later horizons, more uncertainty is associated with the trajectory.

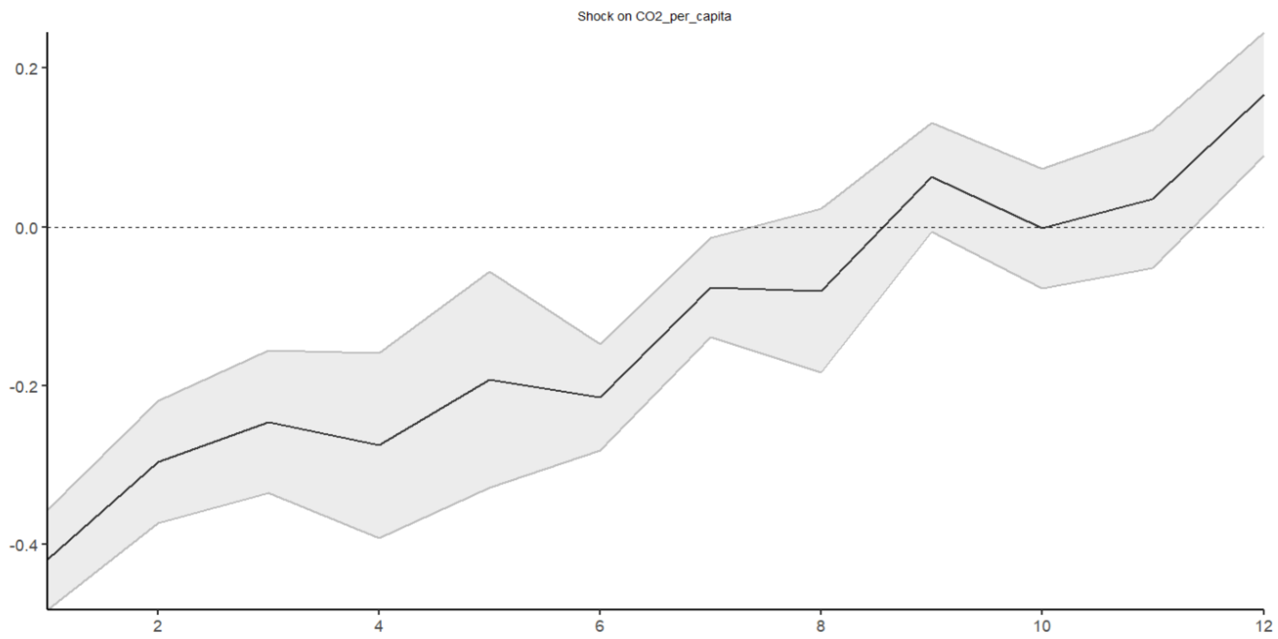
The impulse response function is statistically significant through six horizons. The confidence bands widen significantly after the fourth horizon, indicating a higher degree of uncertainty. The shock on CO_2e emissions per capita is statistically insignificant from the seventh to eleventh horizon. The impact on CO_2e emissions converges back to the pre-shock baseline level. The rebound effect seems to be significant in the twelfth horizon, but due to uncertainty it is not possible to fully conclude that a rebound effect happens, but it suggests that initial gains may be eroded over time due to adaptive behavior or the rebound effect/green paradox.

Overall, the increase in the energy efficiency domain has a significantly large impact on CO_2 emissions in the short and medium term. However, the impact erodes over time, and the trajectory implies no persistent level effect in the long run. As the shock's magnitude diminishes over time, uncertainty about its level effect increases relative to climate change mitigation, air pollution, and fossil fuels domains. Economic drivers of emissions – such as GDP per capita and trade openness – may also dampen its initial impact on CO_2e emissions.

8.7.5 Chemical management domain

The chemical management domain represents energy taxes that are aimed at innovation of safe and sustainable alternatives to harmful chemicals to protect consumers, workers and the environment. This is a category that includes instruments such as tax on chemicals in certain electronic products as mentioned in section 6.2.3. Countries included in this domain are Australia, Austria, Czechia, Denmark, Finland, France, Germany, Greece, Japan, Luxembourg, Netherlands, Poland, Portugal, Slovak Republic, Spain, Sweden, and the United Kingdom. These countries have sufficient data on energy-related taxes that target chemical management.

Figure 16 - A one percentage point shock to the chemical management domain on CO_2e emissions per capita



Note: Figure 16 illustrates an upward and exogenous one percentage point shock to the chemical management domain on CO_2e emissions per capita while controlling for three lags of CO_2e emissions per capita, GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents metric tons of CO_2 equivalents. Source: Own production.

Figure 16 displays a one percentage point shock to the chemical management domain on CO_2e emissions per capita over 12 horizons. The ratio of energy taxes aimed at chemical management to CO_2 emissions increases, which results in an immediate reduction in CO_2e emissions per capita. The reduction is strong and immediate, since the magnitude is approximately -0,42 metric tons per capita. This shows that the shock translates quickly into behavioral or technological changes thereby reducing emissions. The quick response of CO_2 emissions indicates that the shock is effective in the short term in raising costs of polluting the environment with chemicals.

The magnitude of the impulse response diminishes after the first horizon and converges towards the pre-shock baseline level, which is reached in later horizons. This trajectory implies that taxing chemical management does not have a persistent effect on CO_2 emissions per capita long term, since the one-time shock only results in a one-time drop in CO_2e emissions per capita. In the twelfth horizon, emissions per capita increase to a level higher than the pre-shock baseline level.

The impulse response function is statistically significant through seven horizons. The confidence bands widen significantly after the second horizon and the bands continue to fluctuate at varying widths around the impulse response function, indicating a higher degree of uncertainty. The precision of the effect decreases after two horizons, meaning that the impact is unclear. The shock on CO_2e emissions per capita is statistically insignificant from the seventh to eleventh horizon, where CO_2e per capita converges back to the pre-shock baseline level. The rebound effect seems to be significant in the twelfth horizon, but uncertainty makes it unreliable. It is not possible to fully conclude that a positive rebound effect happens, but it suggests that initial gains may be eroded over time due to adaptive behavior or the rebound effect/green paradox.

Despite an underlying upward trend, taxing chemical management reduces CO_2e per capita in both the short and medium term. The long-term impact on per capita CO_2e, since it converges towards the pre-shock baseline level is less clear. Therefore, chemical management does not target CO_2e emissions per capita as effectively as other domains, and economic drivers of emissions may quickly erode the environmental gains in the short and medium term.

8.8 Comparisons of the effectiveness of domains on emissions per capita

Most domains show a significant impact short- to medium-term negative impact on CO_2e per capita, The energy efficiency domain produces the strongest maximum reduction at -0,50 metric tons per capita thereby being the most effective policy from the first two horizons. The shocks to the energy efficiency domain and the chemical management erode quickly compared to the shock on climate change mitigation, air pollution and fossil fuels, respectively. In this respect, it is important to note that energy efficiency and chemical management do not include all countries, which can affect the trajectory, since the impulse response displays the average impact.

However, an upward convergence towards the pre-shock baseline is common in all impulse response functions for domains. Furthermore, the impact of energy efficiency and chemical management erodes quickly, since the convergence happens at the sixth or seventh horizon. The convergence of climate change mitigation, air pollution and fossil fuels, respectively, happens in the ninth or tenth horizon. This implies that concentrating on energy taxes on certain domains does not result in a long-run level shift in CO_2e per capita. While taxes targeting climate change mitigation, air pollution, and fossil fuels deliver significant short- and medium-term effects, those on energy efficiency and chemical management wear off more quickly. Therefore, energy taxes aimed at climate change mitigation, air pollution, and fossil fuel use are more effective for achieving sustained per capita CO_2e reductions.

9. Discussion

This section discusses the economic consequences of increasing taxes imposed on the environment. Mitigating CO_2 emissions is very important to comply with sustainable goals and decarbonization of the economy. However, there are costs associated with the decarbonization of the economy. Therefore, the Environmental Sacrifice Ratio, also referred to as the Green Sacrifice Ratio, is calculated to estimate the costs of tax increases on the economy, which has implications for environmental policy.

The Green Sacrifice Ratio (GSR) computes the cumulative loss in output level when CO_2 emissions permanently decline by 1% (Erdogan et al., 2024, p. 3). Therefore, the measure calculates the output loss associated with a cut in emissions. The ratio is constructed based on the traditional sacrifice ratio, which calculates the tradeoff of economic policies. Empirical best practice among other studies is to log variables in order to obtain a unit-less GSR as done in Erdogan et al. (2024), which makes comparisons easier. Therefore, normalizing GDP per capita and CO_2 equivalents per capita reduces the sensitivity to units and scale, since large values of GDP per capita automatically result in large abatement costs per metric ton of CO_2-equivalents.

When the log-based green sacrifice ratio is obtained, the GSR is an elasticity. The average GSR ratio across 12 horizons is calculated as the ratio of the cumulative impulse response function of GDP per capita to the cumulative impulse response function of CO_2e emissions per capita:

$$GSR = -\frac{\sum_{t=0}^{H} IRF_{GDP\ per\ Capita}(t)}{\sum_{t=0}^{H} IRF_{GHG\ per\ capita}(t)} \tag{9.1}$$

Table 4 – Green Sacrifice Ratio

Shock	Average Green Sacrifice Ratio, %	Average Green Sacrifice Ratio, $
Effective environmental tax rate	-0,67%	$1674,62
Effective environmental energy tax rate	-0,75%	$2588,75
Carbon tax rate	-0,07%	$33,93
Energy carbon tax rate	-0,19%	$188,92
Climate change mitigation domain	-0,23%	$307,53
Air pollution domain	-0,17%	$165,64
Fossil fuels domain	-0,17%	$145,73
Energy efficiency domain	-0,13%	$168.74
Chemical management domain	-0,41%	$1420,31

Note: The table presents the GSR ratio for the shock performed in the study. Furthermore, the table presents the monetary reduction.
Source: Own production

The GSR ratio in dollars is computed as: $GSR_{\$} = GSR_{\%} * \frac{GDP\ per\ capita_{level}}{GHG\ emissions\ per\ capita_{level}}$. Table 8 displays the GSR for the shocks performed in the study. It is noticeable that the shocks to the effective environmental tax rate and the effective environmental energy tax rate induce the highest tradeoff. The GSR for the effective environmental tax rate shows that GDP per capita is lowered by 0,67% percent on average when CO_2e emissions per capita are lowered by one percentage. Similarly, the GSR for the effective environmental energy tax rate shows that to achieve a one percent reduction in CO_2e per capita, GDP per capita is lowered by 0,75% on average. This correlates with the effective environmental energy tax rate having a stronger and more persistent impact than the general effective environmental tax rate. The tradeoff of effective environmental tax rate and effective environmental energy tax rate is quite substantial, meaning that GDP per capita responds strongly to a cut in CO_2e emissions per capita, when environmental taxes and energy-related environmental taxes constitute a higher percentage of the total tax base. However, it is important to note that the GSRs illustrate the average cost over twelve horizons meaning that the time frame of policy shocks should be considered when increasing environmental taxes.

The GSRs of the carbon tax and the energy carbon tax have a smaller impact on GDP per capita. For the carbon tax, GDP per capita is lowered by 0,07%, when CO_2e emissions per capita are lowered by 1%. For the carbon energy tax, GDP per capita is lowered by 0,19% when CO_2e emissions decrease 1%. These GSR ratios are quite low, reflecting a smaller tradeoff. A reason for the smaller tradeoff is the persistence of the shocks, which affects the GSR, as it illustrates the average tradeoff. Consequently, the carbon tax shock and the carbon energy result in minimal tradeoffs, which imply that increasing environmental taxation and energy-related environmental taxation on CO_2 emissions do not decrease GDP per capita substantially on average across time. Increasing environmental taxation relative to CO_2 emissions as done in the carbon tax shock and the carbon energy tax shock could possibly target firms harsher than consumers.

Overall, broad-based tax increases such as the effective environmental tax rate impact GDP per capita the most when emissions are decreased 1% as seen by monetary GSRs. Therefore, it seems that policies achieving persistent per capita emissions reductions tend to have higher economic sacrifice per unit of CO_2e abated. This indicates a lower cost-efficiency compared to the carbon tax, energy carbon tax and shocks related to specific environmental domains.

For domains, climate change mitigation, fossil fuels and air pollution abate more CO_2e per capita. These are broader domains, which indicates more policy instruments. Furthermore, the aforementioned domains are critical elements in mitigating climate change, which make them subject to various policy instruments. The energy efficiency domain has a smaller GSR, whereas chemical management has a larger impact on emissions although it is less cost-effective than other domains – such as the fossil fuels domain.

In general, GSRs suggest that targeted carbon-focused measures like carbon taxes or fossil fuel taxation tend to be highly cost-efficient. The GSR values are relatively low, which means that the cost of abatement is low per unit of CO_2e. Although the economic sacrifice appears minimal, shocks to the carbon tax and fossil fuels domain clearly persist in the short and medium term, while the effective environmental and energy tax rates remain persistent in the long term. Broader environmental taxes such as the effective environmental tax rate or the effective environmental energy tax rate are associated with higher economic sacrifices, but they result in a persistent level shift in CO_2e emissions per capita as seen in figure 8 and 9. Therefore, the economic tradeoff must also be compared to the expected magnitude and persistence of the shocks. Overall, the carbon tax results in the lowest sacrifice ratio, thereby underlining the importance of instruments targeted at CO_2 emissions. Thus, the carbon tax rates prove to be an effective policy instrument due to their short- and medium-term impact as well as low economic costs, which suggests that carbon tax rates are an effective way for countries to obtain reductions in CO_2e per capita and comply with international environmental goals, such as Sustainable Development Goal 13.

Consequently, the GSR highlights the importance of balancing environmental impact with cost-effectiveness and persistence when designing climate policies with the aim of maximizing emission reductions while minimizing economic sacrifice.

10. Thesis research design: the logic of methodological choices

This section outlines the fundamental structure of the project, methodological considerations, delimitation, and assesses the validity and reliability of the data used. Also, methodological choices that affect the content of the thesis are elaborated.

10.1 Limitations to the thesis

In the course of developing this thesis, some delimitations have been made in order to clarify the scope and content.

The thesis includes data from 25 countries in the span from 1995 to 2020. The data spans across a relatively small sample as the annual data is used. The availability of data on environmental taxes is limited both in terms of the number of countries with sufficient data and observations in time. Most countries started documenting environmental tax data in 1994, which puts a lower time limit on the number of observations of each country. This study employs data from 1995 in order to include more countries. The availability of OECD Environmental Policy Stringency Index, which serves as a control variable in the panel local projections regressions, puts an upper time limit to the data as it is only available until 2020. Therefore, the thesis is subject to data availability constraints.

The thesis aims to analyze the general consensus regarding the impact of environmental taxes on carbon dioxide equivalents per capita. Given that data of 25 countries are included, the importance and focus of environmental policies differ. It is not within the scope of this thesis to explore environmental tax policies in each country in depth, but the introduction gives an implicit overview of the importance of environmental tax policy of the countries included.

The thesis also focusses on the energy tax category as a specific tax category within the broad scope of environmental tax revenue. The choice of the energy tax category is motivated by the critical role of energy in the transition towards decarbonization, as energy plays a huge role in emitting greenhouse gases. Therefore, the study focusses on the broad scope of environmental taxes as well as the energy tax category and its related environmental domains.

Various variables are expressed in constant US dollars PPP to correct for inflation and increase the comparability of variables between countries. However, GDP per capita is expressed in 2021 constant international US dollars PPP, while other variables such as the environmental energy tax revenue on certain domains and the petrol tax rate are expressed in 2015 constant international US dollars PPP. The difference in base year implies different constant values of the dollar and different PPP rates. However, due to the limited availability of data, the variables are included with different base years, since it is estimated that the difference does not lead to substantial deviations.

Moreover, one might suspect a potential bidirectional causality between environmental taxes and CO_2 emissions, since environmental policy could respond to changes in emission levels. However, the purpose of this thesis is not to estimate the causal direction between environmental taxes and CO_2 gas emissions, but rather to examine how an exogenous shock to environmental taxes affects CO_2 emissions in terms of magnitude and persistence, when controlled for a variety of economic and environmental control variables.

10.2 Validity and reliability of the data

The data used in the thesis are extracted from the OECD Database and the World Bank database, which are considered well-established institutions. Therefore, given the provenance of the data, the validity is assessed as high.

The reliability of the data is also considered high, since the aforementioned institutions are assumed to follow well-established data-collection procedures based on years of experience. This ensures that the data exhibits a high degree of reliability and accuracy. However, data-processing methods may evolve over time, since the procedures for data collection are presumed to continuously improve (Kærsgaard, Jensen, & Sletskov, 2023, p. 7).

10.3 Scientific theoretical approach

The thesis addresses the impact of environmental taxes as a policy instrument. Section 4 presents a theoretical perspective of environmental taxation as a policy instrument from the perspective of environmental economics. Environmental economics is considered a mainstream approach to the economics of climate change, and this school of economics weighs its decision on whether to improve the state of environment on valuation techniques such as cost-benefit analyses. This way, the benefits from improving the environmental quality are evaluated relative to abatement costs. Consequently, the concept of willingness to pay is particularly central in environmental economics, and it assumes that human preferences decide the valuation of the environment, and all environmental damage can be monetarily valued. Finally, the concept of willingness to pay assumes no uncertainty, meaning that people have all knowledge about the negative impact of environmental degradation. Ultimately, environmental economics is concerned by the resource allocation problem associated with climate change, as the main goal is to determine, how much income or consumption that countries are willing to sacrifice today in order to combat future environmental degradation (Valdecantos, 2023c, pp. 3, 5, 20).

The approach of the thesis aligns with the hypothetico-deductive method. First, environmental-economics theory about environmental taxes is presented, which is then tested empirically. The hypothesis is that environmental taxes decrease CO_2e per capita. Finally, the outcome of the shocks is evaluated relative to the hypothesis.

11. Conclusion

Environmental taxes are increasingly used to curb emissions as they have the ability to change energy consumption patterns and encourage cleaner production. Additionally, environmental taxes impose a price signal, which encourages polluters to consider environmental degradation in their production and consumption. A higher effective environmental tax implies that the country is collecting more environmental taxes relative to the total tax base indicating stronger environmental policies on environmental degradation.

The average ratio of environmental taxes relative to the total tax revenue shows a declining trend, which also applies to the CO_2e per capita. Panel data on 25 OECD countries shows that environmental taxes constitute 5-9% of the total tax base, whereas CO_2e emissions capita are typically in the range of 5-11 metric tons of CO_2e per capita. Some countries with higher environmental taxes tend to have lower CO_2e per capita, but a scatterplot shows that the correlation between environmental taxation and CO_2e per capita is unclear.

Empirically, a one percentage point shock to the effective environmental tax rate results in a persistent reduction in CO_2e metric tons per capita with maximum reduction reaching 0,10-0,12 metric tons per capita. Similarly, the effective environmental energy tax rate results in a persistent level shift in CO_2e metric tons per capita with a maximum magnitude of -0,15 metric tons per capita. The result is stronger for the effective environmental energy tax rate, which shows that imposing higher energy taxes reduces CO_2e per capita more than targeting environmental taxes in a broad sense, which attests to the critical role of energy in the transition to a low-carbon trajectory.

Shocks to the effective carbon tax rate and the effective carbon energy tax rate, that measures the average implicit tax burden on carbon emissions from all sources, also depict a reduction in CO_2e per capita, but the reduction is less persistent than for the effective environmental tax rate. Consequently, shocks to the effective carbon tax rate and effective energy carbon tax rate result in reductions of CO_2e per capita in the short- and medium-term, but uncertainty about long-term persistence. Finally, the shocks to energy-related environmental taxes targeted at environmental domains show varying reductions in CO_2e per capita with some domains exhibiting a clear upward-sloping trend towards the pre-shock baseline level. Therefore, uncertainty about long-term persistence exists. Notably, the energy efficiency domain results in the largest magnitude of reduction at -0,50 CO_2e metric tons per capita, but the effect is short-lived compared to the baseline shock of broad environmental taxes on CO_2e per capita.

To examine the economic sacrifice of environmental taxation, the Green Sacrifice Ratio is calculated. Broader environmental shocks show a larger economic cost, but results in a persistent level effect. Carbon-focused shocks result in a lower economic cost, however the corresponding impulse response functions show a less clear long-term level effect. Based on the GSR, carbon tax rates prove to be effective policy instruments due to their significant short- and medium-term impact on CO_2e per capita and low economic costs. Consequently, the GSR underscores the need to balance climate policies based on environmental impact, cost-effectiveness and the persistence of shocks.

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Appendix

A.1 Driscoll and Kraay standard errors

The model employs Driscoll and Kraay standard errors to control for cross-sectional dependence. Driscoll and Kraay standard errors, used to estimate coefficients, are defined as the square roots of the diagonal elements of the asymptotic covariance matrix (Hoechle, 2007, p. 8):

$$V(\hat{\theta}) = (\boldsymbol{X}'\boldsymbol{X})^{-1}\widehat{\boldsymbol{S}_T}(\boldsymbol{X}'\boldsymbol{X})^{-1} \quad \text{(A.1.1)}$$

$\hat{\theta}$ represents the vector of unknown coefficients, $\boldsymbol{X}$ is a vector of independent variables, and $\widehat{\boldsymbol{S}_T}$ is the Newey West estimate of the covariance matrix.

$$\widehat{\boldsymbol{S}}_T = \hat{\Omega}_0 + \sum_{j=1}^{m(T)} w(j,m)\,[\widehat{\boldsymbol{\Omega}}_j + \widehat{\boldsymbol{\Omega}}_j'] \quad \text{(A.1.2)}$$

In equation A.1.2, m(T) defines the lag length to which residuals can be autocorrelated. The Barlett weights ensure that less weight is placed on higher order lags:

$$w(j, m(T)) = \frac{1-j}{m(T)+1)} \quad \text{(A.1.3)}$$

$\widehat{\boldsymbol{\Omega}}_j$ is a $(K+1) \times (K+1)$ matrix defined in the following way:

$$\widehat{\boldsymbol{\Omega}}_j = \sum_{t=j+1}^{T} \boldsymbol{h}_t(\hat{\theta})\boldsymbol{h}_{t-j}(\hat{\theta})' \text{ Where } \boldsymbol{h}_t(\hat{\theta}) = \sum_{i=1}^{N(t)} \boldsymbol{h}_{it}(\hat{\theta}) \quad \text{(A.1.4)}$$

With $\boldsymbol{h}_{it}(\hat{\theta}) = \boldsymbol{x}_{it}\hat{\varepsilon}_{it} = \boldsymbol{x}_{it} = (y_{it} - \boldsymbol{x}_{it}'\hat{\theta})$ (Hoechle, 2007, p. 8).

A.2 Cross-sectional dependence

Cross-sectional dependence is common in macroeconomic data. Therefore, this thesis also tests for cross-sectional dependence.

To test for cross-sectional dependence, the thesis employs Pesaran's CD test, which is based on pair-wise correlation coefficients. The CD-statistic is calculated as:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \qquad (A.2.1)$$

N is the number of cross-sectional units, and T is the number of time periods. $\hat{\rho}_{ij}$ are the pair-wise correlation coefficients between the residuals of unit i and j, which are calculated the following way:

$$\hat{\rho}_{ij} = \hat{\rho}_{ji} = \frac{\sum_{t=1}^{T} e_{it}e_{jt}}{\left(\sum_{t=1}^{T} e_{it}^2\right)^{1/2}\left(\sum_{t=1}^{T} e_{jt}^2\right)^{1/2}} \qquad (A.2.2)$$

e_{it} is the Ordinary Least Squares estimate: $e_{it} = y_{it} - \hat{\alpha}_i - \hat{\beta}_i' \boldsymbol{x}_{it}$.

Figure 17 – Pesaran CD test for cross-sectional dependence in panel data with twoways fixed effects

```
        Pesaran CD test for cross-sectional dependence in panels

 data:  GHG_per_capita ~ Effective_environmental_taxrate + L1_GDP + L2_GDP +
 L3_GDP + L1_in + L2_in + L3_in + L1_tra + L2_tra + L3_tra +     L1_re + L2_re +
 L3_re + L1_PET + L2_PET + L3_PET + L1_OECD +     L2_OECD + L3_OECD + L1_ghg +
 L2_ghg + L3_ghg
 z = -2.3496, p-value = 0.01879
 alternative hypothesis: cross-sectional dependence
```

Note: Figure 17 shows Pesaran's cross-sectional dependence test. L1,L2, and L3 represent the first, second and third lag of the controls. 'GDP' represents GDP per capita, 'in' represents environmental innovations as a percentage of domestic innovations, 'tra' represents trade openness, 're' represents renewable energy consumption as a percentage of total final energy consumption, and 'ghg' represents CO_2 per capita, CO_2e. The model uses twoways fixed effects.

Figure 17 is based on the baseline model, which includes a shock to the effective environmental tax rate. The model includes twoways fixed effects. The test-statistic has a value of -2,35 corresponding to a p-value of 0,01879. The null hypothesis is no cross-sectional dependence, while the alternative hypothesis represents cross-sectional dependence. The p-value shows that there is no cross-sectional dependence at 5% and 10% significance level, but cross-sectional dependence cannot be rejected at a 1% significance level.

Figure 18 - Pesaran CD test for cross-sectional dependence in panel data with individual effect

```
        Pesaran CD test for cross-sectional dependence in panels

data:  GHG_per_capita ~ Effective_environmental_taxrate + L1_GDP + L2_GDP +
L3_GDP + L1_in + L2_in + L3_in + L1_tra + L2_tra + L3_tra +     L1_re + L2_re +
L3_re + L1_PET + L2_PET + L3_PET + L1_OECD +     L2_OECD + L3_OECD + L1_ghg +
L2_ghg + L3_ghg
z = 26.664, p-value < 2.2e-16
alternative hypothesis: cross-sectional dependence
```

Note: Figure 18 shows Pesaran's cross-sectional dependence test. L1,L2, and L3 represent the first, second and third lag of the controls. 'GDP' represents GDP per capita, 'in' represents environmental innovations as a percentage of domestic innovations, 'tra' represents trade openness, 're' represents renewable energy consumption as a percentage of total final energy consumption, and 'ghg' represents CO_2 per capita, CO_2 e. The model uses individual fixed effects.

Figure 18 is also based on the baseline model, which includes a shock to the effective environmental tax rate. This model is based on individual unit-specific time effects. It is very clear from the test-statistic, which is 26,66, and the very low p-value that cross-sectional dependence is present in the data. Compared to figure 17, employing a twoways fixed effects model gets rid of much of the cross-sectional dependence by including time-specific fixed effects. Therefore, using a twoways fixed effects model with Driscoll and Kraay standard errors handles much of the cross-sectional dependence, and no changes to the data are considered.

A.3 Testing for the optimal number of lags

In order to test for the optimal number of lags, AIC and BIC values are computed for models with two, three and four lags of controls.

The AIC values are computed the following way for the baseline model including a shock to the effective environmental tax rate with two, three and four lags of controls, respectively:

$$AIC(p) = -2l_p + 2k_p \qquad \text{(A.3.1)}$$

L refers to the maximized log-likelihood of the fitted model and k is the number of estimated parameters and is calculated as: $-\frac{n}{2}[\ln(2\pi) + \ln\left(\frac{RSS}{n}\right) + 1]$. The BIC values are computed the following way for the baseline model including a shock to the effective environmental tax rate with two, three and four lags of controls, respectively:

$$BIC(p) = -2l_p + \ln(n)\, k_p \qquad \text{(A.3.2)}$$

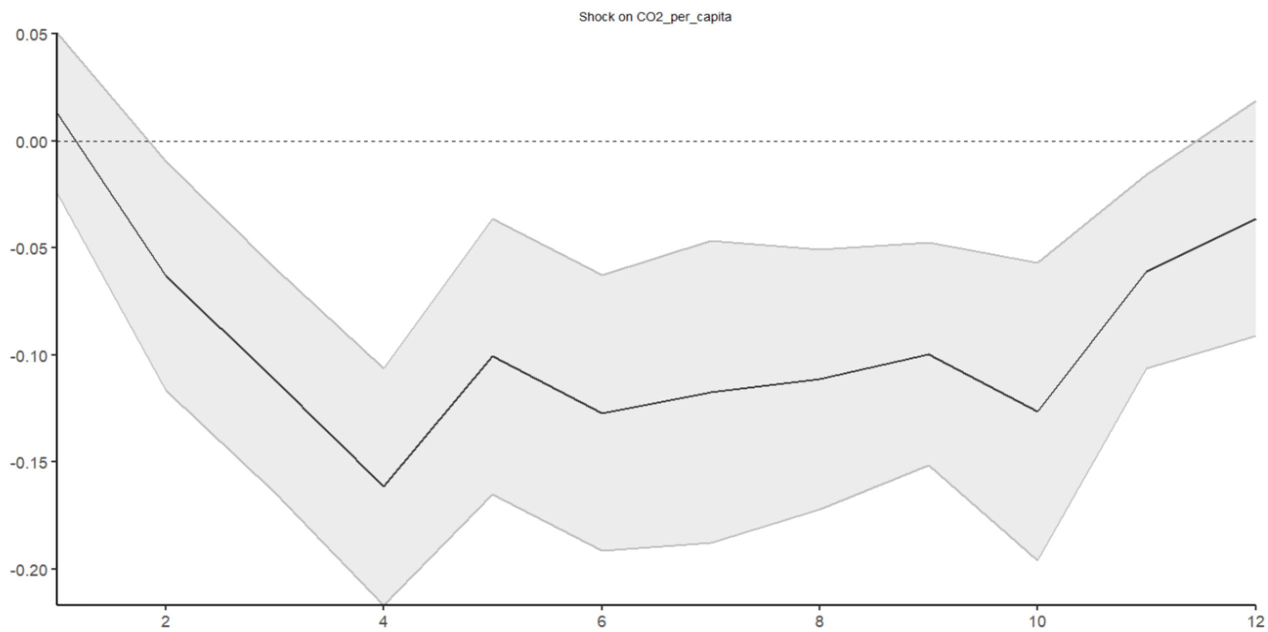
Table 5 – AIC and BIC results

Number of lags	AIC	BIC
2	1276,32	1343,40
3	1280,70	1379,09
4	1281,57	1411,27

Note: This table presents the AIC and BIC results of the baseline model which is based on a shock to the effective environmental tax rate including two, three and four lags of controls, respectively. Source: Own production.

The AIC shows the model with the best expected out-of-sample predictive fit, and it places penalties on complexity. The BIC penalizes extra parameters and measures the trade-off between the model fit and the complexity (Mohammed & Far, 2015). From the results, two lags produce the best fit for the model. However, since the models constructed in this thesis are not used for forecasting, three lags are used for controls. The choice of three lags is motivated by the overall significance of the impulse response functions and the width of confidence bands. The model with three lags (figure 8) produces more statistically significant results based on the width of the confidence bands compared to figure 19.

Figure 19 - A one percentage point shock to the effective environmental tax rate on CO_2e emissions per capita

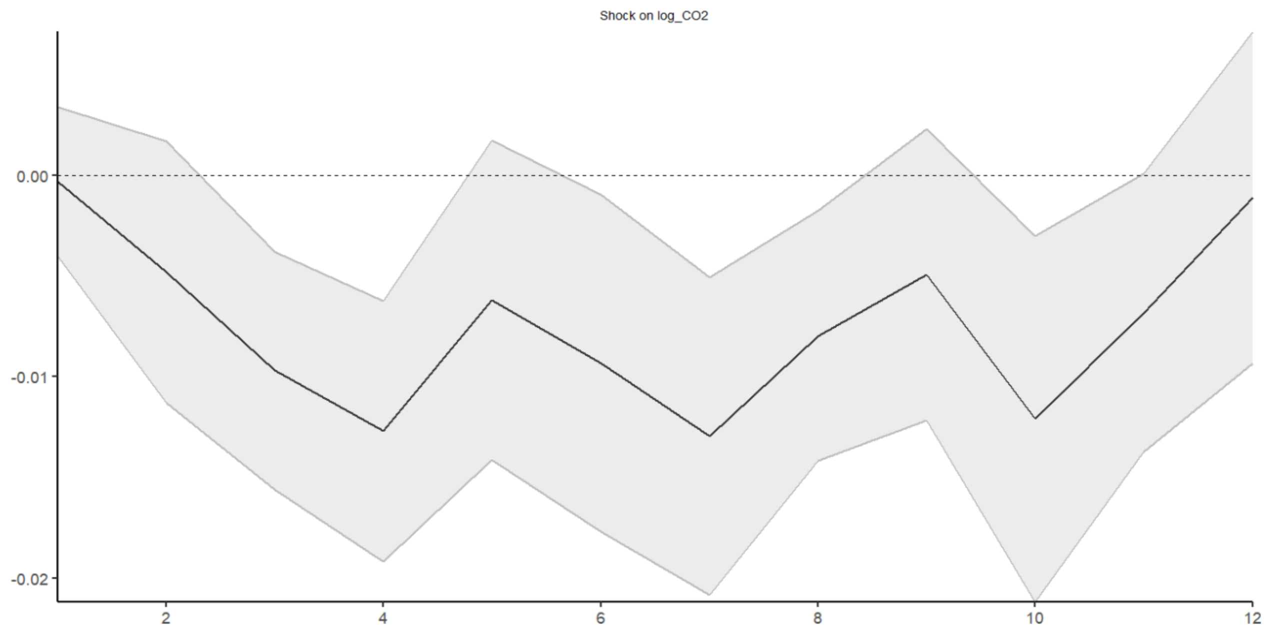


Note: Figure 19 illustrates an upward and exogenous one percentage point shock to the effective environmental tax rate on CO_2e per capita while controlling for two lags of CO_2e per capita, GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents metric tons of CO_2 equivalents. Source: Own production.

A.4 Transformation of variables in the baseline model

This section shows the results of transforming variables by taking the logarithm or difference. To further standardize variables, taking the natural logarithm or differencing are common ways to do so.

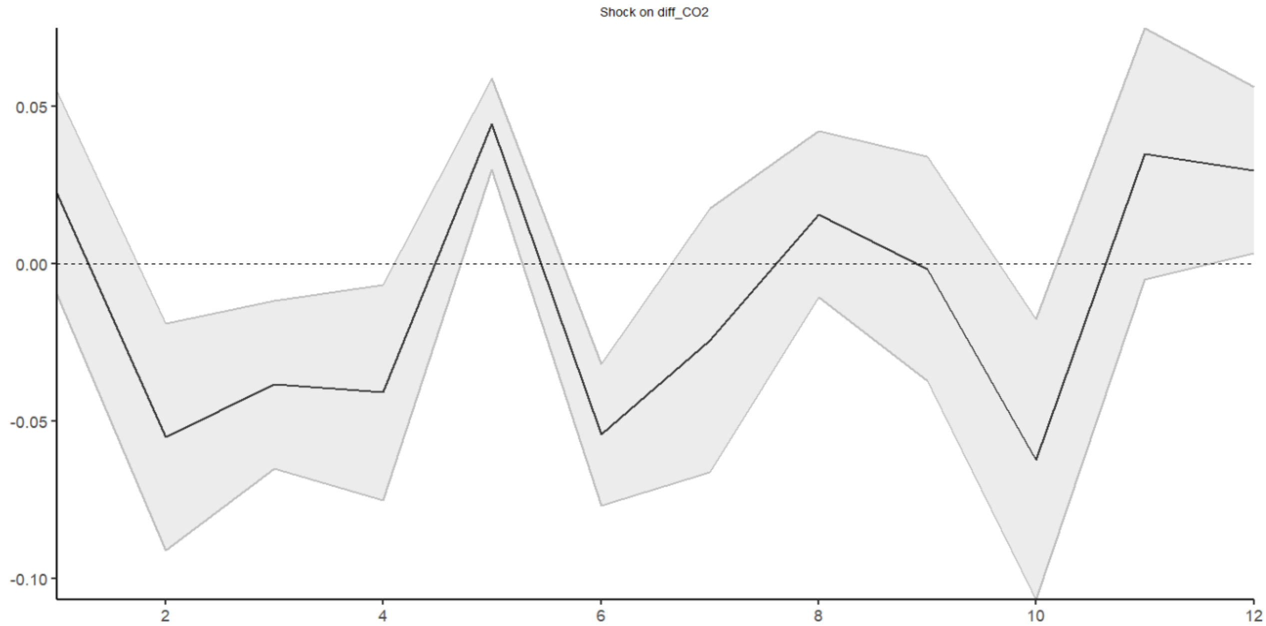
Figure 20 – A one percentage point shock to the effective environmental tax rate on CO_2e per capita with logged values



Note: Figure 20 illustrates an upward and exogenous one percentage point shock to the effective environmental tax rate on logged CO_2e per capita while controlling for three lags of logged CO_2e emissions per capita, logged GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents the percentage change in metric tons of CO_2 equivalents. Source: Own production.

Figure 20 shows the impact of a shock to the effective environmental tax rate on logged CO_2e per capita, where the control variable GDP per capita is logged as well. Logging variables can linearize relationships between variables, and results are interpreted in percentage terms. Figure 20 shows large confidence bands, when logging CO_2e per capita as well as GDP per capita. The results are associated with a lot of uncertainty as seen by the wide confidence bands. The impulse response function is only slightly significant at the third and fourth horizon. Therefore, figure 20 shows that logging CO_2 emissions per capita and GDP per capita distorts the underlying dynamics and results in insignificant results. Therefore, CO_2e per capita and GDP per capita are used in levels.

Figure 21 - A one percentage point shock to the effective environmental tax rate on CO_2e per capita differenced



Note: Figure 21 illustrates an upward and exogenous one percentage point shock to the effective environmental tax rate on differenced CO_2e per capita while controlling for three lags of CO_2e emissions per capita, GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents the change in metric tons of CO_2 equivalents. Source: Own production.

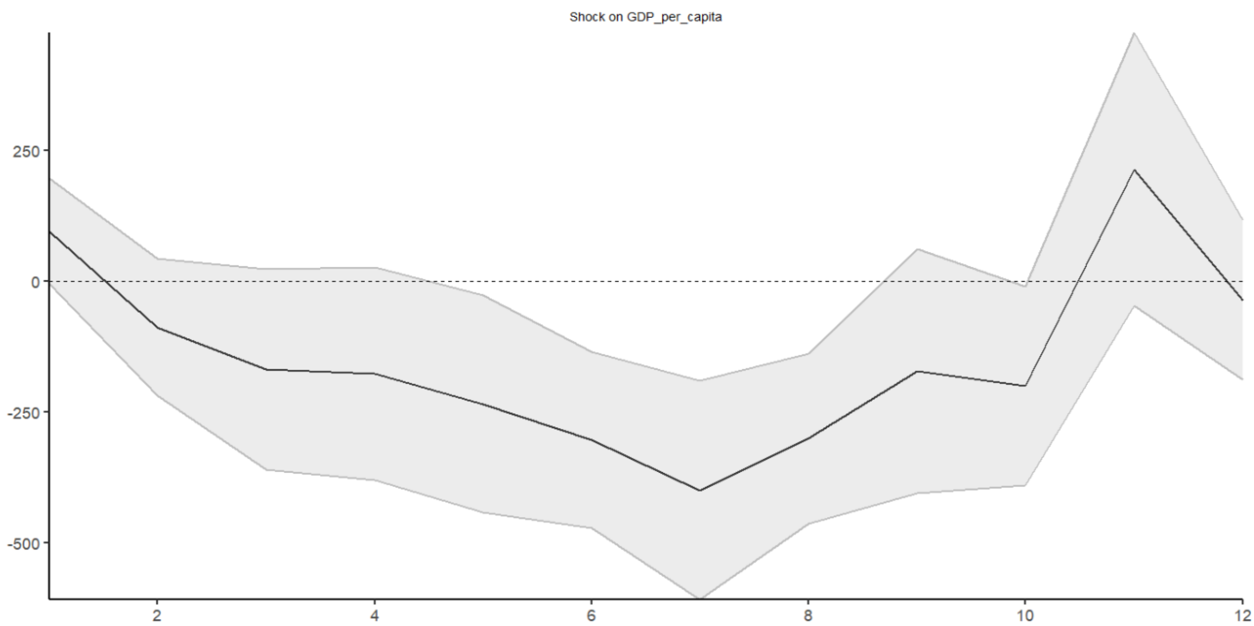
Figure 21 shows a one percentage point shock to the effective environmental tax rate on differenced CO_2e emissions per capita. Consequently, the figure shows the change in CO_2e metric tons per capita between horizons. The figure depicts an impulse response function that fluctuates above and below zero showing a volatile development of the impulse response function, which is also insignificant at some points.

This thesis does not take the logarithm or difference the data and aligns with existing literature, which provides reasons not to transform the data. Sims (1980) argues against putting too many restrictions on data in empirical research as this may distort the underlying data structure and dynamic relationships, which results in the loss of meaningful information. Restrictions may also be false or result in an empirical framework that is too simplistic (Sims, 1980, p. 14). Consequently, this thesis does not take the logarithm or difference variables in order to avoid erasing important dynamics in the data. As seen in figure 20 and 21, the results are associated with more uncertainty, which, as well as existing literature on restrictions to the data, motivates the choice of not taking the logarithm or differencing the data.

A.5 Independent variables and their impact on CO_2e per capita

This section shows the relationship between CO_2e per capita, the effective environmental tax rate, GDP per capita and renewable energy consumption as a percentage of total final energy consumption to further clarify the impact of the control variables in figure 8 by assessing the indirect channels through which environmental taxes reduce CO_2e per capita. Additionally, this section aims to contribute to a deeper general understanding of the research question.

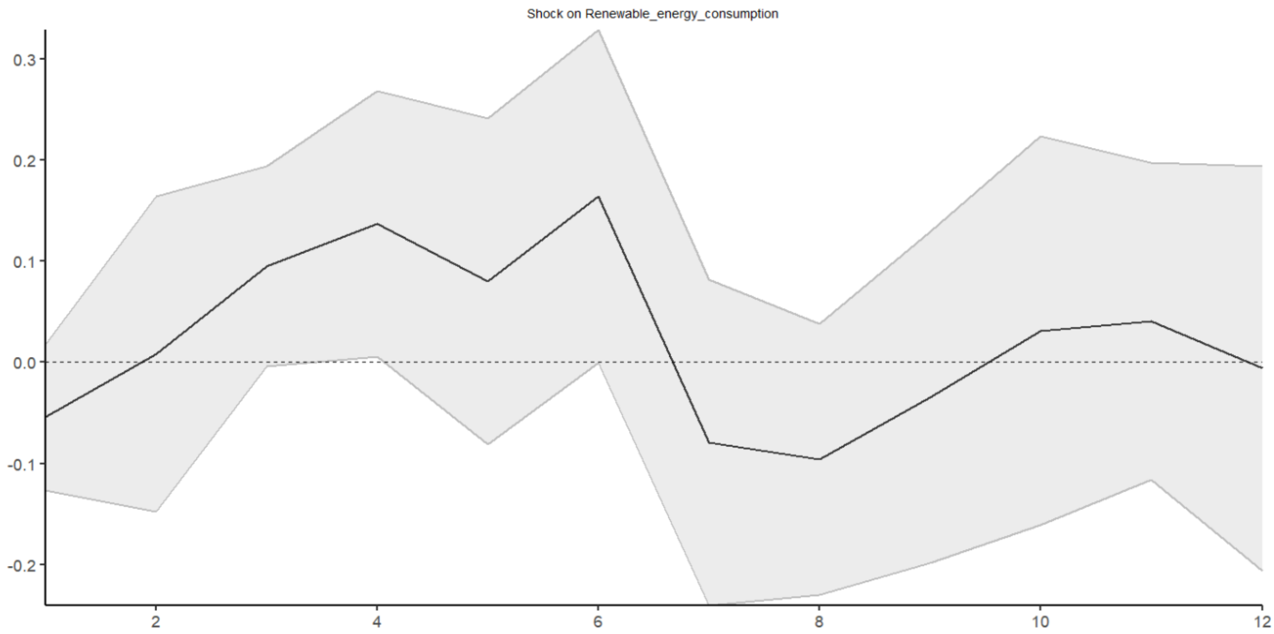
Figure 22 - A one percentage point shock to the effective environmental tax rate on GDP per capita



Note: Figure 22 illustrates an upward and exogenous one percentage point shock to the effective environmental tax rate on GDP per capita while controlling for three lags of CO_2 emissions per capita, GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents GDP per capita in constant 2021 international dollars. Source: Own production.

Figure 22 shows the impact of a one percentage point shock to the effective environmental tax rate on GDP per capita. Notably, figure 8 controls for GDP per capita to isolate the direct impact of environmental taxes on CO_2e per capita, so that the scale effect on income does not distort results. The outline of the impulse response function of GDP per capita shows the indirect income channel on emissions, which has a negative impact. This indicates that the shock affects production and consumption, which can have feedback effects on CO_2 emissions. Figure 22 also shows no clear signs of a path significantly above zero.

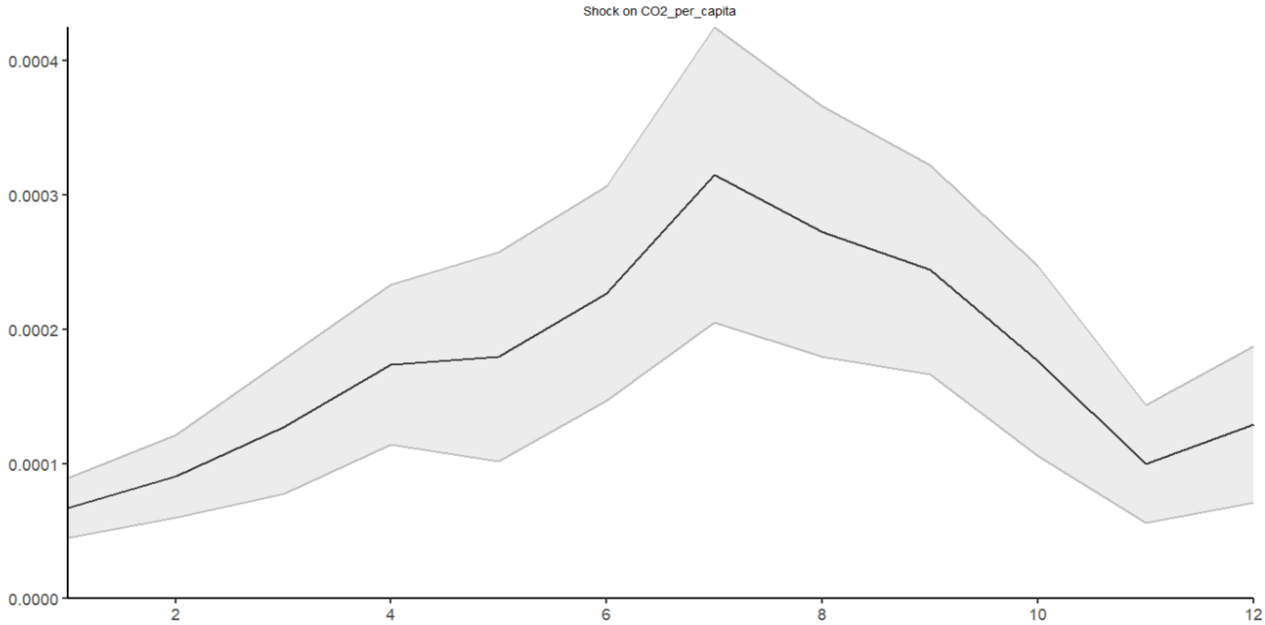
Figure 23- A one percentage point shock to the effective environmental tax rate on renewable energy consumption



Note: Figure 23 illustrates an upward and exogenous one percentage point shock to the effective environmental tax rate on renewable energy as a percentage of total energy consumption while controlling for three lags of CO_2e emissions per capita, GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents the percentage points. Source: Own production.

Figure 23 shows a shock to the effective environmental tax rate on renewable energy consumption. The shock is insignificant, which implies that the impact of environmental taxes on renewable energy consumption is vitiated by much uncertainty. Looking into the path of the impulse response function shows an initial increase in renewable energy consumption after which the impulse response function fluctuates above and below zero. Therefore, environmental taxes are assumed to encourage the use of renewable energy through the substitution channel.

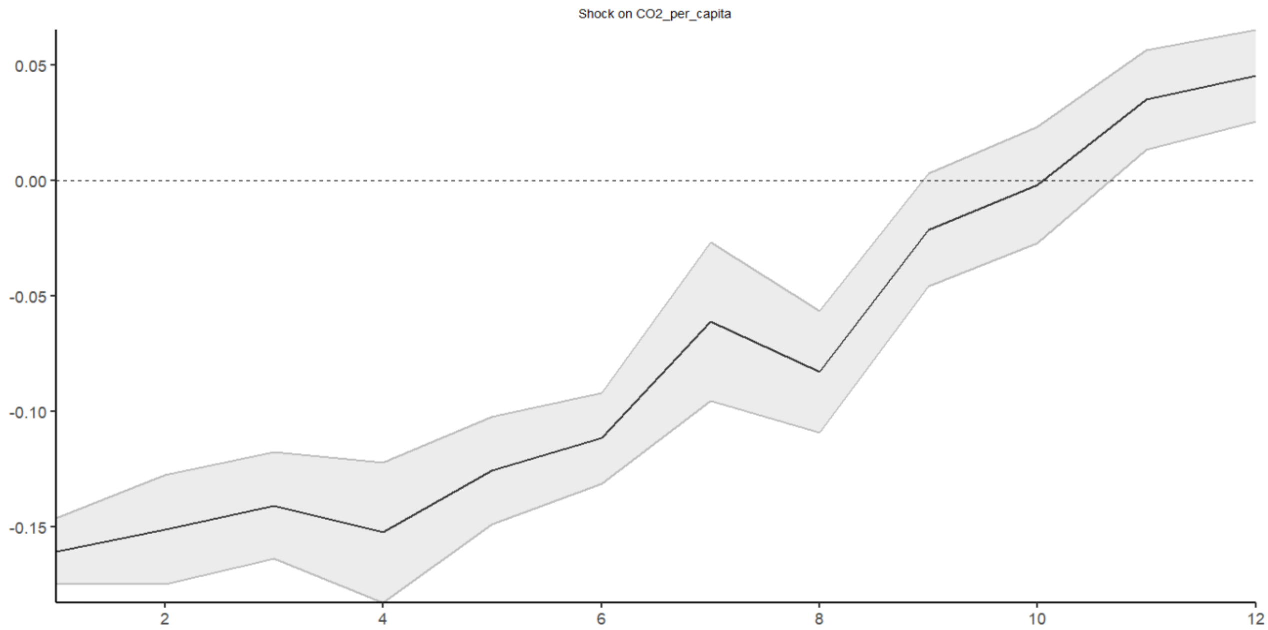
Figure 24 – A one percentage point shock to GDP per capita on CO_2e per capita



Note: Figure 24 illustrates an upward and exogenous one percentage point shock to GDP per capita on CO_2e per capita while controlling for three lags of CO_2e per capita, GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents metric tons of CO_2e emissions per capita. Source: Own production.

Figure 24 shows the impact of a shock to GDP per capita on CO_2e per capita. GDP per capita has a minimal impact on CO_2e per capita, although positive. Figure 24 validates GDP per capita as a control variable and depicts the dynamics of the income channel. It seems that CO_2e emissions per capita peak at the sixth horizon, indicating that the income channel has a gradual impact.

Figure 25 - A one percentage point shock to renewable energy consumption on CO_2e per capita



Note: Figure 25 illustrates an upward and exogenous one percentage point shock to renewable energy as a percentage of total energy consumption on CO_2e per capita while controlling for three lags of CO_2e emissions per capita, GDP per capita, trade openness, environmental innovations, renewable energy of total final energy demand, petrol tax rate and OECD Environmental Policy Stringency Index. The x-axis illustrates the horizons, while the y-axis represents the percentage points. Source: Own production.

Figure 25 illustrates a shock to renewable energy as a percentage of total energy consumption on CO_2e per capita. The development of the impulse response function indicates that renewable energy has a critical and significant impact on the reduction of CO_2 per capita. The trajectory of the impulse response function shows the substitution effect on emissions, indicating that the shift to renewable energy is vital in reducing CO_2 emissions. Emissions seem to increase in the later horizons, which could be due to firms increasing their competitiveness after having switched to cleaner production techniques.

A.6 Use of tools for grammar checking

During the editing of this thesis, OpenAI's ChatGPT (version May 2025) was used to perform grammar checks and suggest minor rephrasings if needed.