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THE IMPACTS OF ENERGY SUPPLY AND ENVIRONMENTAL TAXATION ON CARBON INTENSITY

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Abstract. Carbon dioxide (CO_2) is a significant source of Greenhouse Gas (GHG) emissions and plays a crucial role in climate change and global warming. This study aims to explain the effects of primary and renewable energy supplies and environmental taxation and to analyse how taxation can alter their direct effects on carbon intensity. The research was conducted using a generalized method of moments model that uses instrumental variables with two-stage (2SGMM) estimators to calculate the direct and moderating effects of environmental taxes on carbon intensity. This study confirms the EKC theorem, and results have shown that primary energy supply and environmental-related taxation positively contribute to carbon intensity. The second finding indicates that a major increase in the proportion of renewable energy will greatly slow the rate of carbon dioxide emissions. The study provides additional evidence concerning the moderating role of taxation in amplifying the impacts of primary and renewable energy supply. The empirical findings suggest that the taxation impact is more fiscal than an incentive. In addition to the current energy and economic crisis, considerable funding and fiscal policies are needed to achieve more sustainable development paths towards carbon neutrality and energy security.

Keywords: carbon intensity, energy supply, environmental taxation, Environmental Kuznets Curve (EKC) theory, green growth, Green House Gases (GHGs), dynamic panel regression, Sustainable Development Goals (SDGs).

JEL Classification: C43, C61, E62.

Introduction

Carbon dioxide (CO_2) is a large contributor to GHGs emissions and plays an essential part in climate change.Throughout this paper, the term CO_2 intensity refers to carbon emissions per unit of GDP based on the OECD Green Growth Database (OECD, 2017). Promoting

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economic growth and sustainable development (SD) while assuring that natural resources continue to provide resources and environmental services built on prosperity is the way to achieve green growth (OECD, 2011).

In recent years there has been growing interest in developing a green growth strategy that reforms the structure of taxes and charges to price negative environmental externalities (Milios, 2021; Telatar & Birinci, 2022). At the United Nations Conference on Sustainable Development (Rio+20), governments agreed that a green economy is an essential tool for sustainable development. An inclusive economy promotes economic growth, employment and poverty eradication while maintaining the health of the Earth's ecosystems (Purvis et al., 2019). Investigating sustainable development (SD) is continuously concerned with effectively integrating green policies into national economic and social priorities and objectives to promote the 2030 Agenda and the Sustainable Development Goals (SDGs) (United Nations Development Group [UNDG], 2017).

Besides promoting inclusive and sustainable economic growth, full and productive employment, and decent work for all, the recent changes in global markets have increased the need for energy, water and food security in developed and developing countries across most regions (de Amorim et al., 2018; Taghizadeh-Hesary et al., 2019). Recent evidence implies that energy-related CO_2 emissions will increase by 6% in 2021, reaching their highest level ever, and global temperature will continue to rise, leading to more extreme weather conditions (International Energy Agency, 2021).

There is increasing concern that some SDGs have recently been challenged by the Covid-19 and Ukraine crisis, demonstrating their vulnerabilities (Bendell, 2022; Clemente-Suárez et al., 2022). Though SDG-7 ensures access to affordable, reliable, sustainable and modern energy, research consistently shows that progress on energy efficiency has slowed and needs to accelerate to meet global climate goals (Bhatt et al., 2022). Several attempts have been made to improve electrification and sustainable energy transition (Bogdanov et al., 2021; Kabeyi & Olanrewaju, 2022). Meanwhile, renewable resource expenditure has increased by a quarter in recent decades, but the share of renewables in total final energy consumption in 2019 was only 17.7%, and cc. 2.4 billion people still use polluting cooking systems (Piłatowska & Geise, 2021; Shen et al., 2020).

This study covers the gap in reducing carbon intensity and provides ways towards achieving carbon neutrality. Most studies in the field have focused on the SD and Green growth concepts to reduce carbon emissions (Hao, 2022; Jardón et al., 2017; Leitao, 2014). Much uncertainty still exists about the relationship between carbon intensity and energy supplies. For example, it is inappropriate to make firm statements on the issue because the evidence on the climate change mitigation effects of environmental taxes that support the sustainability transition has only been researched regionally, e.g., in Latin America and the Caribbean (Dogan et al., 2022).

The objectives of this research are to determine whether energy supply impacts and environmental taxation can directly and indirectly affect carbon intensity. The purpose of the study is to better understand the sources of the country-group differences in carbon intensity growth by focusing on examined United Nations (UN) and OECD countries. The Environmental Kuznets Curve (EKC) theory of environmental deterioration and economic growth is presupposed in the study.

This paper follows a study design to evaluate UN and OECD countries in-depth. The methodological approach taken in this study is based on a two-stage generalized method of moments (2SGMM) regression model to analyse the interactions between the selected carbon and energy intensity and fiscal indicators. The study seeks to make a contribution to the examination of the direct and moderating effects of environmental taxation on the growth of carbon emissions from an SDG viewpoint.

This paper begins with a literature review and hypotheses statement. It will then go on to design data and materials. The fourth section of this paper will examine the impacts of primary, renewable energy supplies, trade openness and environmental taxes on CO_2 intensity by dynamic panel regression estimations. The residual part of the paper discusses the implications for future research. The conclusion provides a summary and evaluation of the findings.

1. Literature review and hypotheses statement

In recent years, there has been a growing literature on sustainable energy and related environmental taxation. Since it would be unrealistic to give a comprehensive review of this enormous body of literature, in the following section we will only discuss the publications that have made the most impact.

1.1. Environmental Kuznets Curve (EKC)

The EKC is a proposed correlation between various environmental degradation indices and per capita income (Kuznets, 1955). In societies in the early stages of economic growth, increases in wealth and production have been accompanied by increases in pollution (Yasin et al., 2021). Later, as a certain income level was reached and further growth increased, pollution began to decrease. This level occurs with higher economic growth rates in developed countries and much lower GDP and CO_2 emissions in developing countries (Stern, 2018).

A considerable body of literature has been published on the EKC hypothesis. However, social-economic scientists have reached no consensus on evaluating the Kuznets curve theory, and the research results vary. In 1985, Grossman and Krueger claimed (1995) the importance of initial income levels in environmental pollution. Their data analysis from 42 countries showed that GDP growth increases GHGs and smoke in low-income countries, while in higher-income countries, it reduces them. This phenomenon can be explained by the different pollution intensities of post-industrial economies.

In contrast, Munasinghe (1995) criticizes the lack of empirical evidence for the Kuznets theorem and considers the link between economic growth and the existence of the EKC irrelevant. Such a curve characterizes past growth, and there is no reason to assume that it determines future growth trajectories. In the same vein, Magnani (2000) stated that the link between declining income inequality and the growing role of ecological protection could not be generalized to low-income countries. The research highlights the role of institutions in the relationship between income and pollution. For example, protecting property rights, democracy and respect for fundamental human rights can facilitate the implementation of environmentally protective legislation. Other scholars have shown that corruption probably cannot be excluded from the EKC theory. Countries perceived to be corrupt have higher pollution levels, which are not affected by income status (López & Mitra, 2000). Poumanyvong and Kaneko (2010) have adopted a broader perspective and argued that urbanization impacts energy use and emissions. A sample of 99 countries confirmed the positive impact of urbanization on energy consumption in low-income countries. However, urbanization raises energy consumption and has a detrimental effect on the environment in middle- and high-income countries. Collectively, these studies provide a critical outline of the EKC hypothesis. One of these studies suggests that the EKC is not empirically proven for the EU (Mazur et al., 2015). However, researchers have identified an inverted U-shaped curve and inferred the reaching of tipping points.

1.2. Sustainable energy goals and climate change

Climate change is the greatest threat to sustainable development everywhere today, with widespread and unprecedented negative impacts disproportionately affecting the poorest and most vulnerable. The Paris Agreement and the 2030 Agenda for SD (United Nations, 2015) address the fact that economic and social issues are becoming more global by considering the concerns of industrialized and developing countries, and by placing greater emphasis on ecological challenges (Meinshausen, 2019).

Renewable energy supply and security have recently come under the spotlight. The UN underlined the increased role of renewable energy sources in the Sustainable Energy Goal (SDG-7). Particular attention should be paid to renewable energy projects such as solar, hydro and wind power, among the most promising energy sources for developing countries (Villavicencio Calzadilla & Mauger, 2018). This study focuses on sub-objectives and the renewable energy impacts on carbon emissions. For instance, 7.2 refers to the substantial increase in the share of the global energy mix by 2030. As a result, the 7.3 objective aims for double the rate of world improvement in energy efficiency.

Some researchers argue that adequate, reliable, clean energy services are essential to achieving the SDGs. In essence, access to energy has become one of the insurmountable challenges of development and, therefore, a symbol of the call for poverty eradication and economic and social transformation (Mulugetta et al., 2019). Khan et al. (2022) suggest that there is an improvement in ecological sustainability when there is a positive correlation between energy intensity and environmental footprint. Hence, we assume that the energy supply will also positively affect CO_2 emissions:

Hypothesis 1. The primary energy supply has a positive impact on CO_2 intensity growth.

Numerous studies describe the social and economic importance of renewable energy sources. Gielen et al. (2019) show that energy efficiency and renewable technologies play a vital role in the energy transition. Scalable technologies, ubiquitous resources, and extensive socio-economic benefits underpin this transition (Chen et al., 2022a). Renewables can meet 2/3 of total global energy demand and contribute to reducing GHG to keep the global surface temperature rise below 2 °C (Masson-Delmotte et al., 2019). According to another study, supporting public policies along with the proper legislation and incentives can speed up the development of renewable energy sources (Włodarczyk et al., 2021). We assume that:

Hypothesis 2. The renewable energy supply significantly impacts CO_2 intensity growth.

1.3. The environmental Pigouvian taxation

A considerable amount of literature has been published on environmental taxation. This sub-section deals with Pigou's theory of taxation. Pigou implements the environmental tax as a way of making, for example, the polluter pays for the negative social impacts of any activity (Pigou, 1920). Pollution and increased public healthcare costs are typical examples of negative externalities and market failure. The original argument of Pigou's idea is, therefore, to eliminate inefficient usage of resources and improve the Pareto efficiency of the economy (Delgado et al., 2022).

The generalisability of many studies on the subject is problematic, as researchers have widely divergent views. For instance, Carlton and Loury (1980) criticized the effects of Pigouvian taxes, which are ineffective in the long run, as they regulate the size of firms, not the number in each industry. Even if each firm produced only a fraction of what it polluted, the number of firms increased exponentially. The ecological degradation would worsen (Filipović & Golušin, 2015), and the consequences of externalities are not incorporated in the price of polluting products (Candogan et al., 2012). If pollution can be passed on to the environment without consequences, then polluters and producers will adopt lower prices, leading to excessive demand and more GHG emissions (Kudełko & Wejer, 2014).

Hypothesis 3. Environmental-related tax has a positive impact on CO_2 intensity growth.

The effects of the imposition of ecological taxes are uncertain when estimating the expected results in advance. A study has examined the impact of environmental uncertainty on the Pigouvian tax and on tax reduction policies applied separately or simultaneously to offset pollution (Baiardi & Menegatti, 2011). For example, an increase in tax distortions due to the necessary taxation revenues reduces the optimal tax rate, even if the ecological quality improves (Metcalf, 2003). Theoretically, it would be enough to tax production. However, the reality is that the amount of pollution emitted in the production of a product depends on the technology and raw materials used, and many other factors. It would therefore be more appropriate to tax directly the amount of pollution rather than the amount of production. However, this requires accurate measurement of pollution, which is also a very complex and costly procedure (Muller & Mendelsohn, 2007).

Some argue that environmental regulations and taxes can address environmental externalities. For example, environmental taxes and green financial development optimise ecological quality by reducing CO_2 emissions (Ionescu, 2021) and are appropriate for promoting sustainable economic growth, low-carbon energy, and avoiding climate change (Ionescu, 2022). Others, however, are sceptical about the effectiveness of these policy instruments in mitigating environmental damage (Wolde-Rufael & Mulat-Weldemeskel, 2022). Others point out the existence of a "green paradox", fearing that such policies may lead to unintended and undesirable consequences that exacerbate environmental damage (Sinn, 2015). Those who note this contradiction consider that these inadequate ecological laws solely handle the supply side of externalities, i.e., primary energy consumption, without taking the supply side of energy production into account (Jensen et al., 2015). Therefore, we assume that eco-taxes moderate the effects of energy supplies on carbon intensity:

Hypothesis 4. Environmental-related taxation alters the impacts of energy supply on CO_2 intensity growth.

2. Materials and methods

We build our analysis on the EKC theorem to better understand the interaction between energy supply, environmental degradation and taxation. We will model how primary and renewable energy supplies can significantly affect carbon intensity growth in different countries and how environmental taxes can moderate their impacts.

The dependent variable, CO_2 intensity growth, is calculated by the logarithms of CO_2 emissions per Gross Domestic Product (GDP) unit. Regressor variables were gathered from the OECD Green Growth Database (OECD, 2022). The indicators have been carefully selected according to environmental and resource productivity, socio-economic context and environmental taxation. The energy intensity is measured by Total Primary Energy Supply (TPES) per GDP at tons of oil equivalent (toe). The renewable energy supply gives the renewable energy supply variable as a % of TPES.

In the social-economic context, the real GDP per capita (productivity) is considered at constant US dollar (2015) prices. TPES includes production plus imports minus exports and international marine and aviation bunkers adjusted by stock changes. Renewable energy sources include hydro, geothermal, solar, wind, water, combustible renewables (solid and liquid biomass, biogas) and waste (renewable municipal waste). Environment-related tax revenues (% of GDP) as a proportion of total tax revenues include taxes on energy products for transport, fossil fuels and electricity; motor vehicles and transport; waste management (final disposal, packaging); ozone-depleting substances and other environment-related taxes. The regression models also include trade openness (% of GDP) from the World Bank Database (World Bank, 2022) as a control variable to lessen concerns with model specification and data uncertainty (Meyer & Hassan, 2020). The description and sources of the variables under investigation are shown in Table 1.

Results of the pre-estimation test indicated the existence of a unit root in CO_2 intensity and GDP per capita. Therefore, the logs of these variables need to be differenced (Δ) multiple times to become stationary. First differences of CO_2 intensity I(1) are tested using Fisher-type (Choi, 2001) and Im-Pesaran-Shin (2003) panel unit-root tests and employing 0–2 time lags, as independent variables are unbalanced. Tests (Table 2) allow us to reject the hypothesis of nonstationary CO_2 intensity growth variables, and all panels do not contain unit roots and a stochastic trend in a time series.

An unbalanced panel dataset of 139 UN (and 38 OECD) countries for 2010–2019 was used (see Appendix). The year before the COVID-19 epidemic marks the end of the time frame, which unduly distorts data. The available countries cover 72.0 percent of UN member states, making the study globally representative.

The dynamic panel application framework is suggested to solve serial correlation, heteroscedasticity and endogeneity issues of explanatory variables (Leitao, 2014). In this case, instrumental variables are suggested in a generalized method of moments (GMM) model (Arellano & Bond, 1991), and Stata's "xtabond" command implemented the estimator. Two-stage (2SGMM) estimators are chosen as they do not impose misspecification and restrictions on the data distribution (Chaussé, 2010).

Table 1. Name, abbreviation, description and source of variables (source: OECD, 2022; World Bank, 2022)

Variable	Abbreviation	Description	Source
CO_2 intensity	CO_2INT	CO_2 intensity of Gross Domestic Product (GDP), CO_2 emissions per unit of GDP	OECD Green Growth Indicators
GDP per capita	GDPCAP	Real GDP per capita, US Dollar, 2015	OECD Green Growth Indicators
Energy intensity	ENGINT	Energy intensity, Total Primary Energy Supply (TPES) per unit of GDP Tonnes of oil equivalent (toe)	OECD Green Growth Indicators
Renewable energy supply	RNWSUP	Renewable energy supply, percentage of TPES, (%)	OECD Green Growth Indicators
Trade openness	TRADE	Trade (% of GDP). Trade is the total of goods and service exports and imports expressed as a percentage of GDP	World Bank National Accounts Indicators
Environmental related taxes	ENVTAXGDP	Environmental-related tax revenue. Tax is based on a physical unit of the specific impact on the environment (% of GDP)	OECD Green Growth Indicators

Table 2. Panel unit root tests of carbon intensity growth (ΔlnCO_2INT)

Fisher-type unit-root tests (Augmented Dickey-Fuller)				
Specification	With trend		Without trend	
Variable	χ^2	p-value	$\chi2$	p-value
$\Delta\ln(CO_2INT)_{i,t}$	1182.54^{***}	0.00	862.18^{***}	0.00
$\Delta\ln(CO_2INT)_{i,t-1}$	920.49^{***}	0.00	896.32^{***}	0.00
$\Delta\ln(CO_2INT)_{i,t-2}$	559.85^{***}	0.00	885.44^{***}	0.00
Im-Pesaran-Shin unit-root test				
Specification	W-t-bar	p-value	W-t-bar	p-value
$\Delta\ln(CO_2INT)_{i,t}$	-17.86^{***}	0.00	$-10.4^{***}4$	0.00
$\Delta\ln(CO_2INT)_{i,t-1}$	-11.84^{***}	0.00	-7.78^{***}	0.00
$\Delta\ln(CO_2INT)_{i,t-2}$	-11.72^{***}	0.00	-11.81^{***}	0.00

Note: at period [t] and in country [i]; $\chi2$ – Chi-squared and *W-t-bar* statistics; *** $p < 0.01$.

The following dynamic model is used to consider the EKC theorem and impacts of energy intensity and environmental taxation on carbon emissions employing two lags of the dependent variables (DVs). The following (Eq. (1)) was transformed after taking the first differences of the DVs:

$$\begin{aligned}
&\Delta \ln CO_2INTy_{i,t} = \beta_o + \beta_1 \Delta \ln CO_2INTy_{i,t-1} + \beta_2 \Delta \ln CO_2INTy_{i,t-2} + \\
&\beta_3 \Delta \ln GDPCAP_{i,t} - \beta_4 \Delta \ln GDPCAPsq_{i,t} + \beta_5 \ln ENGINT_{i,t} + \beta_6 RNWSUP_{i,t} + \\
&\beta_7 TRADE_{i,t} + \beta_8 ENVTAXGDP_{i,t} + \varepsilon_{i,t}, \qquad (1)
\end{aligned}$$

where the dependent variable (DV) is the growth of CO_2 emissions intensity [CO_2INT] over time [*t*] and country [*i*]. The first two independent variables correspond to the lagged [*t*–1 and *t*–2] dependent variables. The real GDP per capita growth is the second component. The potential quadratic relationship between emissions and income per capita is examined via [GDPCAPsq]. [ENGINT] denotes the primary energy intensity of the population, and [RNWSUP] refers to renewable energy supply. [TRADE] is the total of exports and imports expressed as a ratio of GDP, and [ENVTAXGDP] is environmental-related taxes per GDP.

3. Results

Results of the dynamic regression estimations based on Eq. (1) are presented in Table 3. The precise selection of the dynamic panel technique is validated by the significant Wald-tests (F-statistics). Wald-tests imply that 2GMM estimators are appropriate in all models and country groups. AR(2) z-tests (p-values) for zero autocorrelation are completed in second-order differences. All estimators are released from serial correlations of the residuals in each model (1–8) (Roodman, 2009). The Sargan-tests ($\chi 2$) of overidentifying restrictions demonstrate the validity of time lags, and the number of instruments is lower than in the observed countries. Therefore, such deviations from the average stationarity cannot be detected (Bun & Sarafidis, 2015).

The first dynamic specification confirmed the EKC hypothesis, with an increase in per capita GDP growth and per capita squared GDP negatively affecting CO_2 intensity growth. A curvilinear inverted U-shaped association is also supported by the results of the overall t-test (value = 1.19*) (Andersson & Karpestam, 2013; Balogh & Jambor, 2017). Models (2–8) indicate that the energy intensity variable [ENGINT] is significant. H1 can be accepted, and all regression models show that it has a positive sign. If primary energy supply per capita increases by one unit, CO_2 intensity increases by 0.455–0.642, if all other variables are unchanged.

Models (3–8) show that the higher share of renewable energy [RNWSUP] negatively contributes to carbon emission growth. H2 can be accepted. The average proportion of the total renewable energy supply is 27.03 percent (see Appendix, Table A1). The marginal (or partial) effects of covariates included in model objects were estimated by Stata's "margins" command. Based on the results, it can be stated that if the share of renewables in global energy increases substantially (see SDG Target 7.2) and doubles compared to the mean, the carbon intensity decreases by 0.203 units (from –0.038 to –0.241) at $p < 0.01$ level. Therefore, if all other variables are held constant, it implies a lower global carbon reduction of about 5.3 times (–0.203)/(–0.038). Trade openness is not significant in these models.

Model 5 shows that environmental taxes [ENVTAXGDP] positively affect emissions growth (H3 can be accepted). In contrast, a significant two-way interaction between taxes, energy intensity and renewable energy supply is found (see Models 6 and 7). However, in model 8, we do not find a significant moderator effect between GDP per capita and taxation.

These two-way interactions are depicted in Figures 1 and 2; the highlighted and dashed lines indicate significant variations in slopes based on Dawson (2014). The impact of energy intensity on CO_2 growth is larger (steeper) in countries with higher taxes. The increasing taxation positively moderates (increases) the impact of energy intensity on carbon emission growth (H4 can be accepted).

Table 3. Dynamic panel regression results of Eq. (1) in the case of total UN countries (source: OECD, 2022; World Bank, 2022)

Dependent variable: CO_2 intensity growth $\Delta\ln(CO_2INT)_{i,t}$								
Independents	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
constant	−0.008 (−2.78)**	−0.254 (−4.70)***	−0.020 (−0.22)	0.038 (0.32)	−0.240 (−2.22)**	−0.239 (−2.17)**	−0.254 (−2.40)**	−0.228 (−2.11)**
$\Delta\ln(CO_2INT)_{i,t-1}$	0.094 (−2.65)**	0.003 (0.05)	0.045 (0.81)	−0.556 (−6.40)***	−0.069 (−3.28)**	−0.062 (−2.87)**	−0.070 (−3.46)***	−0.082 (−3.07)**
$\Delta\ln(CO_2INT)_{i,t-2}$	−0.047 (−1.73)*	−0.015 (−0.35)	−0.013 (−0.29)	−0.638 (−6.20)***	−0.131 (−5.32)***	−0.094 (−3.72)***	−0.118 (−4.64)***	−0.107 (−4.50)***
$\Delta\ln(GDPCAP)_{i,t}$	4.544 (4.26)***	2.421 (2.91)**	2.427 (2.67)**	2.821 (1.85)*	5.836 (5.81)***	6.153 (6.29)***	5.959 (6.36)***	7.368 (5.18)***
$\Delta\ln(GDPCAPsq)_{i,t}$	−0.255 (−4.63)***	−0.147 (−3.38)***	−0.146 (−3.15)**	−0.161 (−2.07)*	−0.305 (−6.27)***	−0.321 (−6.91)***	−0.311 (−6.85)***	−0.386 (−5.70)***
$\ln(ENGINT)_{i,t}$		0.549 (7.24)***	0.455 (5.66)***	0.485 (5.18)***	0.642 (9.02)***	0.600 (7.60)***	0.572 (7.07)***	0.580 (7.66)***
$RNWSUP_{i,t}$			−0.008 (−3.57)***	−0.010 (−3.51)***	−0.006 (−2.31)**	−0.006 (−2.27)**	−0.005 (−1.80)*	−0.006 (−2.02)**
$TRADE_{i,t}$				0.000 (−0.41)	0.000 (−0.33)	0.000 (−0.05)	0.000 (0.21)	0.000 (−0.10)
$ENVTAXGDP_{i,t}$					0.015 (1.80)*	0.012 (1.75)*	0.029 (2.94)**	0.011 (1.42)
$ENVTAXGDP_{i,t}$ x $\ln(ENGINT)_{i,t}$						0.019 (2.51)**		
$ENVTAXGDP_{i,t}$ x $RNWSUP_{i,t}$							−0.001 (−2.52)**	
$ENVTAXGDP_{i,t}$ x $\Delta\ln(GDPCAP)_{i,t}$								−2.275 (−2.00)**
$ENVTAXGDP_{i,t}$ x $\Delta\ln(GDPCAPsq)_{i,t}$								0.122 (2.17)*
Observations	831	830	830	701	438	438	438	432
Countries	139	139	139	133	83	83	83	82
Instruments	30	16	17	12	31	29	29	30
Wald-tests	55.96***	121.08***	156.64***	143.57***	440.39***	402.06***	368.61***	457.31***
AR(2) p-values	0.765	0.314	0.451	0.093	0.738	0.639	0.612	0.673
Sargan-tests	32.183	13.845	15.656	6.041	29.741	24.392	25.530	23.856

Note: z statistics are in parenthesis, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Similarly, we found a significant interaction between renewable energy subsidies and environmentally-related taxes (Figure 2). More interestingly, higher taxation seems to amplify the negative impact of renewable energy supply on CO_2 intensity, as indicated by the disparity in slopes. The increased penetration of renewables has a more substantial (negative) effect on emission intensity growth when taxation increases.

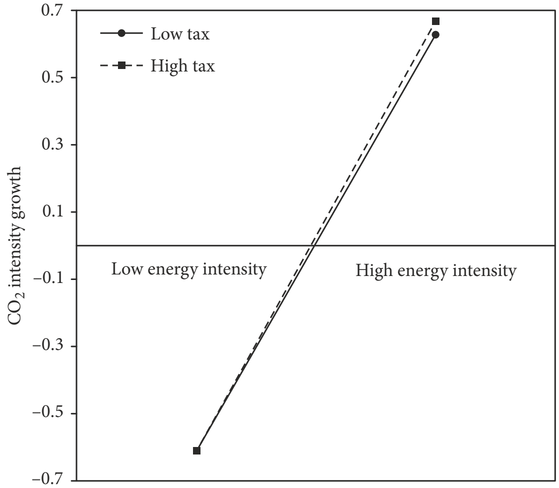

Figure 1. The two-way interaction affects CO_2 intensity growth, energy intensity and the environmental-related tax (moderator), N = 83

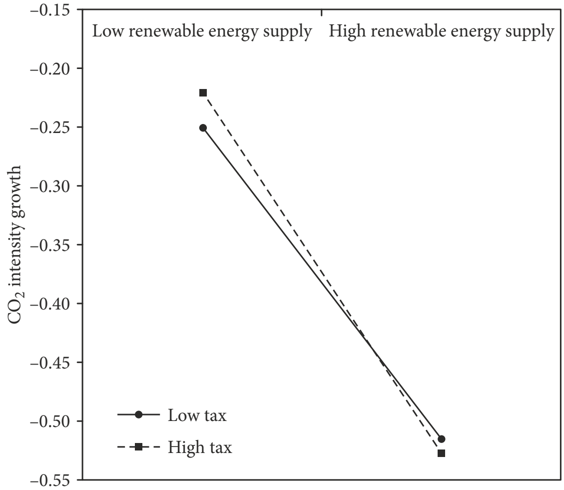

Figure 2. The two-way interaction affects CO_2 intensity growth, renewable energy supply and the environmental-related tax (moderator), N = 83

Table 4 confirms the robustness of the selected model specifications. We also con-firmed the EKC hypothesis for OECD countries. All regression models' energy intensity is significantly positive, ranging from 0.687–0.730. Compared to previous results, the effect of primary energy supply on carbon intensity growth appears to be more significant for OECD countries than for all examined UN countries.

Table 4. Dynamic panel regression results of Eq. (1) in the case of OECD countries (source: OECD, 2022; World Bank, 2022)

Dependent variable: CO_2 intensity growth $\Delta\ln(CO_2INT)_{i,t}$								
Independents	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
constant	−0.038 (−7.36)***	−0.903 (−7.12)***	−0.845 (−8.04)***	−0.929 (−12.06)***	−0.927 (−8.13)***	−0.894 (−8.38)***	−0.927 (−8.31)***	−0.938 (−8.68)***
$\Delta\ln(CO_2INT)_{i,t-1}$	−0.281 (−4.72)***	−0.293 (−4.73)***	−0.291 (−5.98)***	−0.323 (−9.01)***	−0.259 (−4.96)***	−0.246 (−4.26)***	−0.248 (−4.37)***	−0.252 (−4.58)***
$\Delta\ln(CO_2INT)_{i,t-2}$	−0.175 (−4.55)***	−0.133 (−3.34)***	−0.153 (−6.40)***	−0.165 (−8.15)***	−0.153 (−5.27)***	−0.153 (−5.47)***	−0.151 (−5.27)***	−0.164 (−5.76)***
$\Delta\ln(GDPCAP)_{i,t}$	7.185 (2.71)**	4.035 (1.67)*	6.115 (2.98)**	6.514 (4.02)***	4.656 (1.44)	5.164 (1.88)*	5.123 (1.52)	15.159 (2.14)*
$\Delta\ln(GDPCAPsq)_{i,t}$	−0.363 (−3.00)**	−0.218 (−2.00)**	−0.311 (−3.35)***	−0.327 (−4.47)***	−0.244 (−1.67)*	−0.268 (−2.16)**	−0.266 (−1.75)*	−0.761 (−2.32)**
$\ln(ENGINT)_{i,t}$		0.730 (8.25)***	0.699 (14.74)***	0.712 (19.08)***	0.705 (13.15)***	0.687 (13.15)***	0.703 (13.09)***	0.707 (13.65)***
$RNWSUP_{i,t}$			−0.003 (−1.95)*	−0.003 (−1.97)*	−0.003 (−1.90)*	−0.004 (−2.06)*	−0.004 (−1.92)*	−0.004 (−1.96)*
$TRADE_{i,t}$				0.001 (1.67)*	0.001 (2.02)**	0.000 (1.76)*	0.001 (2.11)**	0.001 (2.27)**
$ENVTAXGDP_{i,t}$					0.028 (4.41)***	0.015 (1.86)*	0.027 (3.22)***	0.031 (3.42)***
$ENVTAXGDP_{i,t}$ x $\ln(ENGINT)_{i,t}$						0.023 (1.79)*		
$ENVTAXGDP_{i,t}$ x $RNWSUP_{i,t}$							0.000 (0.26)	
$ENVTAXGDP_{i,t}$ x $\Delta\ln(GDPCAP)_{i,t}$								−18.194 (−2.15)**
$ENVTAXGDP_{i,t}$ x $\Delta\ln(GDPCAPsq)_{i,t}$								0.890 (2.23)**
Observations	228	228	228	228	209	209	209	209
Countries	38	38	38	38	38	38	38	38
Instruments	15	16	26	30	28	29	29	30
Wald-tests	643.8***	1068.8***	1449.2***	2208.5***	2463.6***	2817.1***	4077.3***	3124.5***
AR(2) p-values	0.955	0.681	0.542	0.585	0.568	0.555	0.557	0.461
Sargan-tests	22.994	16.685	28.410	30.319	26.146	25.989	25.858	27.973

Note: z statistics are in parenthesis, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

A higher share of renewables contributes less to carbon emission mitigation in OECD countries. The extended models (4–8) confirm the positive effects of international trade on the growth of carbon pollution. More specifically, increasing trade share in GDP leads to pollution expansion. Environmental taxes positively affect emissions growth and show a significant two-way interaction between taxes and primary energy intensity.

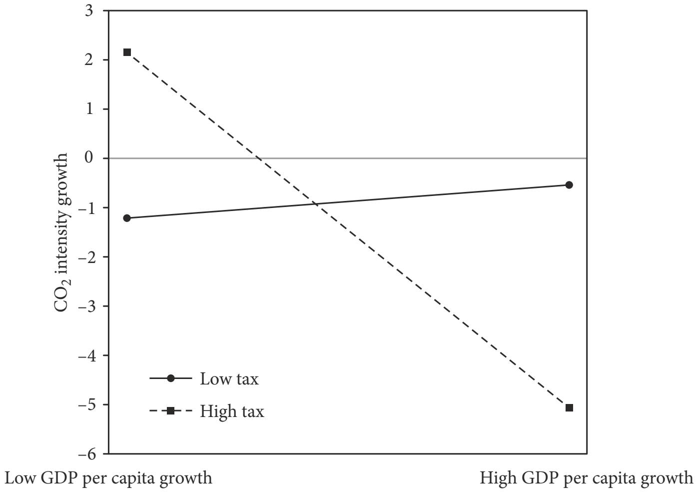

Figure 3. The two-way interaction effects between a curvilinear (quadratic) main effect (GDP capita growth on CO_2 intensity) and linear moderator (environmental-related tax), (N = 38)

In addition, we find a two-way interaction between the curvilinear effect of GDP per capita growth and the linear moderator of the environmental tax. The interactions in Figure 3 shows that the curvilinear relationship between CO_2 emission intensity and GDP per capita growth is positive for countries with low environmental taxes and negative for those with high environmental taxes.

4. Discussion

This study explores the relationships between primary and renewable energy supply, environmental-related taxes and CO_2 intensity growth in a sample of 139 UN and 38 OECD countries from 2010 to 2019. The study confirms the theory of the Environmental Kuznets Curve for CO_2 emissions and economic development for both UN and OECD countries. An increase in income per capita in lower-income countries increases CO_2 emissions in proportion to GDP, while it reduces them in countries with higher incomes. The results explored an inverted U-shaped curve between income per capita and CO2 intensity, consistent with several studies (Churchill et al., 2018; Dogan & Seker, 2016; Seri & de Juan Fernández, 2022). The turning point for model 1 is $7404 at constant US dollar (2015) prices for the UN and 19,865 for OECD countries. However, the points vary significantly from country to country and period (Shuai et al., 2017).

In the panel regression models using a generalized momentum method, the impact of energy intensity, renewable energy supply, trade openness and environmental taxes on carbon dioxide emissions growth as a share of output was also examined alongside GDP. The results of this study are now compared with those of previous work. The present findings seem to be consistent with other research, which shows that primary energy supply positively affects carbon intensity growth (Chen et al., 2022c; Iwata et al., 2012). However, unlike Dogan and Seker (2016), trade openness had no significant positive effect on the explained variable, only for OECD countries.

Increasing the share of renewables and replacing fossil fuels can reduce CO_2 emissions and improve the environment. Many researchers analysed the link between renewables and CO_2 emissions. In most investigations, a negative relationship was revealed between the variables (Mirziyoyeva & Salahodjaev, 2022; Szetela et al., 2022). However, we also found examples of a negative relationship depending on the level of renewable energy (Hao, 2022). The study confirmed the negative impact of renewable energy on CO_2 emissions.

The aim of the analysis also related to the environmental taxes was to investigate the direct effects on CO_2 emissions and explore whether ecological protection has a moderate impact on primary and renewable energy supply and GDP per capita on carbon intensity growth. While taxes can generate revenues for the state (fiscal effect), they can also influence the behaviour of economic agents towards more environmentally friendly product consumption and production solutions and emission reductions (incentive effect) (Carl & Fedor, 2016). In the same vein, there can be a redistributive effect, i.e., environmental taxes can be used to support environmental activities after the taxes have been collected (Rybak et al., 2022). However, companies can pass on a significant part of the increased income costs to consumers; as a result, environmental taxes can have the opposite effect on the environment (Garella, 2021). Environmental taxes have been shown to lower CO_2 and GHG emissions in the empirical research (Ghazouani et al., 2020; Hao et al., 2021). On the other hand, some studies have examined whether taxes do not affect emissions (Telatar & Birinci, 2022) or whether environmental taxes have a heterogeneous effect on CO_2 emissions (Wolde-Rufael & Mulat-Weldemeskel, 2021).

One possible theoretical explanation for these results may be that we could not show that the environmental tax reduces carbon emissions, suggesting that the impact is more fiscal than an incentive. These results have some policy implications. This study will assist policy-makers and managers in reducing carbon intensity through more efficient usage of environmental taxes and renewable energy (Smirnova et al., 2021). This study can serve as a reference to encourage manufacturers worldwide to provide a sustainable energy supply and move towards carbon neutrality. Governments can support green finance strategies to reduce global carbon emissions and energy exposure (Meo & Karim, 2022). Another crucial practical implication is that the impacts of GHGs emissions can be reduced globally through appropriate support for renewable energy resources. The government authorities can achieve this through environmental legislation (Hassan et al., 2019). Delays seriously jeopardize the efforts to achieve the Sustainable Development Goals, especially in developing countries. In addition to the current energy progress and crisis, considerable funding and fiscal policies are needed to achieve more sustainable development paths toward carbon neutrality and energy security (Chen et al., 2022b).

In accordance with the present results, previous studies have revealed a positive impact of environmental taxes on CO_2 intensity in both UN and OECD member countries. Ulucak et al. (2020) discovered that in the earlier stages of globalization, there was a positive link between environmental taxes and CO_2 emissions. Aydin and Esen (2018) revealed that the effect of environmental taxes (excluding transportation) on CO_2 emissions shifts from insignificantly positive to negative effects over a certain (threshold) level. However, the findings of the current study do not support the previous research. Our result is in line with Rybak et al. (2022), who argue that if environmental taxes increase this do not lead to a reduction in emissions.

Few analyses have been carried out to identify the CO_2 moderating effects of variables. Mentel et al. (2022) analysed the mitigating effect of renewable energy sources on CO_2 emissions using the industrial value added variable. Our results show that in addition to the main effect of the environmental tax, it also has a moderating effect on the energy supply. For the same energy intensity, the increase in CO_2 intensity is more significant for a higher tax than for a lower tax (See Figure 1). However, the mitigating effect of taxes through renewable energy supply has only been shown for UN member states. It also accords with our earlier observations, which showed that the effect of a low or high environmental tax depends on the threshold level of the renewable energy supply (See Figure 2). Similarly, environmental taxes have altered the effect on GDP per capita, which differs substantially among OECD countries. The relationship between GDP and CO_2 emissions growth, for example, is positive for countries with low environmental taxes and negative for those with high environmental taxes (See Figure 3).

Further studies could be carried out for groups of countries to investigate whether the impact of environmental taxes on CO_2 emissions is strongly dependent on the level of existing primary and renewable energy supplies. Likewise, there is plenty of room for advancement in determining which countries or groups and under which conditions the CO_2 mitigation effects of environmental taxes through redistribution can be examined.

Conclusions

The current study aimed to determine the impacts of primary and renewable energy supply and environmental taxation on carbon dioxide intensity growth. The study proposes explanations to analyse how taxation can change the effects of the energy supply to reduce carbon intensity.

This study has found that a curvilinear (inverted U-shaped) relationship existed between output per capita and CO_2 intensity growth. This research has shown that the increased primary energy supply and environmental-related taxation positively contribute to carbon intensity. The second main finding was that a substantial increase in the share of renewable energy in the energy supply mix would significantly reduce carbon growth. The present study provides additional evidence concerning the moderating role of taxation, increasing the positive impact of primary energy and amplifying the negative impact of renewable energy supply on CO_2 intensity. The empirical findings in this study support a new understanding of how the curvilinear relationship between carbon intensity and GDP growth differ for countries with low and high environmental taxes.

Several limitations of this pilot research must be acknowledged. As the explanatory variables in the models represent the authors' preferences, this study is mostly constrained by omitted variable bias. The fact that there are still some shortcomings in the socio-economic indicators, means that findings need to be interpreted cautiously. Moreover, the models only consider a few energy-related SDGs that are vital for the future of humanity.

In our subsequent study, we will consider some energy security and socio-economic factors from the supplier and customer side. We will improve the EKC direction to enhance the global green environment. It would be interesting to assess the application of negative emissions technologies and their life cycles, the direct and moderating effects of, for example, end-user oil and gas prices, fossil fuel and consumer support on mitigating the effects of climate change.

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Author contributions

D.M. were responsible for the methodology, software, and validation, J.T.K. conceived to write the original draft, and supervision, L.T. were responsible the theoretical background and project administration.

Disclosure statement

The authors state that they do not have any competing financial, professional, or personal interests.

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APPENDIX

OECD countries: Australia, Austria, Belgium, Canada, Chile, Colombia, Costa Rica, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.

Non-OECD countries: Albania, Algeria, Angola, Argentina, Armenia, Azerbaijan, Bahrain, Bangladesh, Belarus, Benin, Bolivia, Bosnia and Herzegovina, Botswana, Brazil, Brunei Darussalam, Bulgaria, Cambodia, Cameroon, China, Congo, Democratic Republic of the Cong, Côte d'Ivoire, Croatia, Cuba, Cyprus, Dominican Republic, Ecuador, Egypt, El Salvador, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Georgia, Ghana, Guatemala, Guyana, Haiti, Honduras, India, Indonesia, Iran, Iraq, Jamaica, Jordan, Kazakhstan, Kenya, Kuwait, Kyrgyzstan, Lao People's Democratic Republic, Lebanon, Libya, Malaysia, Malta, Mauritius, Moldova, Mongolia, Montenegro, Morocco, Mozambique, Myanmar, Namibia, Nicaragua, Niger, North Macedonia, Nigeria, Oman, Pakistan, Panama, Paraguay, Peru, Philippines, Qatar, Romania, Russia, Saudi Arabia, Senegal, Serbia, Singapore, South Africa, Sri Lanka, Sudan, Suriname, South Sudan, Syrian Arab Republic, Tajikistan, Tanzania, Thailand, Togo, Trinidad and Tobago, Tunisia, Turkmenistan, Ukraine, United Arab Emirates, Uruguay, Uzbekistan, Venezuela, Viet Nam, Yemen, Zambia, Zimbabwe.

Table A1. Descriptive statistics of dependent and independent variables (source: OECD, 2022; World Bank, 2022)

Variables	Obs	Mean	Std. Dev.	Min	Max
$\Delta\ln(CO_2INT)_{i,t}$	1248	−0.014	0.089	−0.599	0.716
$\Delta\ln(GDPCAP)_{i,t}$	1251	0.017	0.067	−0.978	0.797
$\Delta\ln(GDPCAPsq)_{i,t}$	1251	0.325	1.249	−18.843	15.208
$\ln(ENGINT)_{i,t}$	1387	0.416	1.035	−2.811	2.898
$RNWSUP_{i,t}$	1387	27.033	27.806	0.000	149.732
$TRADE_{i,t}$	1320	88.853	53.462	0.200	408.362
$ENVTAXGDP_{i,t}$	785	1.721	1.069	0.000	4.707