Disaggregated energy use and socioeconomic sustainability within OECD countries

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Abstract

This study investigates the relationship between disaggregated energy use, human development, trade openness, economic growth, urbanization, and sustainability index in OECD countries from 2014 to 2019. Static, quantile, and dynamic panel data approaches are employed. The findings reveal that fossil fuels such as petroleum, solid fuels, natural gas, and coal reduce sustainability. On the contrary, alternative sources such as renewable and nuclear energy contribute positively to sustainable development. It is interesting to note that alternative energy sources strongly influence socioeconomic sustainability in the lower and upper quantiles. Also, the human development index and trade openness improve sustainability, while urbanization seems to be an obstacle in complying with sustainability goals within OECD countries. Policymakers should revisit their strategies toward sustainable development by mitigating fossil fuels and urbanization and promoting socioeconomic development, trade openness, and non-fossil fuels as drivers of economic progress.

Keywords: Sustainability index; Fossil fuels; Renewable energy; Nuclear energy; OECD
JEL: Q01; Q40; Q42

1. Introduction

The defense of a more peaceful, safe, healthy, and sustainable world can be described as a great chance to get unequal global development under control through Sustainable Development Goals (hereafter SDGs). Nevertheless, many problems still need to be solved. First, most of the goals are far away from their targets. Rapid growth, inequalities, and uncontrolled use of natural resources will continue to pressure sustainable development. Energy use and sustainability are closely linked, as energy consumption significantly contributes to environmental degradation and climate change. The use of fossil fuels, the primary energy source for most countries, produces greenhouse gases and other pollutants that harm air and water quality contributing to environmental degradation. Additionally, fossil fuel extraction, production, and transportation often negatively impact local communities and ecosystems. Therefore, reducing energy consumption and transitioning to clean and alternative energy sources are crucial for achieving sustainability goals.

Many studies have explored the relationship between energy use and environmental sustainability, showing that increasing energy efficiency and reducing energy demand are cost-effective ways to reduce greenhouse gas emissions, improve air quality, and support sustainable development. Although environmental sustainability is not a new topic, with its most accepted definition existing more than thirty years ago (Brundtland, 1987), achieving sustainable development has not been an easy way forward. Even nowadays, developed countries are the highest polluters (Bruckner et al., 2022), especially those exhibiting very low economic diversification and weak institutional frameworks. Also, most developed economies are OECD members, characterized by relatively high-income and economic stability. Despite this, these countries remain far from achieving SDGs.

The present study contributes to the energy-sustainability literature in the following ways. First, it is well known that numerous studies examine the relationship between economic growth and environmental degradation with mixed results (Mardani et al., 2019; Sarkodie and Strezov, 2019). Nevertheless, only a few have used the sustainability level (Khan et al., 2020) as the core variable of their analysis. The standard limitation is that most studies in this area have not extensively incorporated the broader aspect of sustainability. Sustainability is not only related to the environment. Thus, this research endeavors to fill this gap by exploring socioeconomic sustainability as the primary outcome variable of interest within OECD countries. It is more important for societies to consider both social development and environmental factors, such as quality of education, awareness, and healthcare, since they also significantly impact human well-being.

Second, the present study investigates the impact of disaggregated energy use on the sustainability index within OECD countries. The disaggregated analysis addresses the issue of energy use from a new angle by considering the different types of energy used in different sectors and groups within society. In other words, by separating energy sources, it becomes possible to identify the proportion of energy that is coming from sustainable, renewable and alternative sources, such as wind, solar, hydropower, and nuclear, versus energy that is coming from finite, nonrenewable sources, such as coal, oil, and natural gas. This information is vital for sustainability as it can support policymakers and energy producers in understanding how much progress is being made towards a more sustainable energy mix and what actions need to be taken to increase the use of alternative energy sources. Additionally, knowing the breakdown of fossil and non-fossil energy allows for monitoring the impact of energy production on the sustainability level. In other words, this analysis allows for a more detailed and nuanced understanding of the complex relationship between energy use and socioeconomic sustainability.

Third, this study aims to provide new empirical evidence on the relationship between human development, economic growth, disaggregated energy use, trade openness, urbanization, and socioeconomic sustainability, focusing on a range of quantiles in the conditional probability distribution of the outcome variable. In particular, the current analysis first utilizes econometric panel techniques, which account for issues such as endogeneity, cross-sectional dependence, groupwise heteroskedasticity, and serial correlation. Additionally, as we are not unquestionable whether all types of energy sources have a linear impact on the sustainability index, we employ non-linear specifications to observe location-based asymmetries between the parameters within the conditional probability distribution of the sustainability variable. Also, as benchmark models, we estimate feasible generalized least square approaches in encountering groupwise heteroskedasticity and serial correlation and pooled OLS with Driscoll-Kraay (1998) standard errors to address cross-sectional dependence. In addition to static models and for robustness reasons, we follow the dynamic system generalized method of moments (sys-GMM) specifications that provide reliable results for short-panel data, as in our case.

Overall, the present research validates the direct impact of disaggregated energy sources, fossil, and non-fossil fuels, on socioeconomic sustainability via static linear approaches, quantile techniques, and dynamic specifications. Empirical findings explore the negative but distinct role of fossil fuels (petroleum, natural gas, and coal) and the positive and outstanding impact of non-fossil fuels (renewable and nuclear energy) on socioeconomic sustainability.

Following this introduction, the following section provides the previous literature review. Section 3 details the methodological approach and the data used. Section 4 presents the analysis's empirical results. Section 5 discusses the findings, and Section 6 concludes with recommended policies.

2. Research content

This section consists of four subsections discussing the environment Kuznets curve (EKC) hypothesis, the energy use-environmental quality hypothesis, the trade openness and environment relationship, and the urbanization-environmental quality relation.

2.1 Environment Kuznets curve hypothesis

The Kuznets curve (KC) was derived from Kuznets (1955), who identified the inverted-U-shaped relationship between income inequality and economic growth. This hypothesis has been widely applied in many scientific fields, such as health (Costa-Font et al., 2018) and environmental economics (Koondhar et al., 2021). Grossman and Krueger (1991)are considered the first authors who validated Kuznets' hypothesis using several environmental indicators in environmental economics. Later on, Panayotou (1993) introduced the term "environmental" Kuznets curve in environmental economics literature while examining the relationship between economic growth and environmental degradation using air pollution as the indicator of degradation. After that, many empirical studies examined the EKC hypothesis. However, the empirical results are mixed and inconclusive. Many studies have supported the EKC hypothesis (Ahmed and Long, 2012; Apergis and Ozturk, 2015; Churchill et al., 2018; Esteve and Tamarit, 2012; Kostakis et al., 2023). Others have found little evidence of an inverted-U relationship between economic growth and environmental degradation (Dogan and Inglesi-Lotz, 2020; Gormus and Aydin, 2020; Al Sayed and Kun Sek, 2013; Mazur et al., 2015; Özokcu and Özdemir, 2017). There are also studies with mixed results across different countries, methods, periods, and environmental indicators (Apergis, 2016; Destek and Sarkodie, 2019; Gormus and Aydin, 2020; Kostakis et al., 2017; Ng et al., 2020). EKC studies undertaken explicitly in the OECD countries have failed to provide concessive findings. Some confirmed the existence of the EKC hypothesis (Bhattacharya et al., 2017); others did not (Martino and Nguyen-Van, 2016), while others (Isik et al., 2019) report inconclusive evidence.

Additionally, several studies tried to estimate a modified environmental Kuznets curve hypothesis investigating a broader concept of development rather than pure economic growth (Costantini and Martini, 2006). The human development index (HDI) describes the relationship between higher welfare levels and natural resource consumption and confirms human development's role in environmental sustainability. More specifically, the HDI is a composite index that measures a country's overall level of development, taking into account economic growth and factors such as education and health. This indicator is considered a more comprehensive measure of development than GDP; some researchers argue that it is a better indicator of a country's environmental concern and ability to invest in environmental protection (Hossain and Chen, 2021; Hussain and Dey, 2021; Tenaw and Beyene, 2021).

2.2 Energy use-environmental quality hypothesis

Another group of studies explores environmental degradation and investigates the relationship between economic growth and energy use. The central claim of those papers is that the economy is linked to energy use since most production activities require energy as an input. Several authors have used either time series (Akinlo, 2008; Chiou-Wei et al., 2008; Sari and Soytas, 2007), or panel data (Belke et al., 2011; Kearsley and Riddel, 2010; Lee et al., 2008), or even cross-section datasets (He et al., 2022; Suri and Chapman, 1998) trying to unfold this relationship. Jobert et al. (2014) stated that "*the main reason for introducing energy consumption into the GDP-CO_2 nexus is that, first, energy consumption is a key determinant of CO_2 emissions and has a strong impact on pollution levels, and, second, there is a direct relationship between energy consumption and economic development*".

This hypothesis has also been studied by disaggregating final energy use into renewable and fossil fuels (Depren et al., 2022). For instance, Bölük and Mert (2014) employed panel data analysis in selected EU countries and reported that shifting the energy use mix towards other renewable technologies can reduce emissions. Inglesi-Lotz and Dogan (2018) also utilized panel data for several Sub-Saharan countries to confirm that fossil fuels-oriented energy use increases pollution while renewables positively affect the environment. Balsalobre-Lorente et al. (2018) assessed the nexus between economic growth and CO_2 emissions in five European Union countries from 1985 to 2016. Their empirical results support the EKC hypothesis and found that renewable electricity consumption, natural resources, and energy innovation enhance environmental quality. Hanif (2018) examined the impact of fossil fuels, solid fuels, and renewable energy consumption on environmental degradation in a panel of 34 selected emerging countries. Their findings support previous literature in this field, highlighting that fossil and solid fuels significantly contribute to environmental degradation via increased CO_2 emissions. On the contrary, renewable energy alternatives seem to enhance sustainable development. Pata (2021) looked into the BRICS economies from 1971-2016 and revealed the importance of renewable energy in combating environmental degradation. Sharma et al. (2021) supported that higher use of renewable energy significantly reduces environmental degradation in the case of several Asian countries over the period 1990-2015. Huang et al. (2022), scrutinizing the nexus between renewable energy and the ecological footprint of E-7 and G-7 countries from 1995 to 2018, also confirmed the positive impact of renewable energy on environmental quality.

Another strand of literature has devoted its research to using time series analysis (Isik et al., 2019; M. K. Khan et al., 2020; Lotfalipour et al., 2010; Menyah and Wolde-Rufael, 2010; Shahbaz et al., 2013) to explore the energy use-environment nexus. Most findings suggest fossil fuels negatively impact environmental quality, whereas renewables and alternative energy sources can enhance sustainable development. Similar results have been found using several other techniques and approaches that underline the role of energy in circular and sustainable development (Arauzo-Carod et al., 2022; Menegaki and Tsagarakis, 2015; Papadaki et al., 2022).

2.3 Trade openness and environment relationship

The link between trade openness and environmental quality has attracted many researchers (Le et al., 2016; Sharma, 2011), but the relationship has mixed results. Some authors express that trade openness hurts the environment (Ahmed et al., 2016; Atici, 2012; Le et al., 2016; Mahmoodi and Mahmoodi, 2018; Rahman, 2017; Rock, 1996; Shahbaz et al., 2018). On the contrary, other researchers support that developing trade freedom decreases pollution (Alola et al., 2019; Alpay, 2000; Destek and Sinha, 2020; Dogan and Seker, 2016; Gozgor, 2017). Implicitly on that point, Mavragani et al. (2016) using the "Open Markets Index", supported that more open economies are more likely to have a better environmental performance. Moreover, trade can bring new information that can benefit environmental quality (Dagestani and Qing, 2022). At the same time, some other authors conclude that the impact of trade openness on environmental quality may depend on income level (Dogan et al., 2020), while others indicate that there might be no significant relationship between international trade openness and environmental quality (Bernard and Mandal, 2016; Gangopadhyay et al., 2023; Sharma, 2011).

2.4 Urbanization-environmental quality association

Other studies have incorporated the impact of population density on environmental quality (Dagestani et al., 2022), but with mixed conclusions, too. Some verify the solid and consistent polluting impact of urban population size (Ahmad et al., 2021; Ahmed et al., 2020; Al-Mulali et al., 2015; Kihombo et al., 2022; Hossain, 2011; Zineb, 2016), while others (Munir and Ameer, 2018; Saidi and Mbarek, 2017) support that urbanization can reduce CO_2 emissions in the long run. Martínez-Zarzoso et al. (2007) conclude that the variability of the emissions impact from urbanization is not proportional and can be conditional on income group, vary from nation to nation, and even be insignificant in some specific countries. Generally, urbanization can have a differentiated impact on environmental quality based on three theories; the environmental transition theory, the ecological modernization theory, and the compact city theory (Sadorsky, 2014).

3. Research methodology

Energy use has been identified as a crucial catalyst for economic activities (Stern, 2011) in developing and developed countries, improving livelihood and well-being between societies. However, the trade-off between the burning of fossil fuels and climate change has led energy use to be a hot topic in academic and policymaking circles. The present study explores the relationship between disaggregated energy use and socioeconomic sustainability in OECD countries. The following subsections describe the data and the econometric methods employed.

3.1 Data sources

The data used in this study consists of annual observations over six years for variables obtained from different secondary sources. We consider the global sustainable competitiveness index (*gsci*), provided by the Solability Sustainable Intelligence (SSI) over the period 2014-2019 for the OECD countries, as the outcome variable. The global sustainable competitiveness index is a composite index calculated from several sustainability sub-indices related to natural capital, resource intensity, social capital, intellectual capital, and governance. Higher values of this index indicate a more sustainable economy. The independent variables include the use of coal (*coalpc*), natural gas (*ngpc*), petroleum and other liquids (*petrolpc*), renewables (*renpc*), and renewables combined with nuclear energy (*mixpc*) measured in quadrillion British thermal units (BTU) per capita provided by the Energy Information Administration (EIA). The human development index (*hdi*) was retrieved from the United Nations (UN) database. GDP growth (*gdpgr*) is taken in constant 2017US $ by the Penn World Table (PWT), while trade openness as a ratio of GDP (*trade*) and urbanization level (*urban*) as a ratio of total population retrieved from World Bank Indicators

(WDI). Table 1 presents the variables considered in this study with their description, measurement, and sources.

Table 1. Dependent and independent variables

Variable	Description	Source
gsci	Global sustainable competitiveness (Index)	SSI
coalpc	Coal consumption per capita (quad BTU)	EIA
petrolpc	petroleum and other liquids consumption per capita (quad BTU)	EIA
ngpc	Natural gas consumption per capita (quad BTU)	EIA
renpc	Renewable energy consumption per capita (quad BTU)	EIA
mixpc	Renewables and nuclear energy consumption per capita (quad BTU)	EIA
hdi	Human development index (Index)	UN
gdpgr	Real GDP growth (Rate)	PWT
trade	Trade openness (Share of GDP)	WDI
urban	Urbanization population (% of the total population)	WDI

Notes: SSI Solability Sustainable Intelligence. EIA Energy Information Administration. UN United Nations. PWT Penn World Table. WDI World Bank Indicators.

3.2 Models' specification

For the model specification, we assume that the empirical panel model is based on the following linear equation:

$$lngsci_{i,t} = \beta lnnonfossil_{i,t} + \gamma lnfossil_{i,t} + \theta x_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t}, \quad i = 1,2,\ldots.,N \; and \; t = 1,2,\ldots T \qquad (1)$$

where the dependent variable $lngsci_{i,t}$ is the natural logarithm of the global sustainable competitiveness index of country i at period t; β, γ and θ are the vectors of associated coefficients; and unobserved individual effects μ_i and time effects δ_t enter the model additively while $\varepsilon_{i,t}$ represents the error term. $nonfossil_{i,t}$ denotes renewable and nuclear energy use per capita, while $fossil_{i,t}$ represents natural gas, petroleum, and other liquids and coal per capita. The choice of control variables included in the x vector of Equation 1 is based on previous empirical works on the subject.

To control for groupwise heteroskedasticity and serial correlation, feasible generalized least squares (FGLS) specifications are employed. On top of that, pooled OLS with Driscoll-Kraay (1998) standard errors under cross-sectional dependence approaches are utilized. More importantly, quantile regressions with nonadditive fixed effects (QRPD) introduced by Powell (2016) are appropriate when non-linear and varying effects at different points of the outcome variable distribution are used. The main advantage of QRPD method, relative to the existing quantile estimators with additive fixed effects, is that it does not provide estimates of the dependent variable distribution of $y_{it} - a_i$, which is undesirable, as this can provide biased information about the effects of the policy variables on the outcome distribution. Furthermore, as in our study, it can give consistent point estimates for short periods.

For robustness reasons, being aware that static models might be somewhat restrictive and give biased estimations due to the lag-dependent variable being serially correlated with the error term (Harris et al., 2008), dynamic models are also applied. Several estimators have been proposed to cope with this issue (Anderson and Hsiao, 1982; Arellano and Bond, 1991; Blundell and Bond, 1998; Nickell, 1981). In our case, the one-way dynamic error component is specified as follows:

$$lngsci_{i,t} = \alpha_i + \beta_1 lngsci_{i,t-1} + \beta_2 lnnonfossil_{i,t} + \beta_3 lnfossil_{i,t} + \beta' x_{i,t} + \omega_i + \mu_t + e_{i,t} \qquad (2)$$

where α_i is the (unobserved) individual effect, $x_{i,t}$ is a vector of time-varying explanatory variables, ω_i is a vector of the time-invariant variable encapsulating unobserved country-specific effects, μ_t is the time-specific effects, while the error term $e_{i,t}$ is the idiosyncratic error component. β_1 represents the speed of adjustment to long-run while β_2, β_3 and β' are the vectors of independent and control variable parameters to be estimated.

For our case, we carry out the system generalized method of moments (sys-GMM) approach, which is consistent and asymptotically normal for large n and small t (Chamberlain, 1984), as in our case. However, to obtain consistent parameter estimates, several econometric concerns that mainly arise from the nature of the error term need to be addressed. Equation 2 incorporates both the long-run equilibrium relationship and the short-run dynamics. In addition, we should mention that the GMM first differences estimator might suffer from weak instrument issues if the autoregressive coefficient approaches unity (Blundell and Bond, 1998; Han and Phillips, 2010). Thus, a unit root test has to be applied. To choose the appropriate panel unit root test, we must assess the hypothesis of cross-sectional independence (Pesaran, 2004) in the data.

In the next step, the global sustainable competitiveness index can be estimated using first differences and sys-GMM estimators proposed by Arellano and Bond (1991) and Blundell and Bond (1998), which can be used with relatively small data sets and are preferable to other dynamic approaches. Regarding the specification of instruments, the Arellano-Bond estimator uses the lags-differences, while the Blundell-Bond GMM approach uses the lags in differences and levels as possible instruments (*xtabond2* command by Roodman (2009) is used in our case). Two types of GMM exist, namely, one-step and two-step GMM. The two-step GMM provides more reliable and consistent figures if data are unbalanced and under possible autocorrelation and heteroskedasticity issues in the data.

Finally, the consistency of the GMM specifications depends on the validity of the instruments in the estimation process (Sargan, 1958). Furthermore, the errors' first and second-order serial correlation should be tested. Simultaneously, various restrictions on the number of orthogonality conditions must be addressed, as the proliferation of instruments may also lead to sample bias. This bias is possible because the number of instruments is directly related to the length of the panel (time). To improve efficiency and Sargan test reliability in our models, we should keep the number of instruments as small as possible by limiting the lag depth or collapsing the set of instruments (Mehrhoff, 2009).

4. Empirical results

The following section illustrates some descriptive and preliminary findings before the econometric analysis. After that, econometric results are presented.

4.1 Descriptive findings

Table 2 reports the descriptive statistics before taking natural logarithms regarding the variables considered in this study. As expected, between countries variability is higher than within-country variability. In particular, the average global sustainable competitiveness index equals 50.5 and ranges from 43 to 59 units between OECD and 45 to 54 within OECD countries.

Table 2. Descriptive Statistics, 2014-2019

Variable	Mean	Std. Dev.	Min	Max
sc overall	50.504	4.230	40.490	61.340
between		3.842	43.100	58.838
within		1.860	44.809	54.304
petrolpc overall	0.065	0.038	0.014	0.217
between		0.039	0.014	0.211
within		0.003	0.044	0.088
coalpc overall	0.019	0.020	0.000	0.076
between		0.020	0.000	0.073
within		0.003	0.009	0.031
ngpc overall	0.033	0.024	0.000	0.125
between		0.003	0.000	0.119
within		0.003	0.025	0.045
renpc overall	0.044	0.089	-0.001	0.534
between		0.090	$-3.33x10^{-4}$	0.520
within		0.003	0.021	0.057
mixpc overall	0.055	0.090	$-9.93x10^{-4}$	0.053
between		0.090	$-3.35x10^{-4}$	0.520
within		0.003	0.032	0.069
hdi overall	0.870	0.055	0.710	0.946
between		0.055	0.726	0.941
within		0.007	0.838	0.900
gdpgr overall	2.749	2.111	-0.490	25.176
between		1.514	0.749	9.803
within		1.490	-5.011	18.122
urban overall	77.903	11.093	53.557	98.04
between		11.208	53.817	97.940
within		0.460	75.759	79.894
trade overall	101.282	62.140	26.294	380.104
between		62.640	27.541	354.505
within		4.900	80.206	131.226

OECD countries grew on average at a 2.8% real growth rate over 2014-2019, but with high discrepancies within groups. Regarding the per capita use of different energy types, petroleum and other liquids and renewable energy present the highest per capita consumption for fossil fuels and non-fossil fuels, respectively. The urbanization rate is 77.9% on average, indicating a high level of population density between OECD countries, while the within-country urbanization rate seems to be lower. Trade openness and human development index are 101.3% and 0.8, respectively, revealing the high level of openness and human development between and within OECD countries.

Nevertheless, it is essential to decompose the energy types of per capita use (see Figure S1 and Figure S2 in the supplementary material file). Petroleum and other liquids represent the majority of energy use in OECD countries. It is worth noting that countries with a high sustainability index use more renewable and nuclear energy than others. On the contrary, countries with low socioeconomic sustainability seem to use more fossil fuels. That relationship might provide some information to policymakers about the vital role of alternative energy (renewables and nuclear) use on SDGs. Figure S2 details Figure S1 for developing and developed OECD countries. Based on the UN World Economic Situation and Prospects report (2021), developing countries refer to Chile, Colombia, Costa Rica, Israel, the Republic of Korea, Mexico, and Türkiye. Notably, developed countries achieve higher levels of sustainability and follow the same pattern as described previously. In contrast, developing countries perform much lower based on the sustainability index with low renewable and nuclear energy use per capita. Coal and petroleum are also the most important types of energy use in developing economies.

4.2 Econometric analysis

We initiate our econometric analysis with the Pesaran (2004) cross-sectional dependence (CSD) test that is likely to be consistent in small panel datasets. The null hypothesis assumes cross-sectional independence between countries. It implies that any shock in one country does not impact the rest of the economies. Table 3 provides information about cross-sectional dependence concerning *p*-values, means, and absolute *ρ* values for all considered variables. Following the CD-test and taking care of the *p*-values and correlation, it can be noticed that all variables of interest are correlated across countries.

Table 3. Cross-sectional dependence test

Variables	CD-test	*p*-value	Mean abs(ρ)
lnsc	46.50	0.000	0.77
lnpetrolpc	7.73	0.000	0.51
lnngpc	7.09	0.000	0.56
lncoalpc	20.64	0.000	0.58
lnrenpc	7.60	0.000	0.47
lnmixpc	5.11	0.000	0.45
hdi	52.61	0.000	0.81
gdpgr	6.87	0.000	0.37
trade	14.92	0.000	0.58
urban	20.24	0.000	0.64

Notes: Null hypothesis refers to cross-sectional independence between the groups.

After unfolding CSD in our data, the panel unit root tests for the dependent variable are employed. These tests will indicate whether our dynamic specification might suffer from weak instrument issues (Blundell and Bond, 1998; Han and Phillips, 2010) and if the first difference GMM or system GMM model can provide more robust results. For this goal, Breitung (2000), Harris and Tzavalis (1999), Im et al. (2003), and Pesaran (2007) panel unit root tests are used. All first-generation unit root tests subtract the cross-sectional averages from the series to mitigate the cross-sectional dependence, while the Pesaran test refers to a second-generation unit root test that addresses the CSD issue. Table 4 presents these estimations.

Table 4. Panel unit root tests for the dependent variable

Variable	IPS	Breitung	Harris-Tzavalis	CIPS

lnsc	-2.11	-0.51	-0.04	1.70
Δ.lnsc	-2.49***	-3.82***	-0.21***	2.61***

Notes: IPS, Breitung, and Harri-Tzavalis unit root tests subtract the cross-sectional averages from the series, mitigating the impact of cross-sectional dependence in the data (demeaned option). All tests include trend. The null hypothesis assumes that panel time series are unit root processes. *** denotes a 1% level of significance.

As can be observed, all panel unit root tests reveal that the dependent variable is a unit root process in levels and stationary in its first difference. That result indicates that the sys-GMM estimator might give more robust results, as the first differences GMM approach might suffer from weak instrument issues. Thereupon, Tables 5 and 6 summarize empirical results for the total sample. In particular, Table 5 shows the results from the benchmark cross-sectional time series FGLS specifications (Table S1 of the supplementary file presents the FGLS, including the renewable energy -instead of the combined use of renewable and nuclear energy use- as a regressor). Table 6 presents the Pooled OLS with Driscoll and Kraay (1998) standard errors and the quantile models. (Similarly, Table S2 of the supplementary file presents the Pooled OLS with Driscoll and Kraay (1998) standard errors and the quantile models, including renewable energy use as a regressor. Also, Table S3 presents Pooled OLS and QRPD approaches with all energy use variables in the same model). For the robustness of our results, Table 7 illustrates the empirical results of the two-step dynamic sys-GMM estimators with robust standard errors corrected for finite sample biases (one-step sys-GMM results and renewable energy models are also presented in Tables S4 and S5 of the supplementary file, respectively).

Table 5. Cross-sectional time-series FGLS regressions

Variables	Model 1	Model 2	Model 3	Model 4
Constant	2.901***	2.971***	3.220***	2.710***
	(0.139)	(0.116)	(0.108)	(0.183)
lnpetrolpc	-0.064***			-0.034*
	(0.013)			(0.018)
lnngpc		-0.037***		-0.028***
		(0.007)		(0.010)
lncoalpc			-0.009***	-0.012***
			(0.002)	(0.004)
lnmixpc	0.030***	0.014***	0.018***	0.014**
	(0.005)	(0.005)	(0.005)	(0.006)
hdi	1.004***	1.038***	0.894***	1.166***
	(0.108)	(0.105)	(0.103)	(0.131)
gdpgr	2.37x10^{-4}	6.21x10^{-6}	1.39x10^{-4}	0.001
	(0.001)	(0.001)	(0.001)	(0.001)
trade	4.03x10^{-4}***	2.49x10^{-4}***	1.60x10^{-4}***	2.73x10^{-4}***
	(6.09x10^{-5})	(4.79x10^{-5})	(5.16x10^{-5})	(8.87x10^{-5})
urban	2.81x10^{-4}	-8.29x10^{-4}*	-1.02x10^{-3}***	-5.97x10^{-4}
	(4.97x10^{-4})	(4.60x10^{-4})	(4.28x10^{-4})	(5.26x10^{-4})
Observations	222	210	222	210
Number of countries	37	35	37	35

Notes: Standard errors are in parentheses. ***, **, and * denote 1%, 5%, and 10% levels of significance, respectively.

All models reveal that fossil fuels harm, while renewable and nuclear energy sources contribute to socioeconomic sustainability within OECD countries. Average (across models) long-run elasticities concerning petroleum and other liquids, natural gas, and coal equal -0.05, -0.03, and -

0.01, respectively (Table 5). That means that in the long run, an 1% increase in each one of these fossil fuels could decrease the sustainability index by 0.05%, 0.03%, and 0.01%, respectively. These results also highlight that the most negative impact on sustainability comes from petroleum use among the OECD countries. On the contrary, empirical results confirm renewable and nuclear energy use's positive role in sustainable development. In particular, the average long-run estimate of renewable and nuclear energy (combined) use per capita is around 0.02, implying that an increase in the combination of renewable and nuclear energy use by 1% will increase the sustainability index by 0.02% on average.

Concerning the rest of the control variables, the human development index is statistically significant in all models, underlining its pivotal role in sustainability. The economy's openness also seems to be a significant and positive contributor to sustainability, as the trade openness variable is a positive and statistically significant factor in all employed specifications. More open economies can exchange positive spillover effects, developing several technological and innovative ideas to improve sustainability. In contrast, a higher-density population seems to affect sustainability adversely, possibly indicating that urbanization results in environmental and socioeconomic pressures affecting the quality of life.

Table 6 displays the long-run elasticities based on the Pooled with Driscoll-Kraay standard errors and quantile regressions models.

Table 6. Pooled OLS with DK standard errors and panel quantile regression models (combined renewable and nuclear energy per capita use)

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10	Model 11	Model 12
Variables	Pooled OLS with DK	Quantile 25th	Quantile 50th	Quantile 75th	Pooled OLS with DK	Quantile 25th	Quantile 50th	Quantile 75th	Pooled OLS with DK	Quantile 25th	Quantile 50th	Quantile 75th
lnpetrolpc	-0.073***	-0.026***	-0.075***	-0.023								
	(0.005)	(0.007)	(0.011)	(0.015)								
lnngpc					-0.044***	-0.029***	-0.055***	-0.019				
					(0.006)	(0.003)	(0.002)	(0.036)				
lncoalpc									-0.009***	-0.009***	-0.005***	-0.002
									(0.002)	(0.001)	(0.001)	(0.009)
lnmixpc	0.031***	0.020***	0.016***	0.023***	0.018***	0.033***	0.025***	0.021**	0.024***	0.027***	0.015***	0.027***
	(0.002)	(0.002)	(0.005)	(0.003)	(0.001)	(0.003)	(0.001)	(0.009)	(0.002)	(0.001)	(0.003)	(0.003)
hdi	1.110***	1.131***	1.311***	1.021***	1.019***	0.855***	0.874***	0.596	0.824***	0.847***	0.962***	0.563
	(0.062)	(0.083)	(0.107)	(0.106)	(0.051)	(0.064)	(0.020)	(0.662)	(0.014)	(0.013)	(0.044)	(0.482)
gdpgr	0.002	0.002	0.005	0.004*	0.001	9.14×10^{-5}	-5.16×10^{-4}***	0.002	0.002	-5.21×10^{-4}**	6.05×10^{-4}	0.004*
	(0.002)	(0.001)	(0.004)	(0.002)	(0.001)	(0.000)	(0.000)	(0.002)	(0.001)	(0.000)	(0.001)	(0.002)
trade	3.60×10^{-4}***	1.11×10^{-4}	7.19×10^{-4}***	2.15×10^{-4}***	2.56×10^{-4}***	3.70×10^{-4}***	3.12×10^{-4}***	2.22×10^{-4}	1.48×10^{-4}***	2.48×10^{-4}***	1.54×10^{-4}***	1.76×10^{-4}
	(2.50×10^{-5})	(1.26×10^{-4})	(8.70×10^{-5})	(7.87×10^{-5})	(2.22×10^{-5})	(2.95×10^{-5})	(2.28×10^{-5})	(1.49×10^{-4})	(1.99×10^{-5})	(1.54×10^{-5})	(3.43×10^{-5})	(3.90×10^{-4})
urban	4.61×10^{-4}	8.16×10^{-4}	4.11×10^{-4}	-1.22×10^{-4}	-0.001***	-9.29×10^{-4}***	-5.14×10^{-4}***	-0.002*	-0.001***	-0.002***	-0.002***	-4.34×10^{-4}
	(2.28×10^{-4})	(0.001)	(4.08×10^{-4})	(4.36×10^{-4})	(2.17×10^{-4})	(2.24×10^{-4})	(6.69×10^{-5})	(0.001)	(2.56×10^{-4})	(9.33×10^{-5})	(8.70×10^{-5})	(0.003)
Obs.	223	223	223	223	211	211	211	211	223	223	223	223
No of groups	38	38	38	38	36	36	36	36	38	38	38	38

Notes: Standard errors are in parentheses. ***, **, and * denote 1%, 5%, and 10% levels of significance, respectively. Pooled OLS is applied with Driscoll-Kraay standard errors. Panel quantile regression is applied with nonadditive fixed effects (Powell QRPD approach). Intercept is suppressed.

The elasticity of per capita alternative energy (renewables and nuclear) use (Table 6) equals 0.02 (average across polled OLS models), confirming previous empirical findings. These results indicate that renewable and nuclear energy use positively affects socioeconomic sustainability. However, non-linear results are evident for different sustainability distributions. In particular, panel quantile regression models display that the impact of alternative energy use asymmetrically affects the sustainability index. More specifically, the renewable and nuclear energy use elasticity seems to be higher at the low and upper sustainability index tails. This outcome mainly highlights the vital role of renewables in countries with low levels of socioeconomic sustainability. The role of renewable energy on the sustainability index is presented in the supplementary file (Table S2). Empirical results confirm alternative energy use's positive but asymmetric effect on socioeconomic sustainability. Also, it is shown that fossil fuels decrease sustainability, validating previous findings. Consequently, panel quantile models demonstrate that renewable and nuclear energy use's effect is significant for countries with low socioeconomic sustainability.

In the case of fossil fuels, empirical findings confirm their harmful impact on the sustainability index. Based on the level of coefficients, petroleum seems to have the most damaging impact on socioeconomic sustainability (-0.07 for pooled OLS model and -0.04 average across quantile estimates) and coal the lowest one (-0.01 for pooled OLS model and -0.001 average across quantile estimates). Natural gas use also has a negative statistically significant association with the sustainability index (-0.04 for pooled OLS model and -0.03 average across quantile estimates). All these results settle the overall undesirable impact of fossil fuels on socioeconomic sustainability. However, similarly to the previous analysis, the adverse effects of petroleum, natural gas, and coal seem to be asymmetric to sustainability distribution.

Regarding the rest of the control variables, empirical findings validate that the human development index and not only the economic growth and trade openness positively affect sustainability. On the contrary, urbanization seems negatively correlated with the sustainability level in most of the models.

Furthermore, the robustness of the static model specifications has been tested using dynamic approaches, as presented in Table 7. All GMM estimates are based on the standard two-step sys-GMM specifications adjusted for finite sample bias. Lagged dependent variable levels are used as instruments while all models pass autocorrelation diagnostic tests. Moreover, even if some issues seem to be present, the number of instruments eliminates the possible bias due to the plausible use of instruments.

Table 7. Two-step sys-GMM dynamic panel data specifications

Variables	Model 1	Model 2	Model 3	Model 4
L.lnsc	0.351***	0.379***	0.447***	0.328***
	(0.105)	(0.071)	(0.049)	(0.063)
lnpetrolpc	-0.038*			-0.020
	(0.022)			(0.014)
lnngpc		-0.029***		-0.028***
		(0.008)		(0.009)
lncoalpc			-0.002	-0.033
			(0.002)	(0.003)
lnmixpc	0.016***	0.014***	0.013***	0.015***
	(0.006)	(0.004)	(0.002)	(0.002)
hdi	0.744***	0.646***	0.470***	0.806***
	(0.209)	(0.120)	(0.0820)	(0.137)

gdpgr	0.001	0.005	0.005**	0.001
	(0.002)	(0.003)	(0.002)	(0.001)
trade	2.19x10^{-4}**	1.40x10^{-4}**	7.70x10^{-5}	1.93x10^{-4}***
	(2.02x10^{-5})	(5.16x10^{-5})	(5.00x10^{-5})	(5.09x10^{-5})
urban	-4.94x10^{-5}	-6.91x10^{-4}*	-9.10x10^{-4}***	-4.56x10^{-4}
	(5.66x10^{-4})	(3.86x10^{-4})	(2.41x10^{-4})	(3.82 x10^{-4})
Constant	1.862***	1.851***	1.849***	1.838***
	(0.347)	(0.218)	(0.170)	(0.160)
No of groups	38	36	38	36
No of instr.	18	18	18	20
AR(1) pr.	0.08	0.07	0.02	0.06
AR(1) pr.	0.54	0.62	0.60	0.53
Sargan pr.	0.17	0.03	0.02	0.19
Observations	186	176	186	176

Notes: Standard errors are in parentheses. ***, **, and * denote 1%, 5%, and 10% levels of significance, respectively.

Sustainability persistence is present as the speed of adjustment is highly significant in all specifications and equals 0.38 (average across models). The overall long-run elasticity (calculated by the formula: $\hat{\beta}_{lr} = \hat{\beta}_i / (1 - \hat{\beta}_{lag\ of\ dep})$) concerning per capita renewable and nuclear energy use, is around 10% higher than static estimations confirming, but also highlighting, the critical role of alternative energy use on the sustainability index. This result also indicates that the energy mix transition towards non-fossil fuel use might be long-run but highly efficient for sustainability. Nuclear and renewable energy use per capita results also confirm static approaches indicating their positive effect on sustainability. Also, the dynamic analysis provides some empirical evidence that fossil fuels negatively affect sustainability. Regarding the rest of the variables, empirical findings support the positive role of the human development index and trade openness on the socioeconomic sustainability level. Finally, some models indicate that as urbanization increases, it negatively affects sustainability among OECD countries.

5. Discussion

Overall, the empirical findings support that energy transition can be a valuable tool to improve socioeconomic sustainability within OECD countries. Fossil fuels, including coal, petroleum, and natural gas, decrease sustainability, confirming several previous empirical studies (Balsalobre-Lorente et al., 2018; Bölük and Mert, 2014; Capellán-Pérez et al., 2018). On the contrary, alternative energy sources can provide a solution to higher sustainability (Al-Mulali et al., 2015; Altinoz and Dogan, 2021; S. A. R. Khan et al., 2020; Menyah and Wolde-Rufael, 2010). In particular, as the economic growth of OECD countries is highly dependent on fossil fuels, energy transition towards cleaner energy sources can reduce sustainability degradation by reducing oil, natural gas, and coal use. Even if several economies have not reached a level of non-fossil fuel use that can significantly contribute to reversing environmental degradation, increasing alternative energy sources should be promoted as a panacea for higher socioeconomic sustainability. On the contrary, solid municipal waste, higher resource demand, fossil fuel-powered production, public infrastructure and transportation, and increased supply of high-end goods are only a few factors that can increase sustainability pressure.

Current estimates demonstrate that the energy transition policy from fossil fuels to alternative energy sources can lead to a higher level of sustainability between OECD countries. This transition seems to be accompanied by environmental improvements and substituting polluting fuels with cleaner ones (Capellán-Pérez et al., 2018; Gangopadhyay et al., 2023; Mahdi et al., 2022; Saidi and Omri, 2020). This result aligns with most previous studies that analyze the link between energy consumption and environmental degradation (Al-Maamary et al., 2017; Bhattacharya et al., 2017; Isik et al., 2019). However, this energy transition should be focused on countries with low socioeconomic sustainability index and high petroleum consumers. In other words, it is found that the impact of all energy use sources is not the same across different levels of the sustainability index, pointing out the critical role of energy use in lowering sustainability levels. In the lowest sustainability level economies, the large share of fossil-fuel energy use raises concerns about achieving SDGs. These countries should continue to promote and invest in non-fossil fuel energy use, while the energy transition is a crucial determinant and driver for energy efficiency and climate change. This finding is consistent with previous studies that validate the asymmetric relationship between energy consumption and environmental quality (Altinoz and Dogan, 2021).

Regarding nuclear energy, it can be supported that a mix of renewables with nuclear power plants that do not emit greenhouse gases can make them a key contributor to reducing the impact of climate change (Dong et al., 2018; Iwata et al., 2010; Lee et al., 2017; Saidi and Omri, 2020). Nuclear energy is highly energy dense and reliable, meaning that a small amount of fuel can generate a large amount of energy, allowing for a smaller land footprint than other forms of energy generation. At the same time, from a more socioeconomic perspective, nuclear energy can create construction, operation, maintenance, and decommissioning jobs (Alam et al., 2019; Kenley et al., 2009). Of course, we must underline that nuclear energy has challenges, such as managing nuclear waste and the risks of accidents.

Considering the long-term results of economic development, we find that socioeconomic development (proxied by the human development index), and not only the economic pillar of sustainability (proxied by economic growth), has a crucial role in alleviating sustainability degradation within countries. It indicates that focusing only on the economic pillar cannot enable economies to mitigate sustainability issues. These findings are compatible with the results of Costantini and Martini (2006), Farhani et al. (2014), and Tenaw and Beyene (2021).

Furthermore, trade openness in OECD countries seems to contribute to sustainability, as the estimated models indicate a significant and positive impact of economic trade openness on the socioeconomic sustainability index. This result implies that more open economies can exchange spillover effects, increase comparative advantages, develop technological and innovative ideas, and improve total factor productivity (Saud et al., 2020). Also, countries should adopt policies accelerating trade penetration following green strategies and achieving carbon neutrality to mitigate the issues of socioeconomic sustainability degradation.

Regarding urbanization, in OECD countries, most people live in highly populated areas and seem responsible for lower sustainability levels. Most empirical findings verify its adverse impact on sustainability via the limited resources available. All statistically significant variables discussed are presented in Figure 1.

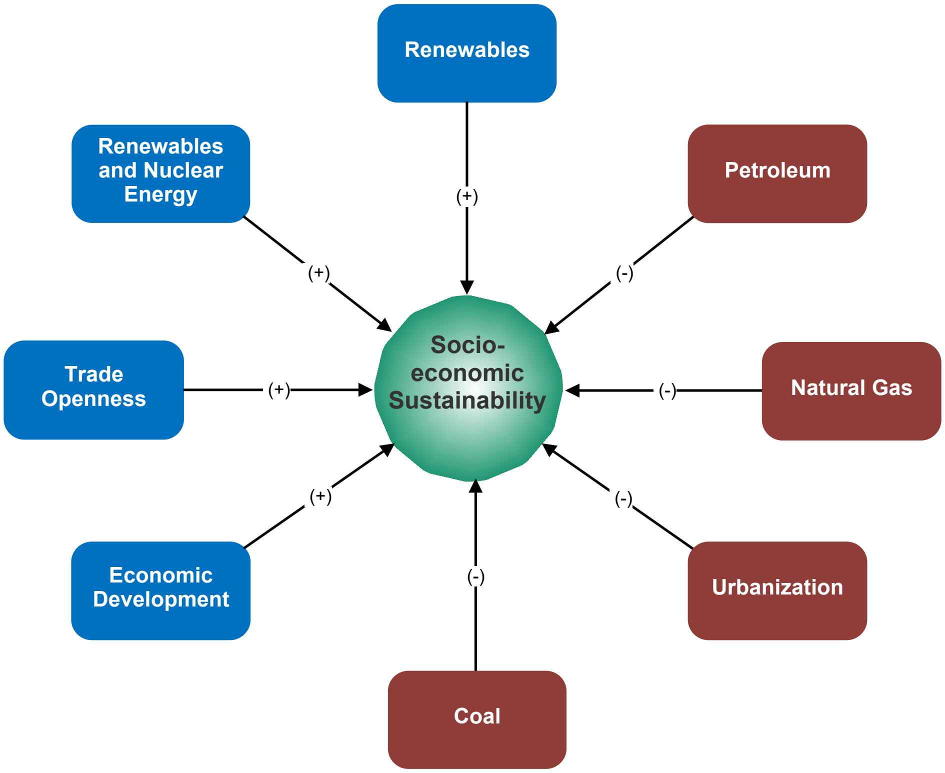

Figure 1. Estimated relationships between the variables of interest

6. Concluding remarks and policy implications

The present research investigates the relationship between disaggregated energy use and the socioeconomic sustainability index. Policies that drive higher quality of life can be derived in developed and developing countries. After disaggregating energy use, this study explores the effect of fossil and non-fossil fuels on the socioeconomic sustainability index within the OECD countries over the period 2014-2019. The key drivers for low sustainability performance are empirically shown to be fossil fuels (petroleum, solid fuels, natural gas, coal) and urbanization. On the contrary, non-fossil fuels such as renewable and nuclear energy, combined with more open economies and higher human development, could play a catalytic role in improving sustainability.

The findings of this study can provide several critical policymaking insights and recommendations that governments can advocate to improve socioeconomic sustainability. First, empirical results show that human development has crucial and favorable effects on socioeconomic sustainability within OECD countries. In particular, policymakers should take various measures to improve human development. For instance, governments can invest in education and provide access to essential services such as healthcare within rural areas. Also, they could implement progressive taxation and social welfare programs to reduce poverty and income inequality. Lastly, policymakers should promote good governance and transparency to create a stable and predictable business environment out of highly dense cities.

Second, fossil fuels deteriorate sustainability, while renewable and nuclear energy increase socioeconomic sustainability with a non-linear trend. In particular, the positive impact of non-fossil fuels on sustainability is more significant and potent within countries with low sustainability than in countries with high levels of sustainability index. Similarly, fossil fuels effects are asymmetric concerning the outcome variable distribution. Thus, countries with low sustainability levels should prioritize transitioning from fossil to non-fossil fuel energy sources. Alternatively, the substitution of fossil fuels energy inputs with more efficient alternatives must be a vital energy policy reform for these countries. Such a policy will lead them to catch up with countries with higher-level sustainability. However, it should be mentioned that the expansion of renewables and nuclear energy must consider the impact of green investments on cropland areas and waste risks, which policymakers and governments still need to discuss.

Third, trade openness must continue to be retained and expanded as it seems to generate positive spillover effects on sustainable socioeconomic development. International policymakers can implement policies promoting fair trade that will set labor conditions and worker rights standards in exporting countries and provide support for creating jobs and endorsing economic growth in disadvantaged communities. Additionally, governments can work together through international trade agreements to establish several standards for the environmental performance of products and services by supporting the development of cleaner technologies that can reduce trade's environmental impact while promoting economic growth. However, this finding must also be interpreted with caution. As we talk about high-income countries, more trade can be translated into displacing several environmental and health impacts to the middle- and low-income countries.

In contrast, urbanization seems to be a barrier to socioeconomic sustainability. Governments and policymakers should give people several financial and structural incentives (through de-urbanization policies) that could lead to a more sustainable way of living among societies or change from the conventional way cities are organized to new green and circular-driven planning policies. For instance, policymakers can promote rural development by providing tax incentives for businesses that operate in rural areas and investing in infrastructure and public services to make them more attractive places to live and work. Additionally, they can encourage the growth of small towns and villages by providing financial assistance to develop local economies and implement policies and programs that help retain younger generations in rural areas through education and job opportunities.

Nevertheless, we should mention some shortcomings of the present study. First, as this study focuses solely on the OECD countries and in light of country characteristics, future research could focus on another pool of countries with different socioeconomic and environmental profiles. Also, more updated data for reproduction research should be conducted. In particular, extending the period of the panel data will allow replicated analysis using additional and more robust statistical evidence. Finally, we should remark that this study is restricted to some variables that influence sustainability performance, but future research may analyze additional factors related to socioeconomic sustainability.

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