Chapter 3

Energy Security and Environmental Efficiency in OECD Countries: Pathways to Sustainable Growth[#]

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This chapter investigates the pathways toward sustainable growth in OECD countries, focusing on the dual goals of energy security and environmental efficiency as critical responses to climate change and increasing energy demands. Balancing economic development with environmental sustainability remains a significant challenge, necessitating policies that support energy resilience while mitigating ecological impact. Leveraging comprehensive datasets from the International Energy Agency, British Petroleum, and the World Bank, this study employs a nonradial Data Envelopment Analysis (DEA) model to assess environmental and energy efficiency metrics across OECD nations. Results reveal substantial variations in energy efficiency performance, with countries such as Iceland and Greece achieving near-optimal efficiency, while others, including Ireland, show significant room for improvement. The findings emphasize the importance of diverse policy approaches tailored to each nation's unique energy landscape, promoting renewable energy integration and increased efficiency to enhance energy security. This study's policy implications advocate for integrated strategies aligning economic growth objectives with environmental sustainability targets, fostering a resilient energy transition. Through this framework, the research provides critical insights for policymakers to facilitate sustainable growth by improving environmental efficiency and securing energy pathways in the OECD context.

Keywords: Assessment; DEA; environment; economy; energy; OECD.

JEL Classification: F14, O56, Q43.

1. Introduction

Growing concerns about climate change have intensified the need for a robust energy strategy that balances economic development with environmental sustainability. For countries in the OECD, achieving this balance means addressing the dual objectives of energy security and environmental efficiency. Energy security is increasingly critical as global energy demand continues to rise, driving interest in alternative energy solutions that can reduce dependence on fossil fuels while meeting economic demands (Mohsin *et al*., 2018; Ikram *et al*., 2019). As the primary source of carbon emissions, fossil fuel-driven electricity production remains a pressing challenge worldwide. Although renewable energy has become a viable alternative, fossil fuels still account for most global power generation (Bang *et al*., 2018; Sun *et al*., 2019a). This reliance on non-renewable energy sources underscores the urgency of transitioning to greener technologies to reduce carbon footprints and mitigate climate vulnerabilities (Taghizadeh-Hesary *et al*., 2013; Kolodko, 2018).

The recent volatility in energy prices and supply disruptions due to geopolitical tensions have further highlighted the risks associated with fossil fuel dependence, reinforcing the strategic importance of diversifying energy sources to improve resilience. This situation is spurring interest in alternative sources, such as wind, solar, and hydrogen, which offer lower risks of price volatility and greater environmental benefits (Zhao *et al*., 2023; Ibekwe *et al*., 2024). Energy security is now closely tied to the transition to renewables, as seen in recent studies that emphasize the need for diversified, reliable, and sustainable energy infrastructures that can withstand external shocks (Rasoulinezhad *et al*., 2023). Increasingly, researchers highlight the importance of secure renewable energy supply chains, including the technological capacity to generate renewable energy and the logistical infrastructure required to store and distribute it effectively.

Policy initiatives to curb emissions, such as CO_2 reduction targets and advancing renewable energy technologies, are now key components of energy frameworks among OECD nations. These efforts, driven by international agreements and increasing climate awareness, reflect a growing consensus that strategic innovation and investment in cleaner energy sources are essential for long-term sustainability (Zhang *et al*., 2018a; Taghizadeh-Hesary and Yoshino, 2015). For example, recent studies suggest that optimizing the integration of renewable energy systems requires technological improvements and methods that support the selection and combination of renewable sources to stabilize national energy systems (Ouyang and Lin, 2014). Emerging research on grid modernization indicates that advances in energy storage technologies and smart grid systems are essential for accommodating the intermittency of renewable energy, which is increasingly seen as vital to ensure both energy security and efficient distribution in OECD nations (Ourahou *et al*., 2020).

Green growth has also become an integral focus within energy policy discussions, with new research showing that investing in green infrastructure can stimulate economic growth while reducing emissions. Studies indicate that green growth strategies — such as expanding the green job sector and improving energy efficiency — contribute positively to economic stability, particularly during global transitions toward decarbonization (Sadiq *et al*., 2022). Research on the economic impacts of green growth suggests that promoting energy efficiency, sustainable infrastructure, and low-carbon technologies can enhance economic resilience by creating jobs and encouraging private investment, even as nations strive to meet carbon reduction targets (Fernandes *et al*., 2021; Dell'Anna, 2021).

Despite notable progress, empirical research demonstrates that achieving a low-carbon society remains challenging, hindered by the complex interdependence of energy production, economic growth, and environmental impacts. Studies reveal that CO_2 emissions, driven by fossil fuel combustion, have risen sharply alongside industrial growth, with emissions currently at approximately 35.7 billion tons globally. This trend indicates a positive correlation between CO_2 emissions and economic expansion, posing a fundamental obstacle to environmentally sustainable growth (Zhang *et al*., 2015; Guo *et al*., 2018). Recent assessments show that decoupling economic growth from emissions remains limited, with a need for new decarbonization policies that account for sector-specific emission patterns, particularly in heavy industry and transport sectors where fossil fuel reliance remains high (Gbadeyan *et al*., 2024).

Furthermore, the transition away from high-emission energy sources varies widely across OECD countries, driven by regional differences in policy adoption, economic constraints, and the availability of natural resources. While some countries have made significant strides toward decarbonization, others continue to struggle with the economic and logistical challenges of reducing fossil fuel dependence (Mollahosseini *et al*., 2017; Olivier *et al*., 2016). For example, countries such as the United States and China still rely heavily on coal and natural gas for energy, whereas European nations have seen emission reductions due to lower demand for space heating and reduced fossil fuel consumption in energy production (Jing *et al*., 2018; Nejat *et al*., 2015). A recent comparative study on energy transitions across OECD nations highlights that economic and geographic disparities influence the pace and effectiveness of the transition, underscoring the need for country-specific policies that address unique national constraints and opportunities in renewable energy adoption (Ma *et al*., 2023).

This study aims to contribute to the growing body of literature on energy and environmental efficiency by evaluating the performance of OECD countries using a nonradial Data Envelopment Analysis (DEA) model. Unlike traditional approaches, DEA provides a comprehensive framework to assess both desirable and undesirable outputs, thereby offering a nuanced view of energy efficiency across diverse economies (Sueyoshi and Wang, 2018; Egilmez *et al*., 2016). By incorporating environmental and energy performance indicators, this study seeks to identify areas where improvements in policy and practice can drive OECD nations closer to achieving sustainable growth. Recent applications of DEA models in environmental studies demonstrate their utility in capturing complex, multi-dimensional data, allowing for a more comprehensive assessment of sustainability that includes both energy efficiency and environmental impact metrics (Arana-Jiménez *et al*., 2024).

The rest of the paper is organized as follows: Section 2 contains methodology, Section 3 explains results and discussion, and Section 4 contains the conclusion and policy framework.

2. Methodology

Most pollution and contamination problems occur from the combined production of undesirable bad outputs during the production of desirable good outputs (Färe and Grosskopf, 2004). For example, the continuous emissions of nitrous oxide, carbon dioxide, and sulfur dioxide are unexpected when the electricity is produced from burning coal and thermal sources. We now consider a production process in which desirable good outputs and undesirable bad outputs are generated together. Let us assume the vector of undesirable outputs, desirable outputs, and inputs — $U \in R_+^J$, $Y \in R_+^M$ and $X \in R_+^N$. The production technology can be expressed as follows:

$$T = \{(X, Y, U) : X \text{ can produce } (Y, U)\}. \tag{1}$$

In consideration of production theory, T is often regarded as bounded and a closed set, which is the assurance of the output closeness, and it means that limited number of inputs can merely generate the limited outputs (Zhou *et al*., 2014; Zhou and Fan, 2010). Also, desirable outputs and inputs in T are considered to be freely disposable or robust. Specifically, if $(X, Y, U) \in T$ and $X' \geq X$ or $Y' \leq Y$, then $(X', Y, U) \in T$ or $(X, Y', U) \in T$. To facilitate the suitable model, a production technology can generate the undesirable and desirable outputs, then the succeeding two assumptions proposed by Zhou *et al.* (2012) are imposed on T.

P.1. Outputs are weakly disposable, i.e., if $(X, Y, U) \in T$ and $0 \leq \theta \leq 1$, then $(X, \theta Y, \theta U) \in T$.

P.2. Undesirable bad outputs and desirable good outputs are null-joint, i.e., if $(X, Y, U) \in T$, and $\mathbf{Y} = \mathbf{0}$ then $\mathbf{U} = 0$.

Assumption P. 1 indicates that the deterioration of undesirable bad outputs is not free, and the comparative decrease in undesirable bad outputs and desirable good outputs is possible. Assumption P.2 explains that a few undesirable bad outputs must also be generated during the production of desirable outputs. Specifically, the only way to eradicate undesirable bad outputs is to end the process of production of desirable outputs. Until now, the polluting technology, also called the weak dispose-off capability reference technology, conceptually modeled by Färe *et al.* (2005), for the concurrent generation of both undesirable and desirable outputs, is explained by the following output formula:

$$P(X) = \{(Y, U): (X, Y, U) \in T\}. \tag{2}$$

$P(\mathbf{x})$ contains all feasible outputs which have the vector of $\mathbf{x}$ inputs and then it may be expressed as $(X, Y, U) \in T \Longleftrightarrow (Y, U) \in P(X)$ (Färe and Grosskopf, 2000). $P(x)$ is a bounded and closed set and its equivalent production technology, while T represents an "environmental output set". Even though the production technology is conceptually well-defined, it cannot be used in the empirical application. Usually, first, it is essential to construct the equivalent relationships among the Shephard distance function, directional distance function and T; after that, it can be generalized as a conventional single-output-oriented production function (*Charnes et al*., 1994). The distance functions can be used to assess on the basis of parametric or nonparametric conditions. For measurement of nonparametric properties, Färe *et al.* (1989) presented the linear production technology, constant returns to scale (CRS), and Zhou *et al.* (2006) claimed that this type of production techniques can be used as environmental DEA technology because it is originated in DEA framework. Suppose that there are $k = 1, 2, ..., K$, DMU. Let our supposition be true for DMU_k the observed data on the vectors of inputs, undesirable bad outputs and desirable good outputs (Färe and Logan, 1983).

$$X_k = (X_{1k}, X_{2k}, \dots, X_{Nk}), \quad Y_k = (Y_{1k}, Y_{2k}, \dots, Y_{Mk}), \quad \text{and} \quad XU_k = (U_{1k}, U_{2k}, \dots, U_{Jk})$$

$$\sum_{j=1}^{J} U_{Jk} > 0 \quad \text{and} \quad \sum_{k=1}^{K} U_{Jk} > 0$$

$$F: (V_{k1}, \dots, V_{kn}) \rightarrow (f_1(V_{k1})$$

$$T_{\text{CSR}} = \left\{ (X, Y, U): \ \sum_{k=1}^{K} Z_k X_{nk} \leq X_n, n = 1, 2, \dots, N \right\}$$

$$\sum_{k=1}^{K} Z_k Y_{mk} \geq Y_m, \quad m = 1, 2, \dots, M$$

$$\sum_{k=1}^{K} Z_k U_{Jk} = U_{IJ}, \quad J = 1, 2, \dots, J$$

$$Z_k \geq 0, \quad k = 1, 2, \dots, K. \tag{3}$$

The construction of T_{CSR} provides a solid foundation for analysts and researchers in order to conduct an empirical estimation such as construction environmental performance index when production technology shows the approximation of CRS. T_{CSR}, i.e., (3), follows the properties of the weak dispose-off capability of null jointness and outputs between undesirable outputs and desirable outputs (Mohsin *et al*., 2018). CRS environmental DEA technology and T_{CSR} can be applied after the availability of suitable evidence of the consideration of production technology CRS. Various scholars have investigated the application and effectiveness of CRS environmental DEA technology in different schemes as well as in the assessment of productive efficiency and measurement of environmental performance having undesirable outputs (Charnes and Cooper, 1984; Zhou *et al*., 2008). However, in practical cases, the reference technology does not always show CRS, while in other cases, VRS might be observed in the actual situation (Färe and Lovell, 1978). Several researchers have proposed the studies with regard to the assessment of the returns to scale property e.g., Färe and Grosskopf (1997) and Rogge (2012). Consequently, it is logical to differentiate between various environmental DEA technologies, and the equivalent DEA-based models for measuring environmental performance. Zhou *et al*. (2012) concluded that the reference technology revealing CRS, and VRS or NRIS is particularly attractive in assessing studies. Hence, it is essential to demonstrate the environmental DEA technologies which validate NIRS and VRS. Like the conventional framework of DEA, NIRS environmental DEA technology (TNIRS) could be developed by imposing the restrictions on the variables of intensity on the CRS environmental DEA technology to reduce data uncertainty (Carstensen and Lindegarth, 2016).

$$
\begin{aligned}
T_{\text{NIRS}} = \Big\{(X, Y, U):\ & \sum_{k=1}^{K} Z_k X_{nk} \le X_n, n = 1, 2, \ldots, N\Big\},\\
& \sum_{k=1}^{K} Z_k Y_{mk} \ge Y_m, \quad m = 1, 2, \ldots, M,\\
& \sum_{k=1}^{K} Z_k U_{Jk} = U_{IJ}, \quad J = 1, 2, \ldots, J,\\
& Z_k \ge 0, \quad k = 1, 2, \ldots, K.
\end{aligned} \tag{4}
$$

In VRS DEA, unlike the traditional DEA framework, the VRS environmental DEA technology (T_{NIRS}) could not remain structured via imposing the limitations due to yielded technology that might infringe environmental DEA technology. Therefore, it is essential to develop a differentiation between traditional DEA and the concept of environmental DEA technology. To endure it, we first make a slight modification on P.1 and P.2, whereby P.1 outputs are weakly disposable, i.e., if $(X, Y, U) \in T$ and $0 \le \theta \le 1$, then $(X, \theta Y, \theta U) \in T$, P.2 undesirable bad outputs and desirable good outputs and are null-joint, i.e., if $(X, Y, U) \in T$. Here P1 still shows the weak dispose-off capability reference technology for the concurrent generation of both undesirable and desirable outputs.

P.2 implies that the desirable good outputs are necessarily insignificant if undesirable bad outputs are insignificant. P3 is to some extent weaker than the previous one, and it can be considered as environmental DEA technology. VRS environmental DEA technology is possibly derived by multiplying the adjusting parameter not less than 1 with the right-hand side of the constraints of undesirable bad outputs. We follow the similar suggestions proposed by Färe *et al.* (1989), but multiply the right-hand side of desirable good outputs constraints with the same parameter. The resultant environmental output is given as follows:

$$
\begin{aligned}
T_{\text{VRS}} = \Big\{(X, Y, U):\ & \sum_{k=1}^{K} Z_k X_{nk} \le X_n, n = 1, 2, \ldots, N\Big\},\\
& \sum_{k=1}^{K} Z_k Y_{mk} \ge \propto Y_m, \quad m = 1, 2, \ldots, M,\\
& \sum_{k=1}^{K} Z_k U_{Jk} = \propto U_{IJ}, \quad J = 1, 2, \ldots, J,\\
& \propto \ge 1, \quad Z_k \ge 0, \quad k = 1, 2, \ldots, K.
\end{aligned} \tag{5}
$$

There is a small difference between (5) and the model proposed by Scheel (2001) whereas model (5) is naturally more similar to DEA. T_{VRS} shows the VRS environmental DEA technology, and it does not have an effect on its assessing property of environmental performance.

3. Results and Discussion

Global assessments of fossil fuel consumption indicate an overall positive evaluation trend despite persisting uncertainties. China, for instance, currently emits approximately twice the amount of CO_2 compared to the United States, although projections suggest that their emissions could converge over the next decade. China's high CO_2 emission level is largely due to its expansive economic growth, significant population size, and strong reliance on coal-based energy sources (Branger & Quirion, 2015). On a global scale, Brazil and South Korea contribute about 1.4% and 1.7% of emissions, respectively, while Mexico accounts for around 1.3% (Yin *et al*., 2015). Notably, global CO_2 emissions surged by 5.2% in 2010, with fluctuations in subsequent years, reaching 1.9% in 2012, 1.8% in 2013, and 2.2% in 2014. Regionally, Mexico reduced its emissions by 1.6%, while Brazil, South Korea, and other countries, including Indonesia and Iran, reported increases during this period (Olivier *et al*., 2016). For developing nations, the Paris Agreement has set a clear agenda to focus on reducing greenhouse gas emissions and improving energy efficiency to support environmental sustainability.

As shown in Table 1, energy consumption (Koe capita) varies considerably, with Israel leading at 14,462.19, followed by Norway (8,160.52), Sweden (6,002.32), Germany (6,568.5), and Australia (5,636.01). Chile, however, recorded the lowest energy consumption. The primary energy supply also shows vast differences, from Luxembourg's 482.79 million tons down to Norway's 4.01 million tons. Renewable energy consumption is highest in Iceland (77.03%), followed by Norway (57.77%), Sweden (53.25%), Finland (43.24%), and Chile (24.88%). Conversely, Korea and Israel exhibit the lowest renewable energy shares at 2.71% and 3.71%, respectively. Regarding greenhouse gas emissions per capita, Australia ranks highest at 24.61 kg per capita, while the Netherlands has the lowest value of 5.28 kg per capita.

It is generally recognized that emission reductions could impact economic growth and may introduce externalities. Countries with faster economic growth tend to have higher energy consumption, often accompanied by increased greenhouse gas emissions. According to a World Bank report (2015), between 1960 and 1990, environmental indicators showed significant degradation, with greenhouse gases, particularly CO_2 from fossil fuel combustion, accounting for approximately 56.6% of emissions. The International Energy Outlook also highlights the worsening impact of fossil fuel-related CO_2 emissions on climate change (Mohsin *et al*., 2019).

3.1. *Empirical results*

According to the 2014 energy statistics, global coal consumption rose 0.4% from the previous year, mainly driven by China, accounting for 50.6% of the total world coal usage (Xie & Weng, 2016). India also saw a notable increase, with coal consumption rising to 11.1% due to high domestic production, compared to 7.3% in 2013. Conversely, lower coal usage trends were observed across several countries, including Germany (5.3%), the United Kingdom (20.3%), Italy (3.7%), Australia (2.5%), Japan (1.6%), and the United States (0.3%) (Vinci *et al*., 2017; Hassan & Salim, 2015).

Table 1. Individual Indicators of OECD Countries

Country	EC (Koe Capita)	PES (Million Ton)	Renewable %	GHG (Kg/Capita, 000)	GHG Per Unit of EC	GDP Growth
Australia	5636.01	119.77	09.18	24.61	1395.22	3.29
Austria	3902.54	32.310	34.39	10.24	326.53	1.90
Belgium	5296.14	56.680	09.21	12.48	379.05	1.80
Canada	8033.36	267.19	22.03	21.79	1356.22	2.36
Chile	1841.08	25.940	24.88	5.360	630.28	5.20
Denmark	4183.86	43.850	33.17	13.54	503.53	1.48
Finland	3390.62	18.570	43.24	11.84	287.07	1.77
France	3979.19	5.3900	13.52	14.58	73.670	1.57
Germany	6568.50	34.870	14.21	13.44	162.98	1.44
Greece	4042.36	258.48	17.17	8.390	1930.62	1.01
Hungary	3999.74	267.24	15.56	11.84	3633.61	1.76
Iceland	2525.82	27.460	77.03	10.90	720.75	2.68
Ireland	2519.47	25.710	09.08	6.830	407.83	4.62
Israel	14462.19	21.280	03.71	14.04	4.51	5.16
Italy	3256.81	14.000	16.52	15.02	297.51	0.73
Japan	2903.28	4.6400	06.31	10.35	316.66	0.93
Korea	2928.13	170.41	02.71	8.760	2662.71	5.28
Luxembourg	3830.65	482.79	09.03	10.68	5331.77	3.68
Mexico	4677.42	234.70	09.22	12.34	1807.36	2.78
Netherlands	2022.87	4.4000	05.89	5.280	84.530	1.99
New Zealand	2548.52	8.2000	30.79	6.500	127.00	2.68
Norway	8160.52	4.0100	57.77	23.92	21.430	2.48
Poland	1553.64	177.35	11.91	5.820	4490.83	3.69
Portugal	4776.17	78.690	27.16	12.55	649.50	1.53
Spain	4255.64	18.220	16.25	18.82	281.24	2.04
Sweden	6002.32	28.640	53.25	11.46	136.76	2.04
Switzerland	2476.78	94.830	25.29	10.35	2395.62	1.55
Turkey	2295.33	24.030	13.37	7.190	492.60	4.01
UK	3287.75	17.720	08.71	8.820	216.79	2.08
US	3477.38	7.0500	08.72	9.650	84.330	2.56

Table 2 illustrates the range of energy intensity values from 0.30 to 0.93, with New Zealand and Norway at the highest values (0.93) and Ireland and Luxembourg at the lowest (0.30). In terms of energy efficiency, Iceland and Greece demonstrated top scores (0.99), while Ireland had the lowest efficiency at 0.34. Specifically, Austria, Australia, Portugal, and Spain had energy intensity values between 0.70 and 0.80, whereas the UK, Sweden, Germany, and the USA had values between 0.40 and 0.50. Detailed efficiency scores reveal

Table 2. Energy Intensity, Energy Efficiency and Environmental Index

Country	Energy Intensity	Energy Efficiency	Environmental Index
Australia	0.72	0.74	0.65
Austria	0.74	0.74	0.65
Belgium	0.62	0.63	0.54
Canada	0.62	0.71	0.62
Chile	0.69	0.69	0.60
Denmark	0.50	0.50	0.41
Finland	0.58	0.56	0.47
France	0.51	0.48	0.39
Germany	0.46	0.49	0.62
Greece	0.84	0.99	0.93
Hungary	0.59	0.58	0.51
Iceland	0.89	0.99	0.97
Ireland	0.30	0.34	0.27
Israel	0.71	0.83	0.76
Italy	0.68	0.63	0.56
Japan	0.53	0.55	0.48
Korea	0.70	0.52	0.45
Luxembourg	0.30	0.37	0.30
Mexico	0.90	0.70	0.62
Netherlands	0.57	0.78	0.71
New Zealand	0.93	0.42	0.64
Norway	0.93	0.65	0.57
Poland	0.36	0.36	0.28
Portugal	0.84	0.95	0.87
Spain	0.89	0.41	0.62
Sweden	0.45	0.46	0.37
Switzerland	0.67	0.72	0.63
Turkey	0.69	0.91	0.82
UK	0.40	0.47	0.38
USA	0.40	0.43	0.34

Australia, Austria, Mexico, and Switzerland scoring between 0.70 and 0.80, while Germany, Sweden, the UK, and the USA ranged from 0.40 to 0.50. Italy's high energy costs have encouraged conservation, while Iceland's power-intensive manufacturing has increased its energy intensity. Over the last two decades, decreasing energy intensity has aligned with improvements in energy efficiency, providing both environmental and economic advantages. Although historically higher in transition economies than in industrialized ones, energy intensity has sharply declined since the start of these countries' economic transitions.

Table 3. Summary Statistics of GHG Emission (Tons of CO_2 Equivalent Thousand)

Sum	239719948.2
Mean	6658887.45
Maximum	104703444
Minimum	65159.976

Significant differences in energy efficiency and structural economic shifts have been observed across OECD countries. Between 2000 and 2015, 24 out of 30 OECD countries saw reductions in average energy intensity thanks to energy efficiency improvements and industrial activity shifts. Countries such as Germany, Ireland, Iceland, the Netherlands, Canada, Japan, Luxembourg, the UK, and the USA achieved these reductions through structural shifts toward less energy-intensive activities. In contrast, rising energy intensity in Israel, Portugal, and New Zealand stemmed from their reallocation of energy-intensive industries. While Spain has seen limited structural improvements, nations like Israel, Greece, Iceland, and Turkey demonstrated gains in energy efficiency. Higher GDP growth rates are generally associated with increased greenhouse gas emissions, particularly in Australia, Canada, Korea, and Poland. At the same time, this relationship appears weaker in countries such as Israel, the Netherlands, New Zealand, Norway, and Denmark.

As shown in Table 3, total greenhouse gas emissions across OECD countries reached 239,719,948.2 units between 2000 and 2015, with values ranging from a high of 104,703,444 to a low of 65,159.976 and an average of 6,658,887.45. Emissions and energy costs are generally reduced by increased renewable energy use; for instance, Japan's limited domestic oil and gas resources make it heavily reliant on imports, potentially driving economic growth alongside increased GHG emissions. Germany, meanwhile, is shifting its energy demand towards renewables and supporting cross-border renewable energy trade. Improving energy efficiency can help reduce CO_2 emissions from energy consumption, a critical approach to mitigating climate change impacts. Balancing economic development with environmental sustainability remains a priority, with many countries, including Australia, Japan, Germany, and Sweden, working towards decoupling economic growth from energy consumption. Absolute decoupling, particularly through reduced fossil fuel dependence, effectively alleviates environmental pressures (Wu *et al*., 2018). Enhanced energy efficiency, particularly when linked to renewable energy, offers a cost-effective path toward reducing CO_2 emissions.

3.2. *Sensitivity analysis*

Various uncertainty factors may affect the results when solving several linear programming models. First, the best practice frontier, developed from attainable entities, estimates the true frontier but is subject to potential variations due to sampling. Although bootstrap methods can help reduce uncertainty by assessing sample variation within the original dataset, it is important to note that constructing the best practice frontier for environmental efficiency differs significantly from frontiers in productivity and efficiency analyses. One common approach to developing environmental efficiency involves a cross-sectional study examining performance over time. This framework allows for new observations across comparable entities at different intervals, thereby refining the frontier for environmental efficiency evaluation.

While variation and sampling uncertainty in the obtained frontier is not the primary focus of this study, ensuring data accuracy in creating a new dataset is crucial for managing these factors. Regarding CO_2 data, as Zhou *et al*. (2012) observed, data accuracy and associated variation complicate the metrics of environmental efficiency assessment. Nevertheless, the sensitivity of the proposed DEA methodology concerning data changes can be theoretically evaluated. This study performs a sensitivity analysis of environmental efficiency measurements, examining observation changes. Data adjustments for all observations are made within a ±10% range to achieve this. By generating random values within the interval [−10%, 10%], we produced 20 datasets for OECD countries, enabling environmental efficiency measurements across these datasets.

Using the 20 simulated datasets, we computed the average environmental efficiency and its standard deviation to evaluate variation in the newly developed dataset. Results indicate that within the tested uncertainty range, each OECD country's average values of environmental efficiency metrics are largely stable. This limited effect of data uncertainty and variation suggests that the standard deviation of the average environmental efficiency values remains minor, as shown in Figure 1. Thus, the results appear reliable and robust,

Figure 1. Original and Newly Simulated Values

with average efficiency values remaining relatively insensitive to moderate variations in data accuracy.

To examine the distribution of environmental efficiency values, significant fluctuations appeared only with higher data uncertainty. Ensuring data accuracy is critical, and comparing environmental efficiency values from the original dataset with those from newly simulated datasets is essential for sensitivity analysis. Figure 1 displays few noticeable changes, especially in the median and range of efficiency measurements, which indicates the model's insensitivity and reliable accuracy when using a substantial sample size. Minimal changes in environmental efficiency values and low standard deviation under data uncertainty demonstrate resilience, supporting the robustness of the best practice frontier under data accuracy fluctuations. This methodological approach effectively addresses data irregularities, such as numerous zero values, and adheres to desired index number properties, confirming the robustness of these results.

4. Conclusion and Policy Implications

This study examined VRS and NIRS environmental DEA methodologies, where outputs maintain weak disposability. Using a framework grounded in nonradial DEA techniques, the analysis assessed energy security and environmental efficiency. The assessment revealed energy consumption values across OECD countries ranging from 14,462.19 Israel to 1,841.08 in Chile. In terms of primary energy supply, Luxembourg registered the highest supply at 482.79 million tons, while Norway had the lowest at 4.01 million tons. Renewable energy consumption also varied widely, with Iceland leading at 77.03%, followed by Norway (57.77%), Sweden (53.25%), Finland (43.24%), and Chile (24.88%), while Korea and Israel showed the lowest renewable shares at 2.71% and 3.71%, respectively. The per capita GHG emissions also fluctuated, with Australia at the highest (24.61 kg per capita) and the Netherlands at the lowest (5.28 kg per capita). In energy efficiency, Iceland and Greece achieved the top scores of 0.99, whereas Ireland was at the lower end with a score of 0.34. Energy intensity values showed that Austria, Australia, Portugal, and Spain scored 0.70 and 0.80, while the UK, Sweden, Germany, and the USA registered between 0.40 and 0.50. Detailed efficiency scores reveal that Australia, Austria, Mexico, and Switzerland achieved values from 0.70 to 0.80, whereas Germany, Sweden, the UK, and the USA had values from 0.40 to 0.50. These findings offer actionable policy insights for governments and decision-makers. Key recommendations are outlined below.

To facilitate a low-carbon transition, OECD countries should implement carbon pricing mechanisms, such as carbon taxes or cap-and-trade, to make greenhouse gas emissions costly and incentivize businesses toward cleaner energy solutions. Additionally, reinforcing Renewable Portfolio Standards (RPS) can drive utilities to achieve specified renewable energy targets, helping to replace fossil fuels with sustainable alternatives systematically. Supporting advanced technologies like energy storage, grid modernization, and carbon capture. Financial incentives for these technologies would help stabilize renewable energy integration and reduce emissions in high-impact sectors like manufacturing. Similarly, stricter energy efficiency standards across buildings, appliances, and vehicles, supported by rebates and tax incentives, can reduce overall energy consumption, aligning economic activities with environmental goals. Green procurement policies prioritizing sustainable suppliers can further push the private sector toward eco-friendly practices. Meanwhile, green financing instruments, such as green bonds and sustainability-linked loans, could lower financing costs for eco-friendly projects, with public institutions playing a pivotal role in facilitating access to capital. Expanding subsidies and tax credits for renewable energy adoption — especially for solar, wind, and geothermal projects — can make clean energy more accessible. Decentralized renewable systems, like community solar microgrids, should be encouraged through grants and low-interest loans to enhance local energy security, particularly in remote areas. Electrification incentives for high-emission sectors, like transportation, industrial heating, and investment in EV infrastructure, are also essential for lowering carbon emissions. Finally, OECD nations should deepen regional energy cooperation through shared infrastructure and energy trade agreements to create an integrated, resilient, and efficient energy network that benefits from each country's resources and capacities.

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References

Bang, Y, Y Hong, NJ Sung, D Lee and SR Lim (2018). Comparative assessment of solar photovoltaic panels based on metal-derived hazardous waste, resource depletion, and toxicity potentials. *International Journal of Green Energy,* 15(10), 550–557, https://doi.org/10.1080/15435075.2018.1505618.

Benromdhane, SA (2015). Energy efficiency through integrated environmental management. *Environmental Science and Pollution Research,* 22(10), 7973–7979, https://doi.org/10.1007/s11356-015-4424-8.

Branger, F and P Quirion (2015). Reaping the carbon rent: Abatement and overallocation profits in the European cement industry, insights from an LMDI decomposition analysis. *Energy Economics,* 47, 189–205, https://doi.org/10.1016d.eneco.2014.11.008.

Bujang, AS, CJ Bern and TJ Brumm (2016). Summary of energy demand and renewable energy policies in Malaysia. *Renewable and Sustainable Energy Reviews,* 53, 1459–1467, https://doi.org/10.1016/j.rser.2015.09.047.

Carstensen, J and M Lindegarth (2016). Confidence in ecological indicators: A framework for quantifying uncertainty components from monitoring data. *Ecological Indicators,* 67, 306–317, https://doi.org/10.1016Zj.ecolind.2016.03.002.

Charnes, A and WW Cooper (1984). Preface to topics in data envelopment analysis. *Annals of Operations Research,* 2(1), 59–94, https://doi.org/10.1007/BF01874733.

Charnes, A, WW Cooper, AY Lewin and LM Seiford (1994). *Introduction. In Data Envelopment Analysis: Theory, Methodology, and Applications. Igarss 2014,* https://doi.org/10.1007/s13398-014-0173-7.2.

Chen, Y and JT Xu (2018). An assessment of energy efficiency based on environmental constraints and its influencing factors in China. *Environmental Science and Pollution Research*, pp. 1–14, https://doi.org/10.1007/s11356-018-1912-7.

Egilmez, G, S Gumus, M Kucukvar and O Tatari (2016). A fuzzy data envelopment analysis framework for dealing with uncertainty impacts of input-output life cycle assessment models on eco-efficiency assessment. *Journal of Cleaner Production,* 129, 622–636, https://doi.org/10.1016/j.jclepro.2016.03.111.

Egilmez, G, M Kucukvar and O Tatari (2013). Sustainability assessment of U.S. manufacturing sectors: An economic input output-based frontier approach. *Journal of Cleaner Production*, 53, 91–102, https://doi.org/10.1016/j.jclepro.2013.03.037.

Färe, R, D-W Nohb, W Weber and S Grosskopf (2005). Characteristics of a polluting technology: Theory and practice. *Journal of Econometrics,* 126(2), 469–492, https://doi.org/10.1016/j.jeconom.2004.05.010.

Färe, R, S Grosskopf, CAK Lovell and C Pasurka (1989). Multilateral productivity comparisons when some outputs are undesirable: A nonparametric approach. *The Review of Economics and Statistics,* 71(1), 90–98, https://doi.org/10.2307/1928055.

Färe, R and S Grosskopf (2000). Research note: Decomposing technical efficiency with care. *Management Science,* 46(1), 167, https://doi.org/10.1287/mnsc.46.L167.15125.

Färe, R and S Grosskopf (1994). Estimation of returns to scale using data envelopment analysis: A comment. *European Journal of Operational Research*, 79(2), 379–382, https://doi.org/10.1016/0377-2217(94)90366-2.

Färe, R and S Grosskopf (1997). Intertemporal production frontiers: With dynamic DEA. *Journal of the Operational Research Society,* 48(6), 656–656, https://doi.org/10.1057/palgrave.jors.2600779.

Färe, R and S Grosskopf (2004). Modeling undesirable factors in efficiency evaluation: Comment. In *European Journal of Operational Research,* 157, 242–245, https://doi.org/10.1016/S0377-2217(03)00191-7.

Färe, R and J Logan (1983). The rate-of-return regulated firm: Cost and production duality. *The Bell Journal of Economics and Management Science,* 14(1), 405–414, https://doi.org/10.2307/3003642.

Färe, R and K Lovell (1978). The measurement of efficiency of production. *Journal of Economic Theory,* 19, 150–162, https://doi.org/10.3390/ijms13056204.

Fleifle, A, O Saavedra, C Yoshimura, M Elzeir and A Tawfik (2014). Optimization of integrated water quality management for agricultural efficiency and environmental conservation. *Environmental Science and Pollution Research,* 21(13), 8095–8111, https://doi.org/10.1007/s11356-014-2712-3.

Guo, J, Y-J Zhang and K-B Zhang (2018). The key sectors for energy conservation and carbon emissions reduction in China: Evidence from the input-output method. *Journal of Cleaner Production,* 179, 180–190, https://doi.org/10.1016d.jclepro.2018.01.080.

Hassan, K and R Salim (2015). Population ageing, Income growth and CO_2 emission: Empirical evidence from high income oecd countries. *Journal of Economic Studies*, 42(1), https://doi.org/10.1108/JES-04-2013-0046.

Ikram, M, A Mahmoudi, SZA Shah and M Mohsin (2019). Forecasting number of ISO 14001 certifications of selected countries: Application of even GM (1,1), DGM, and NDGM models. *Environmental Science and Pollution Research,* https://doi.org/10.1007/s11356-019-04534-2.

Ikram, M, P Zhou, SAA Shah and GQ Liu (2019). Do environmental management systems help improve corporate sustainable development? Evidence from manufacturing companies in

Pakistan. *Journal of Cleaner Production,* 226, 628–641, https://doi.org/10.1016/j.jclepro.2019.03.265.

Jing, Q, H Bai, W Luo, B Cai and H Xu (2018). A top-bottom method for city-scale energy-related CO_2 estimation: A case study of 41 Chinese cities. *Journal of Cleaner Production*, 202, 444–455, https://doi.org/10.1016/JJCLEPRO.2018.08.179.

Kolodko, GW (2018). *Emerging Market Economies.* Routledge, https://doi.org/10.4324/9781315199382.

Mohsin, M, AK Rasheed and R Saidur (2018). Economic viability and production capacity of wind generated renewable hydrogen. *International Journal of Hydrogen Energy*, https://doi.org/10.1016/j.ijhydene.2017.12.113.

Mohsin, M, J Zhang, R Saidur, H Sun and SM Sait (2019). Economic assessment and ranking of wind power potential using fuzzy-TOPSIS approach. *Environmental Science and Pollution Research,* https://doi.org/10.1007/s11356-019-05564-6.

Mohsin, M, P Zhou, N Iqbal and SAA Shah (2018). Assessing oil supply security of South Asia. *Energy,* 155, 438–447, https://doi.org/10.1016/J.ENERGY.2018.04.116.

Molinos-Senante, M, R Sala-Garrido and M Lafuente (2015). The role of environmental variables on the efficiency of water and sewerage companies: A case study of Chile. *Environmental Science and Pollution Research,* 22(13), 10242–10253, https://doi.org/10.1007/s11356-015-4225-0.

Mollahosseini, A, SA Hosseini, M Jabbari, A Figoli and A Rahimpour (2017). Renewable energy management and market in Iran: A holistic review on current state and future demands. *Renewable and Sustainable Energy Reviews*, https://doi.org/10.1016/j.rser.2017.05.236.

Nejat, P, F Jomehzadeh, MM Taheri, M Gohari and MZ Muhd (2015). A global review of energy consumption, CO_2 emissions and policy in the residential sector (with an overview of the top ten CO_2 emitting countries). *Renewable and Sustainable Energy Reviews,* 43, 843–862, https://doi.org/10.1016/j.rser.2014.11.066.

Olivier, JGJ, G Janssens-Maenhout, M Muntean and JAHW Peters (2016). *Trends in Global* CO_2 *Emissions: 2016 Report. PBL Netherlands Environmental Assessment Agency & European Commission's Joint Research Centre (JRC).*

Ouyang, X and B Lin (2014). Impacts of increasing renewable energy subsidies and phasing out fossil fuel subsidies in China. *Renewable and Sustainable Energy Reviews*, 37, 933–942, https://doi.org/10.1016/j.rser.2014.05.013.

Perez, V, F Guerrero, M Gonzalez, F Perez and R Caballero (2013). Composite indicator for the assessment of sustainability: The case of Cuban nature-based tourism destinations. *Ecological Indicators,* 29, 316–324, https://doi.org/10.1016d.ecolind.2012.12.027.

Rashidi, K and R Farzipoor Saen (2015). Measuring eco-efficiency based on green indicators and potentials in energy saving and undesirable output abatement. *Energy Economics*, 50, 18–26, https://doi.org/10.1016Zj.eneco.2015.04.018.

Rogge, N (2012). Undesirable specialization in the construction of composite policy indicators: The environmental performance index. *Ecological Indicators,* 23, 143–154, https://doi.org/10.1016/j.ecolind.2012.03.020.

Scheel, H (2001). Undesirable outputs in efficiency valuations. *Omega,* 132(4), 400–410, https://doi.org/10.1016/S0377-2217(00)00160-0.

Sueyoshi, T and M Goto (2015). DEA environmental assessment in time horizon: Radial approach for Malmquist index measurement on petroleum companies. *Energy Economics,* 51, 329–345, https://doi.org/10.1016Aj.eneco.2015.07.010.

Sueyoshi, T and D Wang (2018). DEA environmental assessment on US petroleum industry: Non-radial approach with translation invariance in time horizon. *Energy Economics*, 72, 276–289, https://doi.org/10.1016/j.eneco.2018.02.003.

Sueyoshi, T and Y Yuan (2017). Social sustainability measured by intermediate approach for DEA environmental assessment: Chinese regional planning for economic development and pollution prevention. *Energy Economics,* 66, 154–166, https://doi.org/10.1016/j.eneco.2017.06.008.

Sun, H, Y Geng, L Hu, L Shi and T Xu (2018). Measuring China's new energy vehicle patents: A social network analysis approach. *Energy,* 153, 685–693, https://doi.org/10.1016/j.energy.2018.04.077.

Sun, H, T Gulzara, M Haris and M Mohsin (2019a). Evaluating the environmental effects of economic openness: Evidence from SAARC countries. *Environmental Science and Pollution Research,* https://doi.org/10.1007/s11356-019-05750-6.

Sun, H, A Samuel, Y Geng, K Fang and C Joshua (2019b). Trade openness and carbon emissions: Evidence from belt and road countries. *Sustainability,* https://doi.org/10.3390/su11092682.

Sun, M, C Gao and B Shen (2014). Quantifying China's oil import risks and the impact on the national economy. *Energy Policy,* 67, 605–611, https://doi.org/10.1016/j.enpol.2013.12.061.

Taghizadeh-Hesary, F, E Rasoulinezhadb and N Yoshino (2019). Energy and food security: Linkages through price volatility. *Energy Policy*, 128, 796–806.

Taghizadeh-Hesary, F and N Yoshino (2015). Macroeconomic effects of oil price fluctuations on emerging and developed economies in a model incorporating monetary variables. *Economic Policy Energy Environment,* 2, 51–75, https://doi.org/10.3280/EFE2015-002005.

Taghizadeh-Hesary, F and N Yoshino (2016a). Monetary policy, oil prices and the real macroeconomic variables: An empirical survey on China, Japan and the United States. *China International Journal*, 14, 46–69.

Taghizadeh-Hesary, F, N Yoshino, G Abdoli and A Farzinvash (2013). An estimation of the impact of oil shocks on crude oil exporting economies and their trade partners. *Frontiers of Economics in China,* 8(4), 571–591, https://doi.org/10.3868/s060-002-013-0029-3.

Taghizadeh-Hesary, F, E Rasoulinezhad and Y Kobayashi (2016b). Oil price fluctuations and oil consuming sectors: An empirical analysis of Japan. *Economics of Energy & Environmental Policy,* 2(19), 33–35, https://doi.org/10.3280/EFE2016-002003.

Taghizadeh-Hesary, F, N Yoshino, MMH Abadi and R Farboudmanesh (2016c). The response of macro variables of emerging and developed oil importers to oil price movements. *Journal of the Asia Pacific Economy,* 21(1), 91–102, https://doi.org/10.1080/13547860.2015.1057955.

Taghizadeh-Hesary, F, N Yoshino and Y Inagaki (2018). Empirical analysis of factors influencing the price of solar modules. *International Journal of Energy Sector Management,* https://doi.org/10.1108/IJESM-05-2018-0005.

Vidadili, N, E Suleymanov, C Bulut and C Mahmudlu (2017). Transition to renewable energy and sustainable energy development in Azerbaijan. *Renewable and Sustainable Energy Reviews,* https://doi.org/10.1016/j.rser.2017.05.168.

Vinci, S, R Boampong, MA Phillips and C Cader (2017). Nigerian Electricity Regulation Commission, Ministry of Energy, Energy access outlook 2017: From poverty to prosperity. *Energy Procedia,* 94(March), 144, https://doi.org/10.1787/9789264285569-en.

Wang, Q and R Li (2016). Impact of cheaper oil on economic system and climate change: A SWOT analysis. *Renewable and Sustainable Energy Reviews*, https://doi.org/10.1016/j.rser.2015.10.087.

World Development Report (2015). Mind, society, and behavior (Vols. 1 of 2). World development report | World development indicators. Washington, DC: World Bank Group. http://documents.worldbank.org/curated/en/645741468339541646.

Wu, Y, KW Chau, W Lu, L Shen, C Shuai and J Chen (2018). Decoupling relationship between economic output and carbon emission in the Chinese construction industry. *Environmental Impact Assessment Review,* https://doi.org/10.1016/j.eiar.2018.04.001.
Xie, Y, and Q Weng (2016). Detecting urban-scale dynamics of electricity consumption at Chinese cities using time-series DMSP-OLS (Defense Meteorological Satellite Program-Operational Linescan System) nighttime light imageries. *Energy,* 100, 177–189, https://doi.org/10.1016/j.energy.2016.01.058.
Yin, X, W Chen, J Eom, LE Clarke, SH Kim, PL Patel and GP Kyle (2015). China's transportation energy consumption and CO_2 emissions from a global perspective. *Energy Policy,* 82, 233–248, https://doi.org/10.1016Aj.enpol.2015.03.021.
Zhang, D, X Shi and Y Sheng (2015). Comprehensive measurement of energy market integration in East Asia: An application of dynamic principal component analysis. *Energy Economics,* 52, 299–305, https://doi.org/10.1016/j.eneco.2015.11.006.
Zhang, Y, Y Jin and B Shen (2018a). Measuring the energy saving and CO_2 emissions reduction potential under china's belt and road initiative. *Computational Economics,* https://doi.org/10.1007/s10614-018-9839-0.
Zhang, Y, Y Sun and J Huang (2018b). Energy efficiency, carbon emission performance, and technology gaps: Evidence from CDM project investment. *Energy Policy*, https://doi.org/10.1016/j.enpol.2017.12.056.
Zhou, P, BW Ang and KL Poh (2006). Comparing aggregating methods for constructing the composite environmental index: An objective measure. *Ecological Economics,* 59(3), 305–311, https://doi.org/10.1016/J.ECOLECON.2005.10.018.
Zhou, P, BW Ang and KL Poh (2008). A survey of data envelopment analysis in energy and environmental studies. *European Journal of Operational Research,* https://doi.org/10.1016/j.ejor.2007.04.042.
Zhou, P, BW Ang and H Wang (2012). Energy and CO_2 emission performance in electricity generation: A non-radial directional distance function approach. *European Journal of Operational Research,* 221(3), 625–635, https://doi.org/10.1016d.ejor.2012.04.022.
Zhou, P and LW Fan (2010). An extension to data envelopment analysis with preference structure for estimating overall inefficiency, 216(3), 812–818, https://doi.org/10.1016d.amc.2010.01.085.
Zhou, P, ZR Sun and DQ Zhou (2014). Optimal path for controlling CO_2 emissions in China: A perspective of efficiency analysis. *Energy Economics,* 45, 99–110, https://doi.org/10.1016/j.eneco.2014.06.019.