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RESEARCH ARTICLE

The dynamic analysis of renewable energy's contribution to the dimensions of sustainable development and energy security

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Abstract

In sustainable development, energy is critical in human activities and shapes a sustainable future. Thus, it is an unignorable element in human development. This paper analyzes the contributions of renewable energy sources (RES)'s to the economic, environmental, and social dimensions of sustainable development. Moreover, we add energy security as a possible fourth dimension into the analysis. For the sample size, we limit the countries members of the OECD and run generalized methods of moments for the period from 1995 to 2015. This method can produce efficient estimators under the problems of endogeneity, omitted-variable bias, measurement errors, and heteroscedastic residuals. According to the results, RES has a small reducing effect (−.007%) on output in the Cobb-Douglas production function for the economic dimension. We found that RES has a positive contribution to the environmental dimension and abates the level of carbon emission (−.093%). RES also confirms the inverted-U shape of environmental Kuznets curve. In the social dimension, RES improves human development and a 1% increase in RES consumption causes to .0045% increase in human development. In the last contribution, RES has a positive effect on sustainable energy supply security in the context of electricity generation (.032%). Although the effects of RES on the environment, social, and energy security are significant, they are limited. These limitations point to barriers that can be overcome over time. Our conclusions recommend that these effects might flourish with technical developments and political support in the long run. Furthermore, public awareness, rising income level, and economies of scale are also beneficial in this process. As a result, RES might be an excellent source for a sustainable future and development. Especially, RES might have remarkable contributions to the 7th, 11th, 12th, and 13th goals of sustainable development.

Keywords Sustainable development · Renewable energy sources · Energy security · Generalized methods of moments

Introduction

When a valuable system, object, process, or symbol is under the strong possibility of danger, we question the sustainability of these elements. Their existence is under threat, and/or qualities are declining seriously. And when the continuity of a being is in a risky situation, necessary steps must be taken to protect its presence (Sutton 2004). Many people started to prevent the extinction of species and destruction of the ecological balance, especially since the beginning of the 1970s. The sustainable development (SD) concept categorizes all these actions. In this vein, SD tries to ensure well-being for all humans in a friendly environment today and after (Klarin 2018). SD also insists that the next generations do not quickly achieve a sustainable future but must experience.

In this context, development is sustainable if it is economically efficient, socially inclusive, and ecologically balanced. The first and second criteria have been debated on economic development since the post-war period. But the third entered definition in the last decades (Romeiro 2012). These three are dimensions of SD, and they are accepted "systems." A sustainable economic system consists of durable goods and services, fulfilling pressing needs, reducing poverty, or ensuring equality (Ergil 1995). Countries use energy as the critical factor in their national development and the public's welfare. Energy improves living standards and quality of

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life. At the same time, increasing rates in energy consumption are the dominant factor in ecological problems such as global warming and environmental degradation. Thus, this consumption damages the planet and becomes a threat to the quality of life for future generations. At this point, the quandary for international communities is simultaneously guaranteeing the equitable global development and welfare of future and current generations (Minelli 2017).

Consequently, we constructed the paper as follows: the first section mentions the link between SD dimensions and renewables. Literature is the second section. The third section explains methodology and analysis. The last section includes the conclusion and policy suggestions.

Renewables and sustainable development

Renewable energy sources (RES)'s benefit in realizing sustainable development goals looks like mostly fossil energy sources. RES mainly gives the opportunity of being more environmentally friendly sources. Hence, they could be beneficial in mitigating global warming and climate change. Furthermore, they might assist the energy security issue by facilitating diversification of energy supply.

Sustainable development dimensions

In such systems, the economically sustainable system necessitates government and external debt at the manageable level, produces goods and services continuously, and avoids sector volatility damaging agricultural or industrial production (Harris 2000). In other words, the economic system must increase production levels, meet necessary needs, or reduce poverty and improve equality (Ergil 1995).

RES has critical economic advantages for achieving SD goals. One of these is to cause diminishing rates of import dependency throughout sources diversification. Mainly, developing countries depend on heavily producing countries for energy supply. Thus, the pressure on the balance of payments will also diminish with RES. Fossil/conventional sources lead to air, water, and soil pollution and health issues such as upper respiratory tract infection because of air pollution. Besides, fixing or treating harmful consequences necessitates an economic burden. It also contributes more to reducing the recovery cost of health and environmental degradation due to fossil fuel pollution from the production and consumption process. Moreover, de-centralized devices or off-grid installation might be efficient because of cost-effective and remote space use (Sawin et al. 2016; Anwar et al. 2021b).

In social sustainability, distributional equality (concerning resources), good social services such as health and education, gender equality, political accountability, and participation must exist for all (Harris 2000). A critical factor in social sustainability is how social values are described and what social capital is called. Values such as transparency, justice, stability, equality, well-being, health, and security will rise in this context. However, social sustainability can get its definition with the protection, presentation, and preservation of these values. This way includes human rights, conservation of diversity, the definition of health and security, and equality for intra-generational and inter-generational (Widok 2009).

The social gains of RES are very closely related to the economic return. One of them is employment growth. There might be new plant establishments for technological devices of RES. As a result, companies require additional workers for these plants. Furthermore, spare industry companies can hire local workers for device setup, spare parts, technical support, etc. More workers can get jobs or more income. Life quality and, thus, the well-being of households increase by higher income levels. Well-being level improves with the help of widespread access to electricity and reasonable energy end-use prices. A cleaner environment makes life more qualified with healthier individuals (Sawin et al. 2016; Schwerhoff and Sy 2017).

Off-grid solutions might have cost-effective implications for rural communities. Also, these solutions might have water-saving and productive usage samples in agricultural areas. Solar power systems can benefit watering systems and cause more productivity in agricultural implications. Increasing productivity leads to income growth, sensitivity reduction to the irregular rains, and decreased difficulties in working conditions for women. In summary, thanks to renewable resources, we can form modern and easily accessible sustainable energy and climate-resistant and ecologically protective infrastructure in rural areas (IRENA 2015).

Environmental sustainability (ES) focuses on a sustainable level of production (sources) and consumption (sinks) activities instead of high growth rates. ES gives importance to economic and social development goals, particularly "maintenance of natural capital." This maintenance is based on input/output functions. On the one hand, we can categorize inputs as the regenerative capacity for a natural system where resources refresh themselves within a lifespan. On the other hand, we classify outputs as a fallout of any actions or projects such as emissions. Inputs must be at a level compensating for the bad side effect of outputs (Goodland 1995).

RES (especially hydropower, wind power, and solar energy) could be an advantageous and robust alternative for the environment regarding a different energy need, particularly electricity production. This contribution results in a reduction in carbon emissions. The EU achieved a 15% for 2012–2013. Also, RES could benefit other hazardous gases (Sawin et al. 2016). Furthermore, RES requires less water in the pumping, desalination, and heating process and less ignition energy input than fossil sources. Power plants such as thermal reactors need massive water input for the cooling phase and produce polluted water output at the end of the process. Moreover, these reactors lead to water and solid pollution due to carbon emissions (IRENA 2015; Chien et al. 2021).

Before explaining the security contribution of RES, the connection between energy security and SD must be clear.

Energy security and SD

In the definition of International Energy Agency (2019), energy security is "the uninterrupted availability of energy sources at an affordable price." SD is "the idea that human societies must live and meet their needs without compromising the ability of future generations to meet their own needs" according to the definition of The Brundtland Report (1987) of G. Harlem (Brundtland 1987). Throughout the definition of these two key terms, we can see that energy is one of the critical elements of life, either as the production process of goods and services or consumption activities, and sustainable and environmentally friendly energy supply is essential for both concepts. Furthermore, sustainable development and energy security are closely connected topics if the connected points become apparent.

Von Hippel et al. (2010) state that SD must manage essential issues like human poverty, impoverishment of the environment, war possibility in all different spatial regions, the pressure of human rights, and wastage of human potential. RES has significant implications on energy security (SEC). Over and above, they argue that energy security, like sustainable development, tries to define economic, social, and environmental goals showing often evidence conflicting with each other. However, overpopulation growth, poor distribution of consumption and investment, misuse of technology, corruption, mismanagement, and lack of knowledge/power on the part of victims are driving forces, and they also affect energy security. There are some obstacles to overcome depending on the nature of RES and technological challenges. But beyond these issues, RES is a promising source for future generations in the security dimension. Possible contributions for security dimensions are connected to the properties of SEC. The Asia Pacific Energy Research Center Report (2007) collects these under the four "A": availability, accessibility, affordability, acceptability (Intharak et al. 2007).

Availability is the meaning of the physical existence of energy sources. The de-centralized renewable structure might increase the possibility of installation close to demand areas. *Accessibility* is related to geopolitical factors and securing energy supply to meet future demand growth. We must overcome barriers such as the possibility of a political instrument or physical weapons of energy. RES can benefit in this regard by making resource diversification. *Affordability* stands for low cost and reasonable price of energy. Conventional sources (CS) are far ahead in price because of technique level and energy generation cost. However, CS is a particularly suitable and efficient on-grid system. RES currently offers very feasible off-grid system solutions for rural and unsuitable regions while promising on-grid solutions in the future. *Acceptability* includes economic elements and environmental concerns, and social acceptance of plants. This issue focuses on environmental awareness about energy power plants. Locals do not think positively about thermal power stations because of air and water pollution. At this line, RES-related techniques as turbines/devices/plants must be in harmony with the region and friendly to the environment (Intharak et al. 2007; Kruyt et al. 2009; Erahman et al. 2016; Lucas et al. 2016).

In summary, renewables are directly or indirectly related to some SD targets in the context of energy security. Close-connected goals are affordable and clean energy (7), sustainable cities and communities (11), responsible consumption and production (12), and climate action (13). Indirect contributions for good health and well-being are (3) clean water and sanitation (6), life below water (14), and life on land (15) (United Nations Development Programme 2019).

Literature

Our goal is to investigate the linkages between economic, social, and environmental dimensions and energy security, probably as the fourth one with RES. As an input factor, the studies generally operate renewable energy consumption (REC), renewable electricity consumption (RELC), biomass consumption (BIOC), renewable combustible and waste consumption (RCW), combined heat and power generation (CHP), and renewable electricity production (RELP).

Impact of RES on GDP

As an input factor, energy is a significant factor promoting output and thus economic growth. Besides fossil energy sources (FES), RES have potential and also green sources. Our analysis focuses on RES as an input factor in production function (Cobb-Douglas). In this context, relevant studies mention the evaluation of possible contribution of RES with the help of to the Cobb-Douglas production function. In time series analysis, Amri (2017) runs ARDL for Algeria and finds an insignificant negative coefficient for the long run and insignificant positive coefficient for the short run. Min et al. (2019) searched combined heat and power generation (CHP) with the help of quantile regression for South Korea and detected the positive effect of CHP. They also imply that optimal CHP share must be 13.8% in output. Mehmood

(2021) investigates the link between REC and GDP for G11 countries for 1990–2019. He runs causality analysis and confirms the feedback effect between renewable and output level.

Moreover, most of the studies related to RES are interested in the economic growth and RES connection. Looking at these studies makes RES contribution more clear. Bilgili and Ozturk (2015) and Ozturk and Bilgili (2015) use ordinary least squares (OLS) and dynamic ordinary least squares (DOLS) for BIOC variable and find a positive effect for G7 and sub-Saharan African countries. Wesseh Jr and Lin (2016) operate RELC and reveal a theoretically suitable solution. Zafar et al. (2019) run full-modified OLS (FMOLS) with REC variable and depict the positive significant contribution of RES. Shahbaz et al. (2022) study on fiscal decentralization as a determinant of renewable usage and also search the correlation between REC and economic growth. They find REC causes to approximately 7% increase income. According to the Gyimah et al. (2022) declare the feedback effect between renewable and economic growth (EG). The indirect impact of REC is not significant; on the contrary, the overall impact is significant for Ghana. Wang et al. (2022) work with different income groups and their findings demonstrate that all income groups have threshold effects. Resource dependence and anti-corruption regulations take the role in these thresholds. As a result, REC effects positively income growth in high-income countries, the relationship between REC and EG is inconsistent for middle-income and U-shaped relationship is valid for the low-income countries. Mohsin et al. (2022) investigate the connection between RES and green economic growth for the ECOWAS. They employ Divisia envelope analysis (DEA) and demonstrate that a 1% increase in RES deployment leads to 3.2% improvement in green growth. Research and development activities also result a higher growth rates in green economy. The discouraging effect of RES is a finding of some papers; de Oliveira and Moutinho (2022) investigate and reveal that REC diminishes economic growth for BRICS countries. Furthermore, the interaction of economic-social or social-political globalization leads to a decrease in EG.

The studies of Menegaki (2011); Alper and Oguz (2016); Rafiq et al. (2016); Halicioglu and Ketenci (2018); Ali et al. (2020), and Wang et al. (2022) employ co-integration and causality analysis. Menegaki (2011), Alper and Oguz (2016), and Rafiq et al. (2016) detect that there is a positive effect of RES on GDP. Ali et al. (2020) find that politically full and partly free countries apply RES-led growth plans out of 100 countries. Furthermore, Halicioglu and Ketenci (2018) run autoregressive distributed lag (ARDL) and GMM and use the RELP variable. Results are heterogeneous so that co-integrated relationship is valid for some countries or not for others for EU15. In addition, fossil resources take a more significant share of electricity generation.

Investigating the multiple efficacies of renewable energy sources, Andini et al. (2019), in their study on Portugal for 1980–2015, investigate the macroeconomic effects of electric power generation projects of renewable resources in multiple ways. According to the structural vector autoregressive (SVAR) model, RES projects lead to product growth, reduce unemployment, play a positive role in import substitution in energy, and improve environmental conditions. Li et al. (2022) search RES's effect on ecological footprint at the expense of economic growth. The results show that RES mitigates ecological footprint (EF) gradually. RES also maintains growth-stimulating behavior globally. Saidi and Omri (2020) analyze both economic growth and emission with REC. The results show a bidirectional causality between REC and economic growth (EG) for both the long and short runs. Besides, this kind of relationship exists for REC and emission level is only for the short term.

Impact of RES on environment

A review of many research studies on the links between emissions and RES has concluded that RES diminishes emissions levels. Furthermore, lots of studies are mainly related to the link between EKC and renewables. On the environmental impact of RES and/or EKC, variables of the studies are different such as BIOC variable in Bilgili et al. (2016); RELP in Chen et al. (2019); RELC in Bélaïd and Youssef (2017), and REC variable in Ben Jebli et al. (2014); Baek (2016); Liu et al. (2017); Inglesi-Lotz and Dogan (2018); Khan et al. (2020); Vo et al. (2020); Anwar et al. (2021e); Yuping et al. (2021), and Zhang et al. (2021). The findings support the argument that RES contributes positively to environmental sustainability by reducing CO2 emissions except for Baek (2016) who finds that RES diminishes CO level in the short run only and is ineffective in the long run.

Ben Jebli et al. (2014)investigate the link between REC and emission in Central and South America. The findings demonstrate the bidirectional relationship between them in the long run. In addition, tourist arrivals and REC together help to fight for the reduction of emissions. Baek (2016) search the contribution of both nuclear and RES on mitigating emissions. While nuclear energy reduce emission level in all models and periods, RES is a significant parameter in the short run. Under the ARDL approach, RELC represents environmentally friendly solutions for Algeria in Bélaïd and Youssef (2017). The analysis of Liu et al. (2017) detects that long-run elasticities illustrate the reducing effect of RES on carbon emission in BRICS countries during 1992–2013. Inglesi-Lotz and Dogan (2018) employ DOLS method for sub-Saharan Africa from 1980 to 2011. They state that there is a long-run relationship among the variables and REC can be remedy to solve air pollution. In the context of consumption-based emission, RES is a critical component to fight environmental degradation in Khan et al. (2020). Vo et al. (2020) work with nine signatories of CPTPP countries and employ FMOLS and DOLS techniques. The results of analysis recognize heterogeneous findings for mitigating impact of REC.

Anwar et al. (2021e) focus and select Asian countries and investigate the efficiency of RES on emission level with three methods. They reveal the long-run diminishing effect of REC. Yuping et al. (2021) estimate both short- and long-term coefficients for Argentina. In the short run, RES is valid in the first models and mitigates environmental pollution. In the long run, RES is valid in all models and diminishes pollution for the period 1970–218. In the study of Zhang et al. (2021), non-parametric analysis results uncover the critical role of RE investment in reducing carbon emissions for China. Similarly, Chen et al. (2019) work with China and state that RELP is a critical component to decrease emission level for the period 1980–2014.

Empirical studies related to the link between RES and environment generally measure emission mitigating effect and the validity test of EKC. In emission focus studies, while most studies use total REC as a variable, some utilize sub-variables of REC. In this context, Bilgili et al. (2016) use wavelet analysis for the effect of BIOC on environment. They find that BIOS has diminishing effect on emission level for the USA in the long run.

Anwar et al. (2021a) search the impact of transportation investment on carbon emission for China and reveal that renewable energy integration into the transportation might reduce emission level produced by the sector. Anwar et al. (2021c) and Anwar and Malik (2021d) find similar findings for REC and also depict that technological innovation and institutional quality contribute positively to the environment for G7 countries. In a different perspective, Wang et al. (2021) analysis both RE scale and REC for 25 countries along the Belt and Road Initiative between 2005 and 2019 years. They depict that the RE scale affects the environment negatively concerning carbon emission, REC does positively. Related to sub-period studies, Dong et al. (2020) divide global financial crisis as pre (1995–2007) and post (2008–2015) period. However, they find the mitigating effect of REC; the effect is higher in post-financial crisis period than that in pre-period.

In addition to the emission-RES connections, many empirical papers work on the testing of EKC validity. We can list the related papers for the last three years such as Acheampong et al. (2019); Adams and Acheampong (2019); Nguyen and Kakinaka (2019); Sharif et al. (2019); Zafar et al. (2019); Akram et al. (2020); Dong et al. (2020); Khan et al. (2020); Ridzuan et al. (2020); Saidi and Omri (2020); Vo et al. (2020); Vural (2020); Anwar et al. (2021a, 2021b); Chien et al. (2021); Mehmood (2021); Wang et al. (2021); Zhang et al. (2021); Ehigiamusoe and Dogan (2022), and Wang et al. (2022). After the testing process, the shape of the curve might be U, inverted-U, N, inverted-N, linear positive, and linear negative. General and expected inference from the results is the confirmation of inverted-U shape EKC.

Impact of RES on human development

Scholars related to the social dimension, such as Pirlogea (2012), find that RES mitigates climate change and contributes to human development for several European Union countries. However, RE technologies and resource use are not detectable in this effect. Wang et al. (2018), in their analysis for Pakistan for the period 1990–2014, detect that the REC variable did not improve the level of human development and that higher income level also brought about a lower HDI value. Another finding is the positive contribution of emission level to the human development. In the analysis of Adekoya et al. (2021), MENA and Central America and Caribbean countries are the sample group of the study. They find that there are heterogeneous results for RES displaying strictly adverse effects, positive and insignificant, in the regions. Similar to Wang et al. (2018), there is a positive correlation between emission level and human development. This link might source from energy-driven emission level; and thus, more energy consumption leads to more developed life quality. Hashemizadeh et al. (2021) employ continuously updated bias-corrected and fully modified estimators for the countries in the G7. There is bidirectional causality between REC and non-REC with human development. For this reason, they imply on careful policy planning to encourage RES usage. Wang et al. (2021) ran the Driscoll-Kraay panel estimation from 1990 to 2016 and find stimulated human development by REC. Furthermore, while human development level becomes better, RES consumption increases. However, the joint effects of public debt and REC reduce the development level. In this context, arranging and limiting public debt but inciting RES deployment must be managed simultaneously.

Impact of RES on energy security

Most studies focus on energy security on possible energy generation scenarios of RES, and empirical research is scarce. In this context, Erdal (2015) investigated the effectiveness of the REC by creating Security Supply Index (ESI). She uses four indices to calculate the energy security supply index: import dependency index, intensity index, domestic production index, and a composite index. The results demonstrate that both primary energy supply and REC contribute positively to energy security. RES is also the best alternative for energy import dependency because of friendly to the environment. On the other hand, Marques et al. (2018) investigate the substitution possibility of RES for fossil fuels in energy security. They look at the electricity generation-RELP connection. While solar cells and hydropower have substitution effects, wind power does not have substitute power. Furthermore, they cannot meet electricity generation without fossil fuel recharge due to the discrete nature of RES. In contrast, flexible and controllable fossil fuels support RES in electricity generation.

In light of all the evaluations, the present paper contributes literature in the four contexts. Multiple analysis of SD dimensions is rarely in scientific papers; one or two dimensions are the general focal point. The second contribution is related to the connection between renewable and human development. The third contribution is energy security as a fourth dimension for SD and investigating the link between renewable and energy security. The last vital aspects are the technique of analysis. The generalized methods of moments (GMM) gives a flexible environment for the data and estimation.

Methodology and estimation results

The data section covers variable source information and descriptive statistics. Methodology explains generalized methods of moments.

Data

Our data includes 36 OECD countries (N) and 21 yearly time series (T). Timespan ranges from 1995 to 2015. Data is obtained from The World Bank (2019); British Petroleum (2018), and The United Nations Development Programme (2018). Variables are included in the analysis with their logarithmic values. Table 1 explains symbols, descriptions, and sources of the variables and Table 2 gives descriptive statistics.

In the analysis, we make four models in the sake of measuring renewables effectiveness. The equations of four models are as follows:

i. Economic dimension: Cobb-Douglas production function

$$lgdp_{it} = \beta_0 + \beta_1 L.lgdp_{it} + \beta_2 lgcf_{it} + \beta_3 lwfp_{it} + \beta_4 lfec_{it} + \beta_5 lrec_{it} + u_{it} \tag{1}$$

ii. Environmental dimension: carbon emission function

$$\begin{aligned} lcop_{it} = {} & \beta_0 + \beta_1 L.lcop_{it} + \beta_2 lfec_{it} + \beta_3 L.lfec_{it} \\ & + \beta_4 lrec_{it} + \beta_5 L.lrec_{it} + \beta_6 lto_{it} + \beta_7 L.lto_{it} \\ & + \beta_8 L.lgdp_{it} + \beta_9 L.lgdp2_{it} + \beta_{10} lurb_{it} + u_{it} \end{aligned} \tag{2}$$

iii. Social dimension: human development function

$$\begin{aligned} lhdi_{it} = {} & \beta_0 + \beta_1 L.lhdi_{it} + \beta_2 lrec_{it} + \beta_3 L.lrec_{it} \\ & + \beta_4 lfec_{it} + \beta_5 L.lfec_{it} + \beta_6 lgcf_{it} + \beta_7 lgdp_{it} \\ & + \beta_8 lcop_{it} + \beta_9 lwfp_{it} + \beta_{10} lurb_{it} + u_{it} \end{aligned} \tag{3}$$

iv. Energy security dimension: energy security function

$$\begin{aligned} lelg_{it} = {} & \beta_0 + \beta_1 L.lelg_{it} + \beta_2 lfep_{it} + \beta_3 L.lfep_{it} \\ & + \beta_4 lrep_{it} + \beta_5 lepc_{it} + \beta_6 L.lepc_{it} + \beta_7 lto_{it} \\ & + \beta_8 lins_{it} + \beta_9 lurb_{it} + u_{it} \end{aligned} \tag{4}$$

Table 1 Description of variables in the model

Variable	Abbr.	Unit	Source
Gross domestic product	lgdp	per 2010 $	WB
Gross fixed capital accumulation	lgcf	% GDP	WB
Labor force participation rate	lwfp	15–64/population	WB
Urban population	lurb	% Total population	WB
Total trade volume	lto	Trade volume/GDP	WB
Human Development Index	lhdi	0–1	UNDP
Carbon emission intensity	lcop	m^3 per capita	WB
Energy consumption intensity	lins	TEC/GDP	WB
Renewable energy consumption	lrec	% TEC	WB
Fossil energy consumption	lfec	% TEC	WB
Electrical power consumption	lepc	per capita kWh	WB
Electricity generation	lelg	gWh	BP
RES electric power generation (exc. hydro)	lrep	% TEP	WB
Fossil electric power generation	lfep	% TEP	WB

Table 2 Descriptive statistics

Variable	T*N	Mean	Median	Min.	Max.	Std. Dev.	Skewness	Kurtosis	Jarque-Bera	Prob.
lgdp	755	10.24	10.46	8.54	11.63	.6866	−.4147	2.2683	38.4875	0.0000
lgcf	756	3.14	3.14	2.28	3.73	.1802	−.0872	4.4506	67.2402	0.0000
lwfp	756	4.26	4.27	3.88	4.48	.0998	−.7623	4.1684	116.2290	0.0000
lurb	756	4.32	4.35	3.92	4.58	.1539	−.6052	2.7023	48.9480	0.0000
lto	756	4.35	4.29	2.81	6.02	.5138	.0886	3.5454	10.3600	0.0056
lhdi	756	−.17	−.15	−.50	−.05	.0745	−1.2864	4.9106	323.4946	0.0000
lcop	720	2.08	2.10	.99	3.21	.4540	.0174	2.6833	3.0447	0.2182
lins	756	1.63	1.56	.67	2.96	.3644	.7507	3.7807	90.2030	0.0000
lrec	756	2.39	2.41	−.81	4.35	1.0238	−.4833	2.8995	29.7488	0.0000
lfec	754	4.25	4.38	2.33	4.59	.3783	−2.4572	10.0587	2324.128	0.0000
lepc	720	8.81	8.78	7.11	10.91	.6517	.2485	3.4400	13.2199	0.0013
lelg	756	11.34	11.22	6.96	15.30	1.5558	.0040	3.1199	0.4550	0.7965
lrep	731	7.70	8.00	.00	12.65	2.1909	−.6555	3.4643	58.9127	0.0000
lfep	754	10.23	10.45	.69	14.98	2.4040	−1.2982	6.3745	569.5371	0.0000

Methodology

Moments representing distributional properties are essential in the estimation process, and related models are classified according to these properties. If $\hat{\beta}$ estimator minimizes or maximizes a scalar objective function under a specific constraint, it is called extremum estimator. The class of these estimators is least squares (linear or nonlinear), generalized method of moments (linear or nonlinear), and maximum likelihood (Hayashi 2000). GMM, unlike maximum probability, does not precisely require defining the distribution's model and shape. GMM only requires defining the set of moment conditions that the model must meet (Harris and Matyas 1999) and thus becomes an alternative method (Nielsen 2005).

In classical regression models, zero conditional mean is a critical assumption for valid estimations. Three situations violate endogeneity (simultaneous determination of regressors and regressand), omitted-variable bias, and measurement errors (Baum and Christopher 2006). GMM is an efficient technique and produces robust estimation against heteroskedastic residuals. Beyond these advantages, if T is smaller than N in panel models and if the independent variables and endogenous variables are weak exogenous, GMM can present flexible options (Hayakawa 2019). Lastly, GMM is a strong estimation technique that does not require an underlying process and, thus, distributional assumptions (Greene 2012).

If θ represents a parameter vector where θ_0 is a real value, moment conditions must satisfy $E(f(x_t, \theta_0)) = 0$ (Nielsen, 2005). But there is no $\hat{\theta}_T$ vector making equal to 0. However, a vector that gets as close to 0 as possible can exist if the criterion function tries to minimize the distance to 0 (Harris and Matyas 1999);

$$Q_T(\theta) = f_T(\theta)' W_T f_T(\theta) \tag{5}$$

Where W_T is WM, the moments depend on their importance. WM is such an optimal matrix making it possible to produce a good estimator and the inverse value of asymptotic variance. It gives small weight to moments with significant variance and high weight to moments with minor variance. Therefore, the generated estimator can be an efficient GMM estimator (Nielsen 2005). In such models, a dynamic (or auto-regressive) panel model with one-lagged dependent variable, error terms might contain unobservable individual effects μ_i (Baltagi 2008; Blundell et al. 2001)

$$y_{it} = \delta y_{i,t-1} + \beta' x_{it} + u_{it} \tag{6}$$

$$u_{it} = \mu_i + v_{it} \tag{7}$$

μ_i indicates time-invariant characteristics in time and v_{it} showing random noise represents remain errors (Baltagi 2008; Harris and Matyas 1999). When μ_i is connected to X_{it}, there might exist three possible explanatory variables; endogenous, weak exogenous or predetermined, and strictly exogenous (Blundell et al. 2001). Except strictly exogenous, the assumption of uncorrelated error terms is violated. Estimation results might be biased and inconsistent, and moment conditions are not valid. In this circumstance, IV can satisfy $E[Z_i' u_i] = 0$ (Bound et al. 1995; Harris and Matyas 1999). Variables in Z must be correlated with variables in the matrix of X but not with each other (multi-collinearity) (Johnston and Dinardo 1997; Stata Base Reference Manual 2012).

Based on $f_T(\theta) = \sum_{i=1}^{N} Z_i' u_i$, the GMM estimator fulfilling these new moment conditions tries to minimize the criterion function in Eq. 5, and the estimator is as follows (Baum and Christopher 2006; Cameron and Trivedi 2005):

$$\hat{\beta}_{PGMM} = (X'ZWZ'X)^{-1}X'ZWZ'y \tag{8}$$

During the process of Z construction, taking the first difference of the variable can eliminate individual-specific effects and provide the uncorrelated error terms with the variables in X. This difference-GMM technique produces a consistent IV estimator in the assumption of “weak exogeneity.” But in a dynamic panel model with relatively significant autoregressive (AR) parameters and short times series data, this might cause substantial sample bias and poor precision. In this situation, one-lagged series might provide weak instruments for the first-differenced values. Arellano and Bover (1995) recommend an augmented GMM estimator. In this estimator, one-lagged variables with levels are in the first-differenced equation, and variables with levels are in the lagged-differenced equation (Blundell and Bond 1998). This method is the system GMM, where We specify the process X_{it} follows to know under what conditions Δy_{it} ve Δx_{it} are not correlated with μ_i (Blundell et al. 2001).

Estimation results

According to the results (Table 3), our first model measures in the context of the Cobb-Douglas production function for the economic dimension of SD. As inputs labor, capital accumulation, fossil, and renewable energy sources. L.lgdp is the most influential variable among others. The previous value of output level is the most inducing factor of itself. The coefficients of lwfp and lgcf are appropriate to the theory, and they contribute positively to the output level. lgcf has a more significant effect than lwfp. A 1% increase in lgcf and lwfp cause approximately 0.22% and 0.15% rise in lgdp. Labor and capital accumulation are the main drivers of production activities. Throughout technical innovations, it is expected that lgcf is more effective than lwfp.

When we look at energy sources as input, lfec has negative and statistically insignificant coefficients. On the other side, lrec has a diminishing impact on the output level same as the finding of de Oliveira and Moutinho (2022). When we compare the coefficients, −0.0072 value of lrec is smaller than −0.1370 and −0.1122 of theirs. Negative value might exist by dint of the lack incentive mechanism and/or high energy production cost. Besides this finding, the contribution of RES is insignificant for Algeria in Amri (2017); Germany, Ireland, and Italy in Halicioglu and Ketenci (2018) and politically not free countries in Ali et al. (2020). Restrictive effects of RES illustrate the inverted N-shape for middle income and U-shape for low-income countries in Wang et al. (2022).

In the second model (Table 4), the environmental dimension, we analyze the emission-reducing effect of renewables and the environmental Kuznets curve (EKC). EKC is statistically valid at the 10 % level. When we interpret the effects of L.lgdp and L.lcop, they are nearly equal. Furthermore, one lagged variable lto negatively affects lcop. This finding is not suitable to the theoretical expectations related to the argument of pollution haven hypothesis. By the time dirty technologies evolve to green with trading, lto turns to the emission-reducing value. Another parameter lurb has an increasing effect on pollution. As communities grow with increasing rates of consumption and production activities, the increase in polluting gases is in line with theoretical estimates. The last two parameters are lfec and lrec; an increase in lfec causes approximately a 0.78 increase in lcop. Fossil fuels is the main source of emission penetration; hence

Table 3 Cobb-Douglas (lgdp)

L.lgdp	lfec	lrec	lgcf	L.lgcf	lwfp	cons.
$.9566^{***}$	−.0014	$-.0072^{*}$	$.2294^{***}$	$-.2197^{***}$	$.1502^{**}$	−.1811
(.0094)	(.0069)	(.0036)	(.0206)	(−.0228)	(.0546)	(0.1754)
N*T	Wald	AR(1)	AR(2)	Hansen (X^2)		
717	107515.59	-4.10^{***}	−1.06	13.71 (8), 0.186		

+, *, **, and *** represent the level of significance at 10%, 5%, 1%, and 0.1% respectively

Table 4 Carbon emission (lcop)

L.lgdp	L.lgdp2	L.lcop	lfec	L.lfec	lrec	L.lrec	lto	L.lto	lurb	cons.
$.8963^{+}$	$.0481^{+}$	$.8870^{***}$	$.7796^{**}$	$-.8799^{**}$	$-.0933^{***}$	.0560	.0869	$-.1229^{*}$	$.3861^{+}$	-4.8751^{+}
(.5124)	(.0259)	(.1237)	(.3164)	(.3124)	(.0255)	(.0358)	(.0559)	(.0488)	(.2036)	−27.586
N*T		Wald		AR(1)		AR(2)		Hansen (X^2)		
683		625.97		-3.63^{***}		−1.04		17.19 (5), 0.102		

+, *, **, and *** represent the level of significance at 10%, 5%, 1%, and 0.1% respectively positive value is foreseen value. A unit increase in lrec leads to an almost 0.09 unit decrease in lcop. This effect is small, but the improving technologies will increase it in time.

When checked with other studies, there is a wide variety of findings between articles, but there are parallel results in different methods of the same study. At this point, Liu et al. (2017) run three techniques and achieve the close result on average like as −0.035. Moreover, some papers investigate short- and long-run coefficients. Similarly to them, Anwar et al. (2021e) employ three methods and reach approximately −0.37 value for long-term estimation. Ben Jebli et al. (2014) maintain their research on two techniques and find −0.11 and −0.12 for the long-run coefficients. Besides, divergent methods might also cause different findings such as Anwar et al. (2021c) in which augmented mean group (AMG) and feasible generalized least squares (FGLS) produce −0.25 and −0.20 relatively. In addition to these results, there might be various values if models include different variables. In these circumstances, Yuping et al. (2021) make estimation with three models. In the long run, RES is valid in all models and diminishes pollution level by −0.008; −0.011; −0.013 in order. The mixed effect of RES and globalization ameliorates the mitigation efficiencies such as −0.025 (model 2) and −0.031 (model 3). Contradictory findings are also valid for time series analysis of countries. Vo et al. (2020) run co-integration test and discover different level of significance and values for CPTPP countries. But overall evaluation is that the REC is beneficial to reduce pollution level. In a nutshell, statistical property of our finding is consistent with almost all papers and theory. Over and above, the magnitude of parameter coefficient is close to that of Ben Jebli et al. (2014).

The third model (Table 5) is about human development; and thus, the social dimension of SD. L.hdi has the most significant coefficient, and if one lagged value of hdi is good, enough human development will improve the following year. Energy consumptions represented as lfec and lrec make better lhdi. However, lfec has a more significant effect than lrec as expected. Energy usage is a critical component of daily human life, so positive contributions are essential. One-lagged value of lfec and lrec is valid and negative. The last variable, lgcf, has a small but statistically valid value. Other parameters, lgdp, lcop, lwfp, lurb, and constant, are not meaningful.

When we focus on literature, Wang et al. (2018) detect the reducing effect of REC (~ −0.22) on the human development index contradictory to ours. They particularly insist on efficient utilization of RES to transform from negative to the positive one. Moreover, heterogeneous findings of Adekoya et al. (2021) are positive for Europe (~ 0.0019) , insignificant for sub-Saharan Africa, and negative for MENA (~ −0.0014) and Central America & Caribbean (~ −0.0006). These four findings are close to each other in absolute values; and thus, negative values might turn into positive in time.

The values of parameters are between the range of 0.0015 for Romania and 1.33 for Poland in Pirlogea (2012). Wang et al. (2021) illustrate 0.034 and 0.102 in different models with main and moderating effects, respectively. Their conclusion also shows bidirectional causality relationship. Similarly, Hashemizadeh et al. (2021) make estimation in two models with different methods. They reveal 0.041 and 0.032 values for RES. If we compare these values, ours ~ 0.0045 is close to that in Hashemizadeh et al. (2021) and is in the middle of other findings.

Our contribution as the fourth dimension of SD is energy security (Table 6). Renewables can be evaluated inside the energy security dimension by substituting the electricity supply of fossil fuels. A 1% increase in lfep and lrep leads

Table 5 Human development (lhdi)

L.lhdi	lgdp	lcop	lfec	L.lfec	lrec	L.lrec	lgcf	lwfp	lurb	cons.
$.9601^{***}$	.0005	.0004	$.0601^{**}$	$-.0632^{**}$	$.0045^{**}$	$-.0049^{**}$	$.0041^{*}$	.0045	−.0012	−.0189
(.0087)	(.0018)	(.0012)	(.0181)	(.0190)	(.0017)	(.0018)	(.0017)	(.0054)	(.0026)	(.0256)
N*T		Wald		AR(1)		AR(2)		Hansen (X^2)		
684		110422.38		-4.27^{***}		−1.09		27.51 (20), 0.122		

+, *, **, and *** represent the level of significance at 10%, 5%, 1%, and 0.1% respectively

Table 6 Energy security (lelg)

L.lelg	lto	lurb	lfep	L.lfep	lrep	lepc	L.lepc	lins	cons.
$.8718^{***}$	$-.1335^{+}$	−.0277	$.4736^{*}$	$-.4370^{+}$	$.0315^{*}$	$.8464^{*}$	$-.7835^{*}$	.0193	.9571
(.0654)	(.0801)	(.0839)	(.2351)	(.2266)	(.0153)	(.3301)	(.3245)	(.0523)	(.7190)
N*T		Wald		AR(1)		AR(2)		Hansen (X^2)	
666		30058.91		-1.88^{+}		−1.19		6.16 (5), 0.291	

+, *, **, and *** represent the level of significance at 10%, 5%, 1%, and 0.1% respectively to a 0.5% increase in electrical power generation when we look at the parameters. Much of the contribution belonging to the lfep (~ 0.47), and lrep (~ 0.03) tends to improve in years. One lagged value of lelg demonstrates the same pattern with one lagged dependent variable in other models and motivates the actual electricity generation. Lepc, electricity power consumption, is the second biggest driver for the lelg and lelg seems to be demand-driven supply. lto had a negative impact on the lelg. Imported goods/services cause this diminishing effect. One-lagged value of lfep and lepc is negative. Lins, lurb, and constant are not statistically valid.

Erdal (2015) measures energy security in the context of indexes and RES enhances import dependency rate (~ 0.58), energy intensity (~ 0.63), and composite index (~ 0.40). In this vein, we look at the substitution rate of FES by RES. Marques et al. (2018) search this possibility and demonstrate that the rate depends on natural resources availability. Hence, the speed of the adjustment mechanism of RES is low. At this point, we can say that RES has the potential to develop but gradually improves.

After model estimations, we run a post-estimation test for the validity of models in the context of instrumental variables and serial correlations in residuals. The Hansen test (or j-test) measures the over-identification problem at the IV side. In this respect, as mentioned in Roodman (2009), all *p*-values are between the desired ranges except the last model. The last model is close to this range and is evolving throughout time. The second test is related to serial correlation in residuals. Because of a dynamic model consisting of one-lagged value of the dependent variable, we can ignore and expect the first-degree auto-regressive part of the model (AR (1)) and negative sign for AR (1) is not informative. But AR (2) gives the detection of first-order serial correlation between the one-lagged and first difference values of residuals (Roodman 2009). AR (1) is valid in all models at 5% for three models and 10% for the last, and there is no serial correlation in residuals for all models.

Conclusion

Renewables support energy generation with all sources, especially wind and solar power. Hence, they might contribute to energy security and the economy by sustaining sufficient and permanent energy at a reasonable price (SDG12). They offer clean energy alternatives for mitigating environmental consequences and climate changes with their more friendly solutions for soil, water, and air (SDG13). Moreover, renewables might give the opportunity of accessible, fair, and equal energy for all (SDG7).

In this study, we analyze the link between RES with SD dimensions and investigate the energy security contribution of RES from 1995 to 2015 and OECD countries. We employ system-GMM in which feasible technique when zero-mean assumption of regression analysis is violated. Endogeneity and multi-collinearity are among the most severe violation conditions and produce bias estimations (Baum and Christopher 2006). Thus, GMM makes the estimation process to be robust even if residuals are not homoscedastic (Hayakawa 2019).

This paper differentiates from others by analyzing the multiple dimension of SD and empirical investigation of energy security. Overall findings imply significant but limited contributions to the SDG except output level. On the economic dimension, we employ REC as an input factor in the Cobb-Douglas production function. According to the results, REC has a small but diminishing effect on GDP. Because of high energy-generation costs, the output-enhancing impact of REC is well below its cost and the net value is negative. Throughout technical developments, economies of scale and increasingly competitive supply chains will reduce costs to a reasonable level (IRENA 2020).

The second result is that REC mitigates emission level and has the inverted-U relationship with GDP. RES has low contributions to reduce the emission level. Policy makers might encourage this contribution by increasing per-capita income, rising the share of RES, restricting the usage of FES, and controlling the urbanization level (Dong et al. 2020). Gradual replacement of FES with RES might help to increase emission reduction effect (Kabeyi and Olanrewaju 2022). Increasing capacity installations, promotions to build RE technologies, and public awareness policies related to being environmentally friendly solutions can flourish RES utilization and thus further improve environmental indicators (Mitchell et al. 2011).

In social dimension, REC stimulates human progress with very little rates. Improving share of RES in energy generation and consumption might increase the rates. Developing community awareness of RES may also be beneficial in increasing their use (Sawin et al. 2016). Additionally, decentralized structures of RES can make possible energy more accessible in rural areas and also create new job opportunities. They can enhance human development and economic growth by this way (Mitchell et al. 2011). In this veil, policymakers can support households with financial incentives for decentralized construction of RES (Anwar et al. 2021e). This improvement causes a higher level of well-being for households (SDG3). RES might give a chance to rebuild the cities and communities with sustainable structure (SDG11).

Furthermore, RES can partake in securing energy supply by improving generation technologies and sources (Mitchell et al. 2011). We obtain similar findings for energy security like emissions and human development having positive but restricted rates of contribution. This limitation is due to intermittency structure, variability, high construction and infrastructure cost, insufficient constitutional, and lack of political support (Marques et al. 2018). So, these obstacles slow down the process. At this point, RES could contribute more to the SD goals and compete with conventional sources. In stimulating process, RE-driven policies are significant factors. These might consist of various kinds of instruments related to barriers faced with RES such as policy-making, implementation, and financing. In policy-making process, RE-driven policies might include fiscal solutions such as tax credits, low interest rates, feed-in tariffs, and quotas. In addition, R&D investments can be an another strong policy instrument to improve demand for RE technologies, reduce production cost, enhance feedback cycle, stimulate private investments, etc. (Mitchell et al. 2011).

Future studies can be carried out on the alternative analysis techniques such as nonlinear regression and spatial methods. Moreover, although there are different index calculations in the literature, effective analysis becomes difficult because of insufficient data size. More data can be created retrospectively and quarterly/monthly in this context. Increasing data size will allow more opportunities for time series analysis in addition to the panel. As seen in the SD subsystems, evaluating any system individually will be insufficient to examine RES and identify other global actions. Therefore, focusing on interdisciplinary studies in terms of assessing the investment projects of RES and investigating their net environmental impact will facilitate obtaining more comprehensive and beneficial results.

Appendix 1 (List of abbreviations)

AMG: Augmented mean group
AR: Auto-regressive
ARDL: Auto-regressive distributed lag models
BIOC: Biomass consumption
BP: British petroleum
BRICS: Brazil, Russia, India, China, and the Republic of South Africa
CHP: Combined heat and power generation
CPTPP: Comprehensive and Progressive Agreement for Trans-Pacific Partnership
CS: Conventional sources
DEA: Divisia envelope analysis
DOLS: Dynamic ordinary least squares
EF: Ecological footprint
EG: Economic growth
ECOWAS: Economic Community of West African States
EKC: Environmental Kuznets curve
ES: Environmental sustainability
ESI: Security Supply Index
EU: European Union
FES: Fossil energy sources
FE-OLS: Fixed effect OLS
FGLS: Feasible generalized least squares
FMOLS: Full-modified OLS
GDP: Gross domestic product
GMM: Generalized methods of moments
gWh: Gigawatt-hour
IV: Instrumental variables
kWh: Kilowatt-hour
MENA: MENA countries consist of Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, United Arab Emirates, and Yemen
MM: Methods of moments
OECD: Organisation for Economic Co-operation and Development
OLS: Ordinary least squares
RCW: Renewable combustible and waste consumption
RE: Renewable energy
REC: Renewable energy consumption
RELC: Renewable electricity consumption
RELP: Renewable electricity production
RES: Renewable energy sources
R&D: Research and development
SD: Sustainable development
SDG: Sustainable development goals
SEC: Energy security
SVAR: Structural vector autoregressive
TEC: Total energy consumption
TEP: Total electricty production
UNDP: United Nations Development Programme
WB: World Bank
WM: Weighted matrix

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