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Industry 4.0 and Renewable Energy Production Nexus: An Empirical Investigation of G20 Countries with Panel Quantile Method

Melike Bildirici [1], Fazıl Kayıkçı [1] and Özgür Ömer Ersin [2,*]

[1] Department of Economics, Faculty of Economics and Administrative Sciences, Davutpaşa Campus, Yıldız Technical University, Esenler, 34220 Istanbul, Türkiye; bildiri@yildiz.edu.tr or melikebildirici@gmail.com (M.B.); fkayikci@yildiz.edu.tr (F.K.)
[2] Department of International Trade, Faculty of Business, Sütlüce Campus, İstanbul Ticaret University, Beyoğlu, 34445 Istanbul, Türkiye
* Correspondence: oersin@ticaret.edu.tr

Abstract: In line with the fourth industrial revolution, most countries have imposed a variety of regulations or policies for the goals of energy conservation, sustainable development, and industrial transition. Renewable energy production and its production process, which is widely discussed, especially in the context of sustainable energy, has become more important with Industry 4.0. This paper tested the relation among economic growth, renewable electricity generations (% of GDP), Industry 4.0, industrial structure, trade openness, financial development, and research and development expenditure for G20 countries in 2000–2021 by employing a panel quantile regression approach and various panel cointegration tests in addition to investigation of panel Granger causality among the analyzed variables. The variables of industrial structure, trade openness, and financial development were selected as control variables. Since this study is the first study on this topic, it will contribute to the development of the literature by providing resources for future studies about I4.0, renewable energy production, and economic growth. Furthermore, this study will not only contribute to the literature by revealing the theoretical and empirical relationship between these variables but will also shed light on the policies that G20 countries will produce in this regard. According to results, all variables examined have significant causal effects: unidirectional causality from economic growth to Industry 4.0, to research and development, and to renewable energy output and, also, from research and development to renewable energy output. Bidirectional causality and feedback effects between renewable energy and Industry 4.0 are determined. Further, unidirectional causality from industrial structure, from openness to trade, and from financial development to renewable energy output are determined. Results indicate renewable-enhancing effects of Industry 4.0.

Keywords: Industry 4.0; renewable energy; economic growth; sustainable economic development; information and communication technologies; research and development; international trade; G20; panel quantile regression; cointegration

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1. Introduction

In recent years, Industry 4.0 (henceforth I4.0) has garnered considerable interest from various economic stakeholders, including companies, consumers, and government policymakers. Developed nations, in particular, have embraced the concept of I4.0, anticipating notable advancements in industrial processes. This vision holds the potential to bring about significant enhancements to industries [1].

According to the World Economic Forum report, I4.0 is projected to have a significant and rapid impact on global industries, leading to systematic and extensive transformations. To embrace the opportunities of the fourth industrial revolution, many countries have implemented policies and regulations targeting energy conservation, sustainable development, and industrial transition. As I4.0 ushers in the next phase of industrial competition, it becomes imperative for nations to formulate development strategies that can adapt to the incoming opportunities and challenges [2]. I4.0 is closely linked to the revolution in information and communication technology (ICT). As industrial operations become smarter, this transformation is facilitated by the integration of technologies such as the Internet of Services (IoS) and the Internet of Things (IoT). These interconnected networks enable industries to establish a seamless supply chain and facilitate intelligent industrial operations throughout the entire process [3].

The I4.0 revolution and the mentioned technologies also impose substantial energy consumption requirements [4]. Consequently, industries and policies focusing on I4.0 need to urgently reconsider their energy strategies to foster an environmentally friendly transformation towards sustainable production within this framework. In this regard, renewable energy (RE) assumes a critical part in paving the way for its future. Emphasizing renewables is essential for addressing energy challenges effectively [4,5]. The share of RE in total energy production is increasing; however, it is criticized that this trend is not adequate to meet global targets stated in the Sustainable Development Goals [6]. A more effective shift to renewable energies is decisive to mitigate the environmental impacts and to reverse climate change. Furthermore, shifting to RE sources holds significant potential for alleviating the numerous issues accompanying conventional energy use, together with environmental and health-associated problems. In terms of the theoretical and technical contributions of I4.0 to RE systems and digital industries, there are three notable capabilities. Firstly, it enhances transparency by providing real-time information on the energy system's status. Secondly, it offers added flexibility to accommodate RE systems effectively. Lastly, it boosts energy efficiency by reducing overall energy consumption [7].

Over the past decade, the G20 countries have demonstrated significant commitment and adherence to achieving I4.0 transformation officially announced after the Platform of Industrie 4.0 (PI4.0) and related consortiums. Germany, in particular, has played a leading role in I4.0 transformation after hosting a meeting that set forth the agenda for I4.0 transformation in 2016 [8]. The transformation to I4.0 necessitated digital transformation and pooling expertise to achieve an I4.0 network. For this purpose, two organizations are put forth, namely the "Platform Industrie 4.0" (PI4.0) and "Industrial Internet Consortium" (IIC) established to function closely in co-operation [8]. PI4.0 project serves as the core network in Germany to enhance and manage digital transformation in I4.0; and PI4.0 of Germany aims for collaboration between many institutions, including not only the industries but academics, trade unions, and political institutions. It also develops and co-ordinates information and networking services to promote I4.0 solutions among companies and facilitate their deployment on site [9]. IIC is an open membership organization with global representation, focusing on accelerating the adaptation and development of interconnected machines, relevant technological advancements coupled with intelligent analytics, and human–machine collaboration [8]. The consortium, founded in 2014, catalyzes and directs and co-ordinates IoT technologies and digital transformation.

The I4.0 platform has been extended to encompass all G20 countries, aiming to accelerate and generalize the I4.0 to G20 countries. In the PI4.0 held in Germany in Berlin in March 2017, representatives from G20 shared their commitment to collaboration of politics, business, and civil society to network and share I4.0 initiatives. The collaboration for and achievement of I4.0 revolution is based on different pillars for G20 countries. These include the share of technological advancement, the digitalization of manufacturing practices within I4.0, and international co-operation to achieve I4.0 in G20 [9]. These pillars also constitute an agenda to achieve promotion of digitalization with I4.0 concepts such as "Digital Twin", sharing internet applications technologies of I4.0 in industries [10], advancing manufacturing digitization within the G20 countries through international co-operation, and standardization efforts for I4.0 [11]. It is clear that G20 will play a crucial role in the future of I4.0 revolution and transformation of production structures in the industries [8–12].

Investigation of RE commitment of G20 is of great importance within the concept of I4.0, economic growth, research and development, and information and communication technologies. Numerous studies have aimed at quantitatively examining or predicting the influence of I4.0 technology on sustainable energy within industries. The initial challenge arises from RE, which still constitutes a 19.2% share of the Global Final Energy Consumption as of 2016 [13]. Various factors impact the progress of RE adoption. As scrutinized by Benson et al., one approach to fostering its growth involves the integration of RE into electrical power systems, a domain where digital technologies can play a pivotal role [14]. Recently, Strielkowski et al. examined benefits of renewables on sustainable development of the energy power sector and the role of renewables on sustainability, utility side, and benefits on the grid [15]. The second crucial element pertains to energy efficiency, driven by digital advancements. Digital technology advancements help in transformation of the sector and aid energy efficiency, therefore gaining importance for sustainable energy [16]. As shown in the literature, renewables also have strong mitigation effects on environmental pollution. These technological innovations can substantially reshape industrial processes, thereby influencing energy consumption patterns and efficiency, and generation process [17].

However, studies on I4 and RE production are rare. Undoubtedly, one of the important factors in this is that the beginning of the I4.0 process is relatively new. The I4.0 concept was used for the first time in 2011; although the concept can be accepted as working on the basic components of I4.0 and can be moved to the early 2000s in the context of artificial intelligence patents, the period is still relatively short. As shown by Bildirici and Ersin, it is advocated to date I4.0 back to 2000, which is also in line with the increasing trend of artificial intelligence innovations data proxied by AI patent applications for I4.0 [4].

This research focuses on the nexus between RE output, I4.0 research and development, and economic growth in the period of I4.0 for the G20 countries. As shown by [18,19], quantile panel regression and causality methods provide efficient results instead of traditional approaches since the effects are heterogeneous at different quantiles. The quantile-specific heterogeneity provides important insights for generating policy recommendations, as shown for G20 countries [19]. Hence, the study benefits from panel quantile regression (PQR), cointegration tests, and causality tests for G20 countries in the context of I4.0. We used I4.0 variables as proxied by information and communication technologies (ICT) exports and R&D, in addition to a set of control variables, namely, trade openness, financial development, and the industrial structure, to achieve robustness of the analysis. The PQR method employed by this paper provided various improvements by incorporating examination of relationships under different quantiles. First, PQR provides more informative results, greater robustness against the loss of degrees of freedom, and efficiency in estimation as shown in the empirical literature [18,20]. Moreover, PQR provides a special case of heterogeneity specified by time-invariant parameter estimates and PQR estimators offer one result for each quantile. The use of control variables aims for robustness by resolving the influence of omitted variable biases in estimators. PQR and causality test results will show if there is relation between the selected variables and RE output in G20 countries in the process of I4.0.

If the other contributions of the article are evaluated, they can be stated as follows: (i) this paper could be accepted as providing a bridge to harmonize earlier empirical papers on I4.0, which are quite a few, especially in terms of the number of papers with empirical econometric results. (ii) When studies on RE and economic activity are analyzed, it is seen that these studies generally analyze the consumption side of energy instead of the production side. As emphasized in [17], while ~2% of the studies in the energy literature focus on energy production, ~98% focus on energy consumption. As shown by [17], the majority of the literature utilizes the energy consumption side instead of utilizing energy production variables in the energy-economic-growth papers. Additionally, these articles adopted real GDP as a measure of economic growth. Investments are what fuel long-term economic growth, and energy investments, in particular, require special consideration. The energy investment, however, which is essential for long-term growth, has largely received minimal attention [17]. (iii) In the frame of selected countries, this paper focuses on an important set of countries. The G20 consists of a mix of developed and emerging nations, spanning RE pioneers as well as significant fossil fuel producers. These countries also play vital roles as key contributors to international energy collaboration and in addressing prevalent energy poverty challenges. These nations recognize the importance of harnessing the potential of these technologies to foster economic growth, innovation, and sustainable development in a rapidly changing global landscape [20]. (iv) From a policy perspective, the outcomes of the study will hinder useful information to economic actors and policy makers since the paper has a pivotal role on the analysis of the nexus among RE output and I4.0 by questioning whether I4.0 encourages or discourages RE production in total energy output in the selected set of countries.

To our knowledge, this paper is the first study in the literature that analyzes I4.0 and RE output in addition to investigating the roles of various economic factors, including the roles of financial development, openness to trade, economic growth, and the industrial structure simultaneously. Thus, it contributes to the existing literature through examining the dynamics between these variables. In addition, this paper focuses on providing insights to the development of the literature by providing an empirical basis for future studies regarding I4.0, RE production, and economic growth. The above-mentioned additional explanatory variables help both researchers and policymakers to understand the economic interaction between these variables. Furthermore, this study will not only contribute to the literature by revealing the theoretical and empirical relationship between these variables but will also shed light on the policies that G20 countries will produce in this regard.

After the introduction, the second section of this study presents the literature review, while the third section comprises data and econometric methodology. The fourth section gives the empirical results. Finally, the last section includes conclusions and economic policy implications.

2. Literature Review

A small set of studies provide important insights regarding I4.0 and RE relations, and the roles of economic factors in this relation is not an explored field of research in the context of I4.0. Scharl and Praktiknjo center their research on Germany as a case study to investigate the status of expert discourse on the role of a digital industry as a potential enabler for energy transition [7]. To this end, they utilize qualitative data based on semi-structured interviews with industry leaders and managers and academic researchers in the field of energy [7]. The future of the energy sector is shown to be dependent on three factors, augmenting transparency in systems of energy, achievement of more flexibility to energy demand, and augmentation of energy efficiency for I4.0 [7]. Recent studies investigated energy efficiency gains of new technologies in energy grid and smarting of energy systems and energy grid with IoT is suggested [21]. Pandey et al. addressed RE in the context of I4.0 and they investigated the potential of I4.0 technologies in optimizing energy production from renewable resources [22]. According to their findings, I4.0 technologies such as IoT and cloud computing could be used to augment efficiency problems in the sector which result from intermittent power supply, grid bottlenecks, and wasting of excess power supply and I4.0 could contribute to sustainable economic development through circular economy [22]. Digital technologies of I4.0 such as IoT are expected to coincide with cryptocurrency use in such systems due to their non-central structure as a digital financial system. Further, cryptocurrency utilization and mining lead to enormous levels of energy consumption due to their energy hunger and energy efficiency is crucial. To this end, Truby proposed rules aimed at boosting miners' energy efficiency in order to reduce energy usage due to Blockchain mining [23]. Sustainable energy transition in I4.0 is of crucial importance subject to various challenges. Hidayatno et al. point out that energy transition in the process of I4.0 is necessary to achieve Sustainable Development Goals (SDG) 7 and 9 and they propose an analyze systemic transition model for I4.0 technology for sustainable energy transition in Indonesia as a pioneering country aiming at transforming its industries to I4.0 [24]. Ukoba et al., investigated the various energy sources that the African continent might invest in and utilize in greater proportion to successfully execute I4.0, and the impact, challenges, and potential of the fourth generation of technologies on African development was examined [25].

Some studies have focused on the relationship between environmental pollution and I4.0. Bildirici and Ersin [4] explored the nexus between I4.0 and environmental sustainability with artificial intelligence (AI) patents, ICT technology patents, energy consumption, ICT exports, research and development (R&D), and bitcoin for nine I4.0 countries with panel Fourier methods and their findings indicate that I4.0 is, so far, contributing to environmental degradation and important steps are needed to mitigate negative effects of I4.0 on environmental sustainability [4]. De Sousa Jabbour et al. analyze the effects of a move to environmentally responsible manufacturing and offer insight into how I4.0 technology and environmentally responsible manufacturing may be combined [26]. The growth of I4.0 and the transformation of industries have been identified as being understudied in policy or industrial development research [27]. Ben-Daya et al. concentrate on the implementation challenge of several IoT technologies in the context of I4.0 on supply chains [28]. Jayashree et al. addressed I4.0 implementation and sustainability impacts and evaluated the roles of IT structure, top management, and supply chain integration, the latter having relatively lower effects [29]. Oks et al. provide a thorough literature analysis too and indicate the roles of AI, big data (BD), real-time augmentation of manufacturing systems, and integration of cyber-physical systems in the context of I4.0 [30].

Pivotal bibliometric research on the examination of I4.0 and several environmental sustainability ideas, such as the circular economy and the green economy, provide important insights for the I4.0 literature [31]. As demonstrated by Bonilla et al., various I4.0 technologies, including IoT, BD analytics, and cyber-physical systems, have significant negative effects on environmental sustainability [32]. It is emphasized that, unless I4.0 is not effectively integrated with SDG, I4.0 cannot be applied in an eco-friendly manner and, to achieve environmental benefits of I4.0, eco-innovation platform investments are necessary during transition, which also include eco-friendly energy production [32]. Raj et al. investigate the obstacles that impede the adoption of I4.0 technologies and underline lack of co-ordination at developing nations, which hinders I4.0 adaptation by the firms [33]. Müller et al. explore the challenges and opportunities of I4.0 in line with its sustainability impacts [34]. Similarly, Breunig et al. highlight one of these hindrances as the substantial research and development costs associated with I4.0 [35]. Recent research by Chauhan et al. sheds light on the intrinsic and extrinsic barriers that hinder the process of digitalization within the realm of I4.0 [36]. Further, health implications of energy intensity and energy consumption as economic development and industrialization accelerates [37]. With panel quantile cointegration methods and with data of a large set of countries, Bildirici and Kayıkçı emphasize the negative effects of energy consumption and energy intensity coupled with economic growth and urbanization, which have strong implications on health through particulate matter 2.5 concentration inclines resulting in accelerated respiratory diseases [37].

3. Data and Econometric Method

3.1. Data

The data utilized in the study are detailed in Table 1. For I4.0, we have used two different indicators; the first one is I4.0 investments proxied by ICT goods and service exports (% of GDP) and the second is research and development expenditure (% of GDP). For renewable energy, we utilized renewable energy production as a % in total electricity production. Additional variables include trade openness, financial development, and the industrial structure, included as controls for robust results to control omitted variable biases and to include the effects of economic factors in the analysis. Further, economic growth is measured with real gross domestic product. Annotations and data sources and descriptive statistics are given in the second part of Table 1. The dataset covers selected variables for G20 nations for the years 2000 to 2021. As given in Table 1, data sources are World Bank, the Statistical Review of World Energy, and British Petroleum. For a number of statistical reasons, including avoiding heteroscedasticity, all variables are converted into natural logarithmic form. A detailed reasoning for selecting G20 countries is given in the first section. Embracing two thirds of the world's population, Group 20 countries represent approximately 90% of world gross production, 80% of world trade, and 85% of world fossil fuel consumption. G20 countries drew attention to the weakness in international growth and emphasized the necessity of establishing a comprehensive and integrated structure where important economies come together for a sustainable, balanced, and inclusive growth. A study covering economic growth and environmental issues will contribute to the policies that these countries can create and implement together. For this reason, G20 countries were selected for this study.

Table 1. Variable definitions and descriptive statistics.

	Variables in Focus				**Set of Explanatory Variables**		
Variables:	Economic growth	ICT exports	Renewable energy output	R&D expenditures	Trade openness	Industrial structure	Financial development
Abbrev.	Y	ICT	REN	RD	OP	IND	FD
Variable Definitions	Real Gross Domestic Product (2005 USD)	Internet and communication technology goods and services exports as a % of GDP	Renewable energy production share in total energy production	Research and development expenditure (% of GDP)	The total of exports and imports as a percentage of GDP	The share of the industry value added to GDP	The total value of domestic loans to the private sector as a share of GDP.
Source	World Bank	World Bank	British Petrol	World Bank	World Bank	World Bank	International Monetary Fund
				Descriptive Statistics			
Kurtosis	2.57	2.31	3.27	3.14	2.32	3.28	3.06
Skewness	0.57	0.32	0.221	−0.98	1.03	0.36	−0.28
s.d.	0.32	0.219	0.309	0.194	0.45	0.33	0.29

Descriptive statistics for the analyzed variables are given at the last section of Table 1. The results indicate that RD and FD variables are subject to negative skewness, while the remaining variables have positive skewness.

Table 2 shows the findings from tests of LLC, IPS, and CSD-ADF 's unit root tests. Hence, all variables are found to follow first difference stationary I(1) processes.

Table 2. Unit root tests.

Level:	**CSD-ADF [1]**	**LLC**	**IPS**	**First Dif.: [2]**	**CSD-ADF**	**LLC**	**IPS**	**Decision:**
Y	0.93	−2.09	1.67	ΔY	−8.39	−6.037	−5.30	I(1)
REN	0.15	1.36	3.07	ΔREN	−8.003	−13.07	−14.95	I(1)
ICT	0.057	−2.074	−1.045	ΔICT	−6.85	−8.19	−7.71	I(1)
RD	0.07	−1.67	1.74	ΔRP	−7.79	−9.15	−7.59	I(1)
OP	0.015	−1.256	−1.856	ΔOP	−5.236	−8.236	−9.04	I(1)
IND	0.25	−1.48	−1.678	ΔIND	−7.256	−6.89	−7.12	I(1)
FD	0.96	−0.86	−1.25	ΔFD	−6.256	−7.864	−8.023	I(1)

[1] CSD-ADF represents cross-sectional dependence augmented Dickey Fuller test of Pesaran, LLC is the Levin–Lin–Chu test, and IPS is the Im-Pesaran-Shin test of unit root for panels. [2] Δ denotes first differencing.

3.2. Econometric Methodology

Various statistical methods were employed in this study to investigate the long-term relationship. Stationarity is tested with CSD-ADF [38], LLC [39], and IPS [40] tests as an initial step. Long-run coefficients are obtained by employing Pedroni's DOLS and FMOLS estimators [41] to derive long-run estimations. However, before the long-run model estimations, existence of cointegration is examined with the tests of Kao, Johansen and Westerlund [42,43]. Additionally, panel quantile regression was utilized to ensure the accuracy and efficiency of economic policy recommendations, which are essential focal points of this research. The presence of homogeneity among the datasets was assessed using ANOVA tests. Finally, Granger causality tests were conducted to investigate the direction of causality, providing crucial insights to guide the formulation of appropriate policy recommendations.

3.2.1. Panel Quantile Regression

In this paper, a panel quantile regression (PQR) method was utilized to examine the influences of I4.0 measured with ICT exports and research and development expenditures on economic growth and the share of renewable energy in total energy production. In addition, models include a set of control variables, namely, financial development, trade openness, and the industrial structure as a measure of industrial development.

The PQR method that was suggested by [44] has some advantages over the OLS regression. More robust results can be obtained from PQR [45]. And, by employing PQR, distributional assumptions are not violated [46]. Additionally, this method can capture the properties of the complete conditional distribution of the chosen variables [47,48]. As shown by [49], PQR is effective to explore asymmetric features of variable distributions [48]. By employing a fixed effect PQR method, the determinants of renewable energy at Model 1 and determinants of economic growth at Model 2 were obtained through the conditional distribution at different quantiles.

The conditional quantile of y_i is given as follows [50]:

$$Q_{yi}(\tau|x_i) = x_i^T \beta_\tau \tag{1}$$

PQR is robust to heavy distributions and outliers. Nevertheless, the unobserved heterogeneity of a country is not taken into account. The fixed-effect PQR method was defined as:

$$Q_{yi}(\tau_k|\alpha_i, x_{it}) = \alpha_i + x_{it}^T \beta(\tau_k),\ i = 1, \ldots, N;\ t = 1, \ldots, T \tag{2}$$

α_i shifts the position of the variable at conditional quantiles. The impacts of x_{it}, the covariates, are modeled to be specific to each quantile t. N is the observation number on the individual i. T is the number of observations on the time t where i is the index of individual and t is the index of time. The parameter estimate is calculated as follows:

$$\begin{aligned} &\underset{(\alpha,\beta)}{min} \sum_{k=1}^{K} \sum_{t=1}^{T} \sum_{n=1}^{N} w_k \rho_{\tau k}(y_{it} - \alpha_i - x_{it}^T \beta(\tau_k)) + \\ &\lambda \sum_{i}^{N} |\alpha_i|,\ i = 1, \ldots, N;\ t = 1, \ldots, T \end{aligned} \tag{3}$$

where K is the index of quantiles, x is the matrix of explanatory variables, and rtk is the quantile loss function. Quantiles were equally weighted $w_k = 1/K$ as in [51] and set $\lambda = 1$ as in [48,52].

3.2.2. Westerlund Test

Westerlund [53,54] suggested tests to detect cointegration, [53] is applied in case of structural breaks in the cointegrating vector. This study assumes [54], Westerlund developed four tests dependent on least-squares estimates of α_i Among these, two tests are named as group mean statistics, which are presented as:

$$G_t = \frac{1}{N} \sum_{i=1}^{N} \frac{\hat{\alpha}_i}{\hat{\sigma}_{\hat{\alpha}_i}} \tag{4}$$

and:

$$G_a = \frac{1}{N}\sum_{i=1}^{N}\frac{T\alpha_i}{\hat{\alpha}_i(1)} \tag{5}$$

The last two test statistics are given as:

$$P_t = \frac{\hat{\alpha}}{\hat{\sigma}_{\hat{\alpha}}} \tag{6}$$

and:

$$P_a = T\hat{\alpha} \tag{7}$$

G_α, G_τ, P_α, and P_τ are test statistics aiming at cointegration testing [54]. The error correction model is given as follows:

$$\Delta y_{it} = \theta_i' d_t + \alpha_i\left(y_{it-1} - \beta_i' X_{it-1}\right) + \sum_{j=1}^{p}\alpha_{ij}\Delta y_{it-j} + \sum_{j=0}^{p}\gamma_{ij}\Delta X_{it-j} + \varepsilon_{it} \tag{8}$$

If Equation (8) is rewritten, Equation (9) is obtained as:

$$\Delta y_{it} = \theta_i' d_t + \alpha_i y_{it-1} + \phi_i' X_{it-1} + \sum_{j=1}^{p}\alpha_{ij}\Delta y_{it-j} + \sum_{j=0}^{p}\gamma_{ij}\Delta X_{it-j} + \varepsilon_{it} \tag{9}$$

with the following properties [54]:

$$\theta_i' = (\theta_{0i},\ \theta_{1i})',\ d_t = (1,\ t)' \text{ and } X_i = \alpha_i\beta_i \tag{10}$$

$$\hat{\alpha} = \left(\sum_{i=1}^{N}\sum_{t=2}^{T}\widetilde{y}_{i,t-1}\right)^{-1}\sum_{i=1}^{N}\sum_{t=2}^{T}\frac{1}{\hat{\alpha}_i(1)}\widetilde{y}_{i,t-1}\Delta\widetilde{y}_{it} \tag{11}$$

$$\hat{\sigma}_{\hat{\alpha}} = \left[\left(\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\hat{\sigma}_i}{\hat{\sigma}_i(1)}\right)^2\right)^{-1}\sum_{i=1}^{N}\sum_{t=2}^{T}\widetilde{y}^2{}_{i,t-1}\right]^{-1/2} \tag{12}$$

3.2.3. Panel Granger Causality Tests

A causality test to examine the relation between the variables is constructed as follows:

$$\Delta y_{it} = \lambda_{1j} + \sum_{k=1}^{m}\alpha_{ik}\Delta y_{it-k} + \sum_{k=1}^{n}\vartheta_{ik}\Delta x_{it-k} + \varepsilon_{1t} \tag{13}$$

$$\Delta x_{it} = \lambda_0 + \sum_{k=1}^{m}\alpha_{2ik}\Delta x_{it-k} + \sum_{k=1}^{n}\vartheta_{2ik}\Delta y_{it-k} + \varepsilon_{2t} \tag{14}$$

In Equation (13), Granger causality is tested with the null hypothesis of $H_0:\ \vartheta_{ik}\ = 0$ against the alternative $H_1:\ \vartheta_{ik} \neq 0$, which tests there is no Granger causality from variable x to y for all i under the null. Similarly, in Equation (14), the null and alternative hypotheses are $H_0:\ \vartheta_{2ik}\ = 0$ and $H_1:\ \vartheta_{2ik} \neq 0$ aim at testing Granger causality from y to x for all i.

4. Empirical Results

4.1. Cointegration Results

Tables 3–5 reported the results obtained by Kao [42], Westerlund [54], and Johansen [43] cointegration test results.

Table 3. Kao cointegration test results.

	DFp* [1]	DFt*	DFp	DFt	ADF
Statistic:	−16.5	−27.7	−5.67	−6.674	−7.0125
p-value:	0.000	0.000	0.000	0.000	0.000

[1] Kao proposes five different tests, based on DFp*, DFt*, DFp, DFt and ADF test statistics of Kao as generalizations of Dickey-Fuller (DF) and Augmented DF (ADF) tests for panel cointegration testing [42]. *p*-value < 0.05 denotes rejection of no cointegration at 5% significance level.

Table 4. Westerlund cointegration tests results.

Westerlund Test No:	Alternative Hypothesis [1]:	VR Statistic	*p*
1	Some panels are cointegrated	−18.450	0.0000
2	All panels are cointegrated	−8.391	0.0000

[1] In both versions of Westerlund tests, the null hypothesis is no cointegration, tested against two different cases. The first assumes some panels are cointegrated; the second assumes all panels are cointegrated under the alternative. VR is the variance ratio test statistic and *p* denotes *p*-value.

Table 5. Johansen cointegration test results.

Null Hypothesis [1]	Fisher Stat. (Max-Eigen Test)	Null Hypothesis	Fisher Stat. (Max-Eigen Test)
None	193.0 ***	At most 4	42.10 ***
At most 1	225.1 ***	At most 5	28.12 **
At most 2	136.7***	At most 6	4.57
At most 3	77.62 ***		

[1] *** and ** denote statistical significance at 1% and 5% significance levels, respectively.

All cointegration tests favor rejection of no cointegration against the alternative of cointegration among the variables analyzed. Westerlund test is conducted for two types of tests, the first testing the existence of cointegration in members of the panel and the second testing cointegration in all panel members. The cointegration is determined in both cases. The Kao test results signify the existence of cointegration; however, the number of cointegration vectors are unknown. Different than the tests conducted, Johansen test tests the possibility of more than one cointegration vector among the variables analyzed. Johansen Fisher panel cointegration test [43] results suggested, at most, five cointegration vectors. This indicates that the existence of a single cointegration vector cannot be achieved among the variables analyzed. In this case, Panel ARDL method cannot be applied since the method requires one cointegration vector only. Under these conditions, the paper follows two different methods to obtain long-run coefficients. In the first one, we use Pedroni's DOLS and FMOLS estimations to determine the long-run coefficients [41]. And, in the second one, we use the PQR method to determine the long-run coefficients. Before presenting the estimation results, ANOVA and equality of variances test results are given below.

4.2. ANOVA Results

The major goal is to determine whether or not the differences between countries are statistically significant. Then, to guard against the likelihood of the findings not matching the assumptions of ANOVA, a non-parametric test, such as Kruskall–Wallis [55], is calculated. It was expected that there would be a statistically larger mean or, at the very least, a non-statistically significant difference between the countries [55].

According to the results given in Table 6, both ANOVA and Kruskal-Wallis (which compares the empirical distribution) tests suggest that the null hypotheses cannot be rejected at conventional significance levels. Bartlett, Levene and Brown–Forsythe tests reported in Table 7 lead to the conclusion of equality of medians and quality of variances. As a result, we conclude that the distributional differences across countries were not statistically significant throughout the time period in terms of the variables analyzed. Both the F and Welch F tests led to F statistics being larger than the critical F value, with *p* values approaching zero. The results signify that, in each group, the dependent variable is normally distributed, and the findings also favor homogeneity of variances.

Table 6. ANOVA tests.

Test Type	F Test Statistic	Significance [1]
Anova F-test	108.3	1.0000
Welch F-test	51.73	1.0000

[1] Significance = 1 − *p* value.

Table 7. Tests for equality of variances and medians.

Tests for Equality of Variances			Tests for Equality of Medians		
Method	F-test	Significance	Method	F-test	Significance
Bartlett	0.392	1.00	Kruskal–Wallis	1.18	1.00
Levene	0.940	1.00	Kruskal–Wallis	1.34	1.00
Brown–Forsythe	1.017	0.99	van der Waerden	0.73	1.00

The results given in Table 7 cover a wide variety of tests for testing equality of variances with Bartlett test, Levene test, and Brown–Forsythe test and equality of medians, including Kruskal–Wallis and van der Waerden tests. According to the results, despite the different characteristics of countries, the observed differences among the countries are not statistically significant.

4.3. Long-Run Coefficients

The cointegration test results showed the presence of cointegration. In this process, Pedroni DOLS and FMOLS results together with PQR estimated the long-run coefficients, which are presented in Tables 8 and 9.

Table 8. Panel quantile regression and FMOLS and DOLS regression results for Model 1.

Dependent Variable: REN							
Variable	FMOLS and DOLS Estimates:		Panel Quantile Regression Estimates at 0.10th to 0.90th Quantiles [1]:				
	FMOLS	DOLS	0.1th	0.25th	0.5th	0.75th	0.9th
Y	2.175	3.01 **	0.68 **	0.56 ***	1.09 **	1.113 **	1.764 *
	(0.74)	(2.51)	(1.96)	(2.82)	(2.15)	(2.04)	(1.83)
RD	1.04 **	1.76 ***	0.053 ***	0.363 **	0.422 **	0.26 **	0.25 **
	(2.57)	(2.62)	(2.76)	(2.45)	(2.23)	(1.99)	(1.96)
ICT	−1.20 ***	−0.85	0.415 *	−0.413 **	0.467 **	0.557 ***	0.63 **
	(−4.81)	(0.308)	(1.89)	(−1.98)	(1.98)	(2.81)	(2.11)
OP	−1.256 **	0.56 *	0.15 *	0.036 *	0.097 *	0.27 **	0.46 ***
	(2.07)	(1.93)	(1.89)	(1.86)	(1.93)	(2.07)	(2.75)
IND	0.23 *	0.35	0.28 *	0.69 *	0.256 *	0.301 **	0.73 **
	(1.86)	(1.23)	(1.76)	(1.82)	(1.93)	(1.96)	(2.33)
FD	−0.256 **	−1.26	0.11 *	0.23 **	0.28 *	0.34 *	0.56 **
	(2.35)	(0.86)	(1.81)	(2.07)	(1.93)	(1.93)	(2.53)

[1] t statistics are given in parentheses. *, **, and *** denote statistical significance at 10%, 5%, and 1% significance levels.

In Model 1, reported in Table 8, we present estimation results of the long-run effects of ICT goods and service exports, GDP growth, research and development expenditures, trade openness, financial development, and industrial structure on REN. The coefficients of RD and Y are positive in all models and, accordingly, both research and development and economic growth have significant positive effects on REN in all quantiles in addition to overall results obtained with PDOLS. One exception is the Y for the FMOLS estimator only. Coefficients of I4.0 investments proxied with ICT variable are also positive in all quantiles of the PQR results, except one negative estimate in the 25th quantile. This negative effect also cannot be rejected with the FMOLS estimator. However, investigating the quantiles clearly indicates that this negative effect does not hold for all cases and, for the majority of quantiles, the coefficient is positive, confirming positive effects of ICT on REN. GDP growth is statistically insignificant in FMOLS method and ICT exports are insignificant in DOLS method. Coefficients can be evaluated as elasticities; growth elasticity of REN is greater than 1 in more cases and other elasticities are lower than 1.

Table 9. Panel quantile regression and FMOLS and DOLS regression results for Model 2.

Dependent Variable: Y							
Variable	**FMOLS and DOLS Estimates:**		**Panel Quantile Regression Estimates at 0.10th to 0.90th Quantiles [1]:**				
	FMOLS	**DOLS**	**0.10th**	**0.25th**	**0.50th**	**0.75th**	**0.90th**
REN	0.275 (1.03)	0.429 (1.28)	0.161 ** (2.17)	0.235 ** (2.45)	0.323 * (1.93)	0.453 ** (2.06)	0.111 ** (2.11)
RD	0.512 * (1.86)	0.314 * (1.78)	0.27 * (2.17)	0.131 *** (3.46)	0.645 ** (2.12)	0.38 * (1.83)	0.46 * (1.86)
ICT	−0.0018 (−0.87)	−0.078 (−0.46)	0.498 *** (3.18)	0.425 * (1.89)	0.65 ** (2.44)	0.57 * (1.89)	0.73 ** (2.56)
OP	0.23 * (1.65)	0.56 * (1.75)	0.136 * (1.84)	0.254 * (1.93)	0.289 ** (1.96)	0.31 * (1.78)	0.38 * (1.93)
IND	0.23 * (1.86)	0.29 ** (1.96)	0.256 * (1.93)	0.32 ** (1.97)	0.38 * (1.88)	0.94 ** (1.96)	0.78 ** (1.88)

[1] t statistics are given in parentheses. *, **, and *** denote statistical significance at 10%, 5%, and 1% significance levels.

As observed with the cointegration tests, a second possibility of cointegration vector is the model with real gross domestic product (Y) being the dependent variable. Hence, in Model 2, we presented estimation results, where the dependent variable is taken as Y. With this respect, Model 2 aims for investigation of the long-run effects of ICT, research and development expenditures, trade openness, industrial structure, and REN on the real GDP. The results are reported in Table 9.

The coefficients of research and development expenditure and renewable energy output are positive in all models and they have effects on GDP growth; however, this effect cannot be confirmed statistically for renewable energy for the FMOLS and DOLS estimations, since the parameter of REN is insignificant under these settings. However, PQR results point to statistical significance of both REN and RD on real GDP at a conventional significance level in addition to confirming positive effects of renewable energy and research and development on economic growth. A similar result also holds for ICT parameter. While FMOLS and DOLS results point to insignificance of the effect of ICT on economic growth, by dividing the regression space into quantile sub-spaces, the PQR results point to varying but positive effects of ICT in all quantiles. Therefore, the statistical evidence could be taken as significant and positive effects of I4.0 investments on economic growth. Trade openness has positive and significant effects at a 10% significance level only under FMOLS and DOLS, which also is confirmed with PQR results, except for the 0.50th quantile, at which the effect is significant at a 5% significance level. A similar result also holds for industrial structure, for which the parameters are significant at 10% for FMOLS and 5% for the DOLS estimator. Coefficients of IND are also positive, showing positive and significant effects ranging between 0.25 and 0.94 depending on the quantile. It should be noted that the estimates could also be evaluated as economic elasticities, given that all variables are in logarithmic form. Accordingly, results approve renewable energy production elasticity of growth and I4.0 elasticity of growth being positive but lower than 1. Hence, results given in Table 9 confirm the previous results in terms of the magnitude and sign of the long-run elasticities reported in Table 8.

4.4. Comparative Results and Robustness Check: PQR Results without Control Variables

For comparative purposes and to check the role of control variables, we also estimated models without the control variables, namely, the variables of FD, OP, and IND. With this respect, we aim at focusing and evaluating the nexus between renewable energy, research and development, I4.0, and economic growth. The comparative results obtained by excluding the control variables are reported in Table 10 for Models 1 and 2, respectively.

Table 10. Panel quantile regression results for Models 1 and 2; control variables excluded.

Quantiles [1]:	**0.10th**	**0.25th**	**0.50th**	**0.75th**	**0.90th**
			Model 1: Dependent variable REN		
Y	0.468 * (1.88)	1.322 *** (4.8)	1.575 *** (4.5)	1.843 *** (4.04)	2.574 *** (3.36)
RD	0.066 *** (2.76)	0.483 *** (2.7)	0.502 *** (2.71)	0.156 * (1.87)	0.115 * (1.86)
ICT	0.335 * (1.89)	0.213 * (1.93)	0.347 * (1.95)	0.467 *** (2.51)	0.913 ** (2.24)
			Model 2: Dependent variable Y		
	0.1th	0.25th	0.5th	0.75th	0.9th
RD	0.356 *** (3.77)	0.493 *** (11.46)	0.592 *** (18.76)	0.56 *** (6.56)	0.300 * (1.74)
ICT	0.498 *** (3.18)	0.551 *** (5.86)	0.588 *** (24.22)	0.607 *** (5.87)	0.861 *** (6.78)
REN	0.206 *** (4.37)	0.171 ** (6.85)	0.150 (5.23)	0.185 (6.46)	0.091 (2.28)

[1] t statistics are given in parentheses. *, **, and *** denote statistical significance at 10%, 5%, and 1% significance levels.

First, there is a clear positive relationship between industry and renewable energy production. Second, the financial development coefficient is positive and significant in all quantiles. Financial development helps the economic growth, which results in more energy generations and increasing energy consumption. If compared to the results reported in Tables 8 and 9, the industrial structure variable has a larger effect on economic growth. On the other hand, as a typical example, Ref. [56] displays that financial development has a larger effect on economic growth. Similarly, Refs. [51,57] debate that financial development is positively connected to economic growth. Given the connection between these variables, we conducted model specifications. Models 1 and 2 exclude financial development, trade openness, and industrial structure and the results reported in Table 9 indicate that the results are not sensitive to their exclusion, since the estimates do not change in a large magnitude if control variables are omitted from the models compared to previous results in Tables 8 and 9. Hence, we can conclude that our results are robust in different model specifications in addition to the findings obtained under different estimations.

4.5. Causality Results

Determination of the direction of causality is of crucial importance for policy recommendations. Since there is a cointegration relation among the variables analyzed, it is expected that a change in one variable could also have an impact on the other variable through a feedback mechanism. Causality test results are reported in Table 11. Results indicate that there is a unidirectional causality from economic growth to ICT goods and service exports, from economic growth to research and development expenditure, from economic growth to renewable energy output, from research and development expenditure to ICT goods and service exports, and from research and development expenditure to renewable energy output. There is also two-way causal nexus between renewable energy output and ICT goods and service exports, between economic growth and industrial structure, between economic growth and openness, and between economic growth and financial development. There is also a unidirectional causality from industrial structure, openness, and financial development to renewable energy output.

Table 11. Causality results.

Direction of Causality [1]	Test Stat.	Decision	Direction of Causality	Test Stat.	Decision
Y→ICT	3.29	Y→ICT	Y→IND	2.89	Y↔IND
ICT→Y	0.106		IND→Y	3.16	
Y→REN	4.128	Y→REN	Y→OP	2.85	Y↔OP
REN→Y	0.917		OP→Y	3.75	
Y→RD	3.16	Y→RD	Y→FD	4.15	Y↔FD
RD→Y	0.47		FD→Y	3.73	
REN→ICT	3.09	REN↔ICT	REN→IND	1.85	IND→REN
ICT→REN	3.98		IND→REN	3.86	
RD→ICT	4.19	RD→ICT	REN→OP	0.56	OP→REN
ICT→RD	0.84		OP→REN	3.75	
RD→REN	3.93	*RD→REN*	REN→FD	*1.25*	FD→REN
REN→RD	0.16		FD→REN	4.86	
RD→IND	4.25	RD↔IND	FD→OP	2.93	OP↔FD
IND→RD	3.89		OP→FD	3.88	
RD→OP	0.86	OP→RD	IND→FD	3.27	IND↔FD
OP→RD	3.89		FD→IND	3.61	
RD→FD	0.156	FD→RD	IND→OP	3.88	IND→OP
FD→RD	4.36		OP→IND	0.16	

[1] Unidirectional and bidirectional causal links are given by → and ↔, respectively.

4.6. Discussion

The results of Granger causality determined that there is a unidirectional causality from economic growth to ICT, research and development expenditure, and renewable energy output. There is also bidirectional causality between renewable energy output and ICT goods and service exports and between economic growth and industrial structure. There is also a unidirectional causality from industrial structure, openness, and financial development to renewable energy output. In the context of our results, Granger causality between I4.0, renewable energy production, and economic growth determined important policy results.

I4.0 has a significant impact on renewable energy production. I4 components can provide efficiency in the production and distribution of renewable energy. G20 countries have a significant share in renewable energy production. Except for Germany and Saudi Arabia, most countries rely heavily on hydropower as the dominant source of renewable energy capacity. Nonetheless, non-hydro renewable sources, particularly wind and solar energy, have witnessed a rapid surge in several nations. Germany stands out with the largest proportion of non-hydro renewables in its energy mix, constituting over 26% of its power generation. In terms of sheer capacity, China takes the lead with nearly 200 GW of total installed non-hydro renewable capacity [58,59]. Conversely, the integration of non-hydro renewables remains in its early stages in Russia and Saudi Arabia. Brazil has historically leaned on hydropower for electricity generation and boasts a substantial utilization of biofuels in its transportation sector. The nation's strong backing of ethanol as an alternative fuel has positioned it as a global frontrunner in this domain. Renewable promotion has been a consistent theme in the energy strategies of pioneers such as Brazil and Germany. Reflecting their domestic energy trajectories, Brazil champions biofuels internationally, while Germany fervently advocates for wind and solar energy advancements. Instead of focusing on the energy production side, as in our study, Pao and Fu show that Brazil has strong commitment to renewable energy consumption in addition to non-renewable and all energy sources have significant causal relations with economic growth [60].

As renewable energies gain worldwide traction, the desire to promote their expansion is gaining traction in other countries, including France and the United States [61]. Reduced usage of nuclear energy is a key driver of renewable energy expansion in France and Germany. In Germany, this has been combined with ambitions to become a leader in a burgeoning renewable industry, an aim shared by countries such as China and the United States. In Argentina, for example, investments in renewables are supported by support for the country's burgeoning shale gas industry. The availability of resources and low costs have always been important factors in the use of hydropower. Falling costs have also fueled the growth of solar and wind power. Wind energy, for example, has grown in popularity in Brazil [61].

In the effect of I4, the expansion of renewable energies and improvements in energy efficiency are key pillars of a decarbonized global energy supply. The role of energy efficiency is shown to be an almost 1 to 1 reduction in environmental degradation [62] and is crucial for the energy sector. ICT encompasses a spectrum of technologies associated with the storage, retrieval, transmission, and manipulation of digital data. This encompasses computers, networks, software, and telecommunications. In the context of I4.0, ICT serves as the cornerstone for transforming the vision into reality. It establishes the framework for interconnecting diverse devices, sensors, and systems within manufacturing environments, facilitating the seamless exchange of data and enabling automation. The amalgamation of ICT within I4.0 bestows the capacity for real-time supervision and regulation of manufacturing processes, anticipatory maintenance of equipment, data-informed decision making, and the conception of digital twins—virtual renditions of tangible assets. These functionalities are pivotal in attaining the envisaged efficiency enhancements and innovative breakthroughs promised by I4.0.

Another link is for energy storage, because I4.0 technologies can help with energy storage and distribution optimization. Sensors and analytics can aid in the prediction and prevention of equipment failures in renewable energy systems, extending their life and decreasing downtime. The integration of I4.0 and renewable energy helps to produce smart networks, energy-efficient cities, and long-term energy solutions. Furthermore, integrating I4.0 and renewable energy necessitates innovation and collaboration among numerous stakeholders, such as governments, industries, researchers, and technology providers. G20 countries frequently collaborate to exchange best practices and set common standards for the implementation of these technologies. G20 governments play a critical role in influencing the link between I4.0 and renewable energy. They can encourage the use of both technologies by implementing supportive policies such as tax breaks, research funding, and renewable energy objectives. In G20 nations, I4.0 can play a role in achieving sustainability goals. G20 countries can explore how these technologies can be utilized to reduce environmental impact and promote circular economy principles.

In the context of economic policies, there is a strong link between I4.0 technology and renewable energy in the policy formulation process. Integration with I4.0 has the potential to have a substantial influence on the renewable energy sector. Smart energy management, for example, is critical because IoT sensors and data analytics help optimize the operation and maintenance of renewable energy systems, increasing their efficiency and reliability [7,21]. The relationship between I4.0 technologies and renewable energy is critical for distributed energy systems. Decentralized and distributed generating is common in renewable energy systems. I4.0 makes it easier to manage these systems by enabling communication and collaboration across numerous components. Further, industrial development is expected to couple with economic growth and urbanization, which have strong effects on environmental degradation [37]. According to our results, renewable energy is shown to have strong role on reducing environmental degradation and helping on achieving sustainable economic development. Such findings are in line with the literature suggesting positive association between renewable energy and economic growth [63]. According to our findings, policies should focus not only on renewable energy investments, but also on eco-friendly and green I4.0 technology investments. Further, findings of the paper underline the importance of financial development, institutional structure, and trade openness in the above-mentioned relation. Nevertheless, findings indicate positive effects of trade openness on renewable energy and economic growth. As our results confirm causal relations between trade openness and emissions, increasing the share of renewable energy production rapidly is vital for sustainability. Such findings are in line with renewable energy and current account balance relations [6].

The research in this study has data limitations due to I4.0 data availability in short time periods. As a result, the research cannot be conducted with a set of nonlinear panel regression methods that necessitate a higher number of time observations. To avoid the sample size limitations, the analysis in this study is extended by including G20 countries with the justification made for country selection in Sections 1 and 3. Similar to all research, this paper is based on assumptions including the homogeneity of the variables for the G20. With statistical tests, the study confirmed homogeneity in the context of G20. For future studies, heterogeneous panels with a larger number of countries are advised. Future studies are also expected to utilize advanced deep learning neural networks models as sample sizes advance with availability of data in higher frequencies.

5. Conclusions

In this paper, we analyze the effects of I4 both on the renewable energy production and on the economic growth. We tested the relations among economic growth, renewable electricity output (% of GDP) and I4.0, which is proxied by ICT goods and service exports (% GDP), and research and development expenditure for G20 countries for the 2000–2021 period by employing panel quantile regression and causality approaches. Models assume a set of additional explanatory variables consisting of trade openness, financial development, and the industrial structure for both controlling possible omitted variable biases in the estimators and, also, to include effects of these economic and industrial factors to the models. As shown in the literature section, different to the energy and economic growth literature, this study utilizes renewable energy production instead of consumption and, by taking the share of renewable energy output in total energy output, this study aimed to test whether the I4.0 had been encouraging the commitment to renewable energy production during the transformation to I4.0.

The PQR and panel FMOLS and DOLS estimators were used to identify the effects of I4.0 and the economic factors analyzed. The PQR results indicated strong positive effects of I4.0 on both economic growth and on renewable energy production share in the total energy output in the context of I4.0, in addition to putting forth positive effects of financial development, trade openness, and industrial structure complexity. Though these effects are varying relative to different quantiles, positive effects of I4.0 on renewable energy and economic growth are confirmed at all quantiles. Such positive effects are also confirmed for industrial structure and financial development at different quantiles.

Johansen Fisher panel cointegration test results suggested more than one cointegration vectors at 5% and the existence of single cointegration vector is questionable. In this case, the panel ARDL method is not an appropriate method. Thus, we obtain long-run coefficients from DOLS and FMOLS estimations and from the PQR method to examine long-run relationships. We also performed ANOVA and Kruskall–Wallis tests, which suggest that the differences in variances and means in data are not statistically significant.

Most of the coefficients are positive when renewable energy is treated as a dependent variable. Growth elasticity of renewable energy production is greater than 1 in more cases and other elasticities are lower than 1. Few of the coefficients are negative when economic growth is treated as a dependent variable, however, with statistical insignificance. Renewable energy production elasticity of growth and I4.0 elasticity of growth are lower than 1 and direction of causalities generally comes from economic growth and research and development expenditure to other variables.

If the causality results are evaluated, there is a unidirectional causality from economic growth to ICT goods and service exports, from economic growth to research and development expenditure, and from economic growth to renewable energy output. According to the results of this study, policymakers should try to boost economic growth, which also translates into inclined production in ICT goods and services exports coupled with research and development expenditures and generating an upward shift in renewable energy output in G20. With the help of this policy, governments could not only increase the economic well-being of people and generate technological progress but the international trade balances and environmental protection are also positively affected.

Another policy implication of this study results from the findings regarding R&D expenditures. Findings indicated unidirectional causality from R&D expenditures to ICT goods and service exports and from R&D expenditures to renewable energy output share in total energy output. These findings indicate that R&D investments are crucial for supporting economic growth, creating more output and increases in ICT exports in the context of I4.0. Regarding the effects on generating inclines of the share of renewable energy production in total energy output, the policies aiming at I4.0 are expected to influence the environment positively in the long run.

The study evaluated a set of control variables, including industrial structure, trade openness, and financial development. For these variables, positive effects on renewable energy output were observed at all quantiles without exception. In addition, causality test results indicated unidirectional causality from industrial structure, from trade openness, and from financial development to renewable energy output share in total energy output. Thus, it is better for policymakers to improve industrial structure and to increase trade openness. To this end, subsidies to exporters and especially in the ICT sector and reduction in restrictions on imports could be considered as viable options. Further, steps to improve financial development are expected to affect renewable energy. In these ways, they will contribute to the protection of the environment more effectively.

The results indicated bidirectional causal nexus between a set of variables. Such effects are crucial since they are subject to feedback effects. Bidirectional relations are observed between renewable energy output share in total energy production and ICT goods and service exports, between economic growth and industrial structure, between economic growth and trade openness, and, lastly, between economic growth and financial development. These findings lead to a set of policy recommendations: policymakers should be aware of feedback effects between these variables and the investments on ICT export goods and the relevant R&D should be invested in a balanced way by also investing proportionately in the structure of the industry and energy sector prioritizing renewable energies in the context of I4.0. Such policies should also be carefully applied with policies on financial development and economic growth by focusing on environment-friendly technologies to couple economic growth carefully by applying policies to achieve environmental sustainability, especially by the policies focusing on the I4.0 transition for G20 countries.

Last but not least, the results in this paper indicated that economic growth improves both I4.0 process and renewable energy output, while I4.0 process improves renewable energy commitment observed by the inclines in the renewable energy share in total energy production during the pace of I4.0. These results suggest important relations between economic growth, I4.0 advancements, and renewable energy production. The transition to I4.0 policies should be coupled with greater focus on eco-friendly energies for a cleaner environment.

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