

## Article

# ICT-Driven Strategies for Enhancing Energy Efficiency in G20 Economies: Moderating the Role of Governance in Achieving Environmental Sustainability

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**Abstract:** Achieving environmental sustainability has become a global priority, with energy efficiency (EE) emerging as a critical pathway. This study examines the influence of information and communication technology service exports (ICT) on EE by integrating the moderating role of regulatory quality. We employ a super-slack-based measure (Super-SBM) and generalized least squares models in G20 economies throughout 2001–2023. The findings show that the average EE is 0.855, which indicates a potential for further improvement of 14.50%. The findings further show that ICT is positively related to EE, and regulatory quality delivers a conducive environment for the adoption of technologies to optimize energy usage. The findings also indicate a synergistic effect between ICT and regulatory quality, which can lead to substantial improvements in EE, emphasizing the importance of governance in facilitating technological advancements. The findings highlight the role of renewable energy and economic openness in shaping EE. Furthermore, Argentina and South Africa achieved the highest EE, reflecting their proximity to the efficient frontier. In robust tests, this study verifies its results using the generalized method of moments, panel-corrected standard error, and feasible generalized least squares models. The findings suggest that ICT and governance perspectives can provide valuable insights for policymakers aiming to enhance energy sustainability through digital transformation and institutional reforms.



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**Keywords:** energy efficiency; ICT; regulatory quality; environmental sustainability; renewable energy

## 1. Introduction

Energy efficiency (EE) is an important factor for sustainable development and welfare in nations and regions because of its diverse environmental, economic, and social benefits [1,2]. It reduces dependence on fossil fuels by optimizing energy resource utilization for higher or equivalent output, thereby aiding in the reduction of greenhouse gases and carbon footprints [3]. Moreover, it plays a pivotal role in combating environmental change, helping regions achieve global climate objectives outlined in the Paris Agreement [4]. It mitigates expenses for consumers and businesses, enabling corporations to enhance profitability while allowing households to allocate more funds toward other expenditures,

thus stimulating local economies [5]. From an energy security perspective, EE fosters independence from imported energy, contributing to the creation of more secure and resilient energy systems [6]. It protects public health by decreasing air pollution, which reduces the incidence of respiratory and cardiovascular diseases [7]. Therefore, promoting EE stimulates innovation and the development of environmentally friendly technologies, creating job opportunities in different sectors [8,9]. These combined environmental, economic, and health benefits make EE a cornerstone for sustainable development, enabling countries and regions to build safer, more resilient, and prosperous futures [10,11].

Technological advancement is another critical determinant of economic growth [12]. It enhances corporate efficiency, reduces energy costs and waste, and improves product quality, leading to market expansion and increased investments [13,14]. Technology fosters the creation of new industries and employment opportunities, promoting the acquisition of new skills and inspiring further innovation for sustainable development [15,16]. Additionally, it elevates living standards by improving infrastructure, healthcare, and communication systems. Notably, sustainable technologies address global challenges, such as environmental change, while responsibly creating opportunities for economic growth [17,18]. In this context, technological advancements, particularly through information and communication technology service exports (ICT), emerge as critical drivers of sustainability and optimize energy resource utilization via digital content, data management, and technological devices [19]. ICT fosters innovation, boosts EE, and connects individuals, businesses, and governments globally, driving further growth and development in the digital economy [16,20–22]. ICT-based platforms can enhance EE in buildings by involving consumers and optimizing energy usage through automation [23]. These platforms incorporate load disaggregation, forecasting, and behavior prediction features to maximize energy savings while maintaining comfort [24].

Numerous studies have shown that EE depends on various interrelated factors, including technological advancements, economic conditions, government policies, and the sustainability of energy resources [25–29]. For instance, technologies such as energy-efficient industries and smart grids can significantly reduce energy utilization [30]. Economic factors, such as energy costs and national wealth, influence the ability of individuals and organizations to invest in energy-efficient systems [31]. Government interventions are dynamic in spurring efforts to reduce energy waste and improve utilization with effective standards and regulations [32,33]. Furthermore, budgetary constraints and access to modern technology affect a country's ability to implement energy-saving measures across sectors [34]. However, these factors determine a nation's EE and capacity to transition to more sustainable energy consumption patterns [35–38]. For the G20 economies, as major global energy consumers, improving EE enables these nations to save costs, reduce emissions, and enhance energy security through technological advancement, thus supporting sustainable economic growth [39,40]. Simultaneously, ICT drives economic progress through innovation and leadership in the digital economy. The G20 nations can achieve significant milestones by implementing energy-efficient standards, investing in smart technologies, promoting digital infrastructure, and expanding ICT access [41–44]. Therefore, EE progress aligns with ICT advancements, enabling G20 economies to contribute to global economic and environmental goals.

Moreover, governance indicators are critical for advancing EE and technological innovations [45] as they reflect the effectiveness of institutional and policy frameworks. Sun [10] shows that countries with strong ICT infrastructure and high governance quality have better EE performance. Therefore, robust governance facilitates EE initiatives' successful design and implementation, promoting sustainability and optimizing energy consumption [46,47]. It also creates an environment conducive to innovation, encourag-

ing the adoption of energy-efficient technologies and supporting digital transformation across industries. In the context of ICT, strong governance supports corporate growth and strengthens digital infrastructure [10]. By fostering innovation and supporting digital transformation across industries, governance enhances both EE and the global competitiveness of a nation's ICT sector [48,49]. As countries expand their ICT, they gain access to advanced technologies such as smart grids, energy-efficient software, and data analytics, which help optimize energy use and minimize waste. These innovations benefit the technology sector and contribute to broader improvements in national EE [50,51].

Understanding these governance dynamics is critical for translating EE improvements into actionable energy policies, especially in the context of diverse governance structures of G20 nations [52–54]. Governance quality plays a pivotal role in enabling the adoption of energy-efficient technologies and practices, influencing the design and enforcement of energy policies [55–57]. For instance, nations with strong regulatory frameworks are more likely to implement policies that incentivize investment in renewable energy and energy-efficient infrastructure, whereas those with weaker governance may struggle to enforce such policies effectively [46–48,58]. Earlier studies indicate that governance quality affects the effectiveness of energy policies and determines the degree to which ICT-driven innovations are adopted and integrated into national energy systems [59–61]. In addition, variations in governance structures among G20 economies, such as decentralized systems in federal states and centralized approaches in unitary systems, create unique challenges and opportunities for energy policy design [62,63]. For example, decentralized governance may facilitate localized energy solutions tailored to regional needs, whereas centralized systems can implement more efficient large-scale and uniform energy strategies. Recognizing these differences is essential for designing policies that align with each country's institutional context.

Despite advancements in technology and governance, the specific impact of ICT on a country's EE remains an underexplored area, presenting a valuable research gap. While ICT advancements promote energy management and sustainability, there has been limited research on how ICT interacts with governance indicators to influence energy management. This study aims to address this gap by investigating the role of ICT in shaping EE by integrating the moderating role of governance indicators in G20 economies. Specifically, this study focuses on how regulatory quality can amplify the positive impact of ICT on EE through institutional quality, effective policymaking, and technological adoption. This study offers new perspectives on how sound governance can enhance both domains. First, this study applies the data envelopment analysis super-slack-based measure (DEA Super-SBM) model to estimate EE. It identifies average EE levels, distinguishes efficient countries from inefficient ones, and evaluates resource utilization based on input reduction and output improvement. Second, we examine the impact of ICT on EE. Third, we examine how ICT influences EE by integrating the moderating role of regulatory quality. We also consider control variables such as renewable energy consumption, urbanization rate, economic openness, and industrial value added. The control variables help elucidate the broader dynamics affecting the relationship between ICT and EE.

This study contributes to the literature in several ways. First, it offers novel insights into the relationship between ICT and EE. Earlier studies considered technological advancement to be one of the potential ways to help improve energy management. However, our study analyzed how ICT directly influences EE, addressing a critical but unexplored research gap. This study includes the DEA Super-SBM model and offers a strong framework for assessing EE in the G20 economies, underlining the gaps separating efficient nations from inefficient ones regarding their opportunities to improve energy resource use. Second, this study examines the moderating role of regulatory quality in the relationship between

ICT and EE, emphasizing institutional quality and effective policymaking. The outcomes show that strong governance amplifies the effect of ICT on EE since it creates an enabling environment for technological adoption and energy optimization. It highlights the critical role that governance can play in shaping both digital and energy transitions, with clear implications for policymakers seeking to enhance energy performance while simultaneously promoting economic competitiveness in the digital economy. This study further contributes to the theoretical understanding by evidencing that ICT and regulatory quality are not only separate drivers of EE but also mutually reinforcing factors. The moderating role of regulatory quality enriches the existing literature on energy sustainability by emphasizing how governance structures amplify the impact of technological advancements. It extends the existing literature by combining ICT and governance under a common analytical framework. This integrated approach offers pathways to achieve sustainable development goals (SDGs) through the combination of technological, economic, and environmental policies. It thus gives a more detailed understanding of how institutional factors influence the effectiveness of technology in driving EE and provides actionable insights for policymakers seeking to enhance national energy performance and global economic competitiveness.

The rest of this study follows: Section 2 shows a literature review. Section 3 indicates the data sample and methodology. Section 4 shows the empirical results. Section 5 includes the robustness tests, and Section 6 provides a conclusion with policy implications.

## 2. Literature Review

EE has become one of the main themes of sustainable development as it is critical in reducing global energy consumption, mitigating environmental impacts, and enhancing economic performance [47,64,65]. Studies show that high levels of EE can be crucial in providing solutions to energy security concerns as well as meeting climate policy goals [6,26,27]. Earlier studies show significant disparities in EE across countries. For instance, Shah [11] indicates that Saudi Arabia, South Africa, and the United Kingdom mostly work near the efficiency frontier by embracing new frontier technology or frontier policy frameworks for efficient resource exploitation. On the other hand, India, Indonesia, and the Russian Federation remain relatively inefficient due to structural inefficiencies, mostly related to higher dependence on non-renewable sources of energy and less efficient industrial practices [11]. In addition, this inequality is further magnified by differences in technological infrastructure, including how nations cope with energy resources and optimize their respective energy consumption [25,27]. This is supported by the fact that nations with more developed institutional frameworks and technological infrastructures have been found to exhibit higher levels of EE [10]. The significant variation in EE performance reflects the multifaceted nature of EE improvement, encompassing technological, economic, and regulatory aspects.

Moreover, the integration of ICT into energy systems has been one of the driving forces toward EE [66]. ICT can optimize energy consumption through the real-time monitoring and management of resources more effectively [19,21]. Mickoleit [20] and GeSI [67] suggest that technologies have a beneficial role in curbing energy demands and avoiding the wastage of resources. Additionally, ICT enhances energy management by providing detailed data on consumption patterns, which allows for more precise forecasting and more effective decision-making [21]. ICT has the potential to transfer advanced energy management technologies to less developed nations and accelerate the adoption of energy-efficient solutions globally [20,41,67]. The exportation of ICT not only diffuses energy-efficient practices but also contributes to the modernization of infrastructure in importing countries and the implementation of technologies that reduce energy consumption.

In addition, the effectiveness of ICT-based solutions often depends on the governance environment [68]. In particular, governance quality is important in determining the extent to which ICT can lead to measurable improvements [21,69]. The regulatory frameworks that encourage innovation, ensure transparency, and incentivize energy-efficient practices are most likely to successfully integrate ICT solutions into national energy systems [67]. Countries with strong governance structures are better equipped to adopt and leverage ICT and improve energy usage [46–48,58]. For instance, nations with sound regulatory frameworks can incentivize the adoption of energy-efficient technologies through policies such as tax incentives, subsidies for renewable energy, and strict standards on energy consumption [25]. Further, economies with strong ICT infrastructures and high governance often perform better in terms of EE, benefiting from both the technological capabilities and the favorable governance structures [59–61]. However, ICT solutions cannot be effectively implemented to realize their full impact on EE in countries with weak governance structures or less developed technological infrastructures [70]. This suggests that ICT has the potential to drive EE improvements, and its impact amplifies in countries where regulatory frameworks are aligned with technological advancements and SDGs [10,61].

### 3. Data Sample and Methodology

#### *Data Sample*

This study employs data for G20 countries sourced from the World Development Indicators (WDI), Worldwide Governance Indicators (WGI), and Our World in Data databases, covering the period from 2001 to 2023. We apply a natural logarithmic transformation to address scale discrepancies among variables and drop the missing values from the dataset. This study includes EE as a dependent variable following Shah [11] and Elfarra [30]. Further, selecting the appropriate input-output data for DEA efficiency estimation is crucial [71] because ignoring undesirable outputs can lead to misleading DEA results [72]. Labor, capital, and energy consumption are key factors that contribute to economic value, such as GDP [73]. Following Zhang and Choi [65] and Wang [64], we select the inputs and outputs to calculate the EE. Following Tian and Son [50], Kashif [21], and Sinha [19], we incorporate ICT as an independent proxy and governance indicator as a moderating proxy, which is regulatory quality (RQC). The controlled variables are renewable energy consumption (REC), urbanization rate (U\_Rate), economic openness (Eco\_Opn), and industrial value added (Ind\_Value), following Kashif [21] and Luan [74]. This ensures that the analysis considers various factors that may differ across contexts, enhancing the generalizability of the results beyond the specific conditions of this study. Table 1 presents the proxies' names, symbols, definitions, and data sources.

**Table 1.** Variable Definitions.

Variable	Symbol	Definition
Energy Efficiency Score	EE	Energy Efficiency Score is Self-Estimation using Inputs and Outputs.
Inputs	Outputs	
Total Labor Force	GDP (Constant 2015)	
Gross Fixed Capital Formation (Constant 2015)	CO <sub>2</sub> Emissions Million Tones (Bad-Output)	
Primary Energy Consumption (TWH)		
Information and Communication Technology Service Exports	ICT	ICT Service Exports.

Table 1. Cont.

Variable	Symbol	Definition
Regulatory Quality	RQC	The Country's Estimated Score on the Aggregate Indicator is Expressed in Terms of a Standard Normal Distribution.
Renewable Energy Consumption	REC	Total Final Energy Consumption.
Urbanization Rate	U_Rate	Annual Urban Population Growth.
Economic Openness	Eco_Opn	Exports of Goods and Services in the GDP.
Industrial Value Added	Ind_Value	Captures the Intensity of Industrialization in GDP.

Databases: WDI, WGI, and Our World in Data.

#### 4. Methodology

This study employs two key methodologies to examine the relationship between ICT, RQC, and EE. First, we include the DEA Super-SBM model to assess EE scores by incorporating inputs, outputs, and undesirable outputs. Earlier studies used the DEA Super-SBM model for energy estimation in different scenarios for G20 economies [11,39,75]. It identifies average EE levels, distinguishes efficient G20 countries from inefficient ones, and evaluates resource utilization based on input reduction and output improvement. We choose the DEA Super-SBM model due to its unique ability to evaluate EE while incorporating undesirable outputs, such as carbon emissions, into the efficiency assessment. Unlike traditional DEA models, the Super-SBM model provides a more comprehensive measure of efficiency by addressing slacks in inputs, desirable outputs, and undesirable outputs. It is particularly suitable for studies focusing on energy and environmental performance. Additionally, the Super-SBM model can distinguish between efficient and inefficient decision-making units (DMUs) and rank them, which overcomes the limitation of traditional DEA models that treat multiple efficient DMUs as equivalent. While alternative methods like Stochastic Frontier Analysis (SFA) are widely used for efficiency evaluation, SFA relies on a predefined functional form, which may introduce bias when modeling complex EE relationships. The DEA Super-SBM model is non-parametric and does not require any assumptions about the production function, making it more flexible and robust in capturing the multi-dimensional aspects of EE. Furthermore, its capability to integrate undesirable outputs aligns with the objectives of this study, which emphasizes environmental sustainability alongside EE. These advantages make the DEA Super-SBM model the most appropriate choice for analyzing the EE of G20 economies.

Second, we incorporate random year effect generalized least squares (GLS) regression to examine the effects of ICT and RQC on EE following Appiah-Otoo [76], Rehan [77], and Uddin [42]. Moreover, we employ the two-step system generalized method of moments (GMM), panel-corrected standard error (PCSE), and feasible generalized least squares (FGLS) models to ensure the robustness and reliability of our main findings. These methods address endogeneity, heteroskedasticity, and cross-sectional dependence, providing more consistent and accurate estimates. The methodological framework is shown in Figure 1.

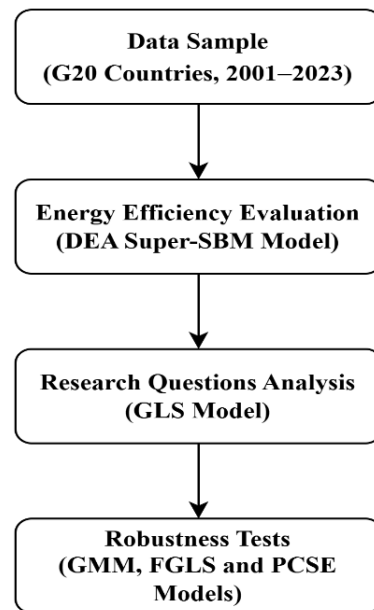


Figure 1. Methodological Framework.

#### 4.1. DEA Super-SBM Model

Efficiency evaluation of DMUs within a specific industry is typically conducted using two well-known techniques: SFA and DEA. In SFA, the production frontier is estimated by regressing observed outputs on inputs through a stochastic production function. The coefficients of this production function reflect the efficiency with which inputs are converted into outputs and can help identify sources of inefficiency in the production process. However, DEA considers multiple inputs and outputs to assess the efficiency of specific DMUs. Unlike other methods, it enables comparing energy use and output efficiency across nations without requiring any predefined production function [78].

This study first employs the DEA Super-SBM model to assess the EE of G20 nations, a well-known linear programming method used to evaluate the efficiency of homogenous DMUs. Tone [72] introduced a modified SBM model that incorporates undesirable outputs into the evaluation process. The following explains how the SBM model operates.

$$\begin{aligned}
 \theta^* = \min & \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{i0}}}{1 + \frac{1}{s_1 + s_2} \left( \sum_{r=1}^{s_1} \frac{s_r^g}{y_{r0}^g} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{r0}^b} \right)} \\
 \text{s.t.} & \quad \lambda X + S^- = x_0 \\
 & \quad \lambda Y^g - S^g = y_0^g \\
 & \quad \lambda Y^b + S^b = y_0^b \\
 & \quad S^- \geq 0, S^g \geq 0, S^b \geq 0, \lambda \geq 0
 \end{aligned} \tag{1}$$

In this context,  $\theta^*$  denotes the efficiency score of DMUs<sub>0</sub>. The proxies  $S^-$ ,  $S^g$ , and  $S^b$  represent the slack in inputs, outputs, and undesirable outputs, respectively. Here,  $m$  indicates the number of inputs,  $s_1$  represents the number of desirable outputs and  $s_2$  corresponds to the number of undesirable outputs. Lastly,  $\lambda$  serves as the intensity vector.

The values obtained from Equation (1) range between 0 and 1. When  $\theta^* = 1$ , all slack values  $S^-$ ,  $S^g$ , and  $S^b$  are zero, which means the DMUs are considered SBM-efficient. However, the model cannot differentiate among multiple efficient DMUs. To address this limitation, Tone introduced the Super-SBM model in 2002 [79], which provides a clearer ranking of efficient DMUs. However, the Super-SBM model does not account for undesirable outputs. To address this limitation, we employed an enhanced version

of the Super-SBM model that incorporates undesirable outputs, enabling more precise differentiation among SBM-efficient DMUs [80]. If DMU<sub>s</sub> is SBM-efficient, it can be defined as follows:

$$\theta_* = \min \frac{1 + \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{ik}}}{1 - \frac{1}{s_1 + s_2} \left( \sum_{r=1}^{s_1} \frac{s_r^g}{y_{rk}^g} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{rk}^b} \right)}$$

$$\text{s. t}$$

$$x_k - \sum_{j=1, \neq k}^n \lambda_j x_j + s^- \geq 0$$

$$-y_k^g + \sum_{j=1, \neq k}^n \lambda_j y_j^g + s^g \geq 0$$

$$y_k^b - \sum_{j=1, \neq k}^n \lambda_j y_j^b + s^b \geq 0$$

$$1 - \frac{1}{s_1 + s_2} \left( \sum_{r=1}^{s_1} \frac{s_r^g}{y_{rk}^g} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{rk}^b} \right) \geq \varepsilon$$

$$\lambda, s^-, s^g, s^b \geq 0$$
(2)

The fractional program can be transformed into a linear programming problem to solve the given model. This involves introducing a variable:

$$t \left[ 1 - \frac{1}{s_1 + s_2} \left( \sum_{r=1}^{s_1} \frac{s_r^g}{y_{r0}^g} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{r0}^b} \right) \right] = 1$$

The corresponding linear programming formulation is presented below.

$$\theta_* = \min t + \frac{1}{m} \sum_{i=1}^m \frac{S_i^-}{x_{i0}}$$

$$\text{s. t}$$

$$t - \frac{1}{s_1 + s_2} \left( \sum_{r=1}^{s_1} \frac{S_r^g}{y_{r0}^g} + \sum_{r=1}^{s_2} \frac{S_r^b}{y_{r0}^b} \right) = 1$$

$$tx_0 - \sum_{j=1, \neq 0}^n \Delta_j x_j + S^- \geq 0$$

$$-ty_0^g + \sum_{j=1, \neq 0}^n \Delta_j y_j^g + S^g \geq 0$$

$$ty_0^b - \sum_{j=1, \neq 0}^n \Delta_j y_j^b + S^b \geq 0$$

$$\Delta, S^-, S^g, S^b \geq 0$$
(3)

In Equation (3),  $\Delta$ ,  $S_i^-$ ,  $S_r^g$ , and  $S_r^b$  are the transformed versions of the intensity and slack variables from Equation (2), denoted as  $\lambda$ ,  $s_i^-$ ,  $s_r^g$ , and  $s_r^b$ , respectively. By solving Equation (3), we can determine the optimal values for all slack variables and the variable  $t$ . If all slack variables are zero and  $\theta^* = 1$ , the evaluated DMUs are considered efficient. Otherwise, the DMUs are classified as inefficient.

#### 4.2. Generalized Least Squares Model

This study further employs the random year effect GLS regression to examine the impacts of ICT and RQC on EE, as represented in Equation (4).

$$EE_{it} = \alpha_0 + \beta_1 ICT_{it} + \beta_2 RQC_{it} + \beta_3 REC_{it} + \beta_4 U\_Rate_{it} + \beta_5 Eco\_Opn_{it} + \beta_5 Ind\_Value_{it} + e_t \quad (4)$$

where EE is the dependent variable and ICT and RQC are independent and moderating variables, respectively. The controlling variables are REC, U\_Rate, Eco\_Opn, and Ind\_Value.

$i$  is the country,  $t$  is the period throughout 2001–2023,  $\alpha_0$  ( $a = 1 \dots N$ ) represents the unknown intercept for each parameter,  $\beta$  represents coefficients for independent and control parameters, and  $e_t$  is the error term. Equation (5) extends the model to incorporate the moderating impact of RQC on the relationship between ICT and EE through the interaction term ( $ICT \times RQC$ ).

$$EE_{it} = \alpha_0 + \beta_1 ICT_{it} + \beta_2 RQC_{it} + \beta_3 ICT_{it} \times RQC_{it} + \beta_3 REC_{it} + \beta_3 U\_Rate_{it} + \beta_6 Eco\_Opn_{it} + \beta_7 Ind\_Value_{it} + e_t \quad (5)$$

The initial phase of the analysis involves conducting a preliminary assessment of the data using descriptive statistics and a correlation matrix. To address potential econometric challenges, we test for cross-sectional dependency (CSD) following Pesaran [81]. CSD is critical in panel data analysis, particularly for G20 nations, where trade agreements, socio-cultural ties, and economic integration influence interconnected economies. In such contexts, the actions or behaviors of one country can significantly affect others. Assessing CSD is essential, as overlooking it may lead to serious econometric biases and unreliable results. To further strengthen the analysis, the slope homogeneity test (SHT) test developed by Pesaran and Yamagata [82] is employed to evaluate model heterogeneity among G20 nations. This step is crucial in determining whether the relationships between variables vary significantly across nations. After confirming both CSD and SHT tests, the stationarity of the variables is examined using a second-generation unit root test. Unlike first-generation tests, which fail to account for CSD, the second-generation approach, specifically the Pesaran [83] CIPS test, effectively evaluates stationarity properties while addressing CSD. This study uses the Kao [84] cointegration test to investigate long-run relationships, which assumes a homogeneous covariance structure. While the Pedroni [85] test accounts for some heterogeneity, both tests rely on the assumption of cross-sectional independence for asymptotic consistency. Given this limitation, the Kao test, which employs pooled regression with individual fixed effects to identify uniform cointegrating relationships, is applied as an alternative. Although the Westerlund test is often used for cointegration analysis, its reliance on bootstrapping methods makes it less effective in addressing CSD, further justifying the choice of the Kao test. Additionally, we employ the GMM, PCSE, and FGLS models to ensure the robustness and reliability of our main findings. These methods address issues such as endogeneity, heteroskedasticity, and cross-sectional dependence, providing more consistent and accurate estimates.

## 5. Empirical Results

### 5.1. Descriptive Statistics

Based on the DEA Super-SBM model, Table 2 shows the EE of all nations, providing insight into their ability to optimize energy usage while maintaining economic output. We utilize input-output indicators along with undesirable outputs to measure EE. The average EE for the G20 nations is 0.855, indicating potential for an improvement of 14.50%. The findings suggest that to drive further improvement; the G20 nations can focus on increasing desired outputs like GDP while controlling carbon emissions or reducing input variables such as energy consumption, labor, and capital. Moreover, Argentina, South Africa, the United States, Saudi Arabia, Australia, and the United Kingdom show the highest EE among the G20 nations, indicating their proximity to the efficient frontier. These nations reveal effective utilization of inputs to maximize GDP while minimizing carbon emissions. Conversely, India, China, Indonesia, and the Russian Federation are among the least efficient economies in terms of energy usage. As indicated by their lower EE, these nations face challenges in efficiently converting resources into economic growth.

Factors contributing to their inefficiency include excessive input usage, GDP stagnation, and rising emissions.

**Table 2.** Country-Level Energy Efficiency.

Country	Energy Efficiency Score
Argentina	1.337
Australia	1.083
Brazil	0.799
Canada	0.774
China	0.522
European Union	0.932
France	0.908
Germany	0.845
India	0.422
Indonesia	0.556
Italy	0.900
Japan	0.783
Korea, Rep.	0.635
Mexico	0.692
Russian Federation	0.592
Saudi Arabia	1.094
South Africa	1.237
Turkey	0.753
United Kingdom	1.078
United States	1.159
Avg. Val.	0.855

For less efficient economies, it is critical to adopt measures such as improving energy resource utilization, reducing carbon emissions, increasing investments in renewable energy, advancing technological innovation, and boosting GDP growth. Earlier studies by Bargaoui and Amamou [86] and Shabalov [25] emphasize the importance of REC, energy savings, technical progress, and efficient economic input usage to enhance EE levels. Furthermore, the environment has benefited from enhanced environmental policies and increased public awareness regarding the importance of conservation, both of which have contributed to improved EE. Chen [87] suggests that enhancing EE is the most effective approach to improving environmental quality. Therefore, G20 economies can enhance their ecological well-being by efficiently utilizing energy resources while minimizing emissions. Moreover, in the early 2000s, EE levels remained relatively stable, fluctuating between 0.74 and 0.76. However, a gradual decline was observed in the following years, with significant drops, reaching a low point of around 0.72 in 2010. A sharp recovery began after 2020, with EE levels steadily increasing and peaking at approximately 0.82 in 2023. The excessive use of labor and capital, rising energy prices, and substantial carbon emissions are likely key contributors to this decline in EE. Moreover, this trend reflects the varying challenges faced by G20 nations in maintaining EE and their concerted efforts to improve performance in recent years. Blackburn and Moreno-Cruz [88] supported our findings, highlighting how input-output linkages can influence EE levels, and concluded that the extensive use of inputs could lead to a decline in EE levels.

Table 3 presents the descriptive statistics for G20 countries, offering insights into the dataset's characteristics. The mean value of EE is 0.663, with an SD of 0.253, over the sampling period. Notably, Argentina achieved the maximum EE value of 1.337, indicating highly efficient energy utilization. In contrast, India records the minimum EE value of 0.422, highlighting significant potential for improvement in energy optimization. ICT has a mean value of 22.219, with an SD of 1.812, over the sampling period. The European Union leads with a maximum ICT value of 26.973, indicating advanced technological adoption, whereas Indonesia reports the lowest value of 18.210, indicating a slower pace of ICT development. RQC has a mean value of 0.616 with an SD of 0.809, demonstrating notable variability among countries. Australia demonstrates the highest RQC value of 1.942, revealing robust governance and effective regulatory systems, while the Russian Federation records the lowest RQC of  $-1.142$ , suggesting significant challenges in its regulatory framework.

**Table 3.** Descriptive Statistics.

Variable	Mean	SD	Min	Max
EE	0.663	0.253	0.238	1.000
ICT	22.219	1.812	18.210	26.973
RQC	0.616	0.809	$-1.142$	1.942
REC	2.333	0.937	$-2.303$	3.912
U_Rate	0.065	0.938	$-6.098$	1.444
Eco_Opn	3.253	0.404	2.201	4.129
Ind_Value	3.315	0.284	2.797	4.196

REC has a mean value of 2.333, with an SD of 0.937, over the sampling period. Brazil leads with a maximum value of 3.912, showing its reliance on renewable sources. The U\_Rate has a mean value of 0.065, with an SD of 0.938, over the sampling period. China reports the highest level of urbanization at 1.444, while Germany records the lowest at  $-6.098$ , indicating substantial differences in urban population densities across the G20 nations. The Eco\_Opn has a mean value of 3.253, with an SD of 0.404, over the sampling period. Saudi Arabia achieves the highest value of 4.129, indicating high trade integration. The Ind\_Value has a mean value of 3.315, with an SD of 0.284, over the sampling period. Saudi Arabia shows the highest value of 4.196, indicating significant contributions of industry to GDP, while France shows the lowest value of 2.797, reflecting its smaller industrial base relative to other G20 countries.

## 5.2. Correlation Matrix

Table 4 shows the correlations among the variables, with the strongest association observed between REC and U\_Rate, with a coefficient of 0.348. According to Kashif [21] and Zahid [89], multicollinearity becomes a concern when correlation coefficients exceed 0.700 in absolute value. In our study, all variables have correlation coefficients below 0.400, indicating that the data are within acceptable limits and free from multicollinearity issues.

Moreover, the Breusch–Pagan LM and Pesaran CD test statistics indicate significant CSD in the panel data across all models, confirming the presence of interdependencies among the series. These findings highlight the interconnected nature of G20 countries regarding energy and economic dynamics, suggesting that developments in one country can substantially affect others. Further, the statistical tests confirm that the SHT coefficients for G20 nations are heterogeneous. The Kao cointegration test strongly suggests a cointegration relationship. Moreover, Pesaran's CIPS test indicates that proxies are stationary at first difference.

**Table 4.** Correlation Matrix.

Variable	EE	ICT	RQC	REC	U_Rate	Eco_Opn	Ind_Value
EE	1.000						
ICT	0.193 *	1.000					
RQ	0.343 *	0.343 *	1.000				
REC	−0.169 *	0.114 *	−0.255 *	1.000			
U_Rate	−0.312 *	−0.326 *	−0.350 *	0.348 *	1.000		
Eco_Opn	−0.148 *	0.087 *	0.112 *	−0.165 *	−0.194 *	1.000	
Ind_Value	−0.256 *	−0.320 *	−0.380 *	−0.014	0.338 *	0.330 *	1.000

\* shows the statistically significant level at 5%. All variables' measures are presented in Table 1.

### 5.3. Influence of ICT and Regulatory Quality on Energy Efficiency

This section incorporates random year effect GLS regression to examine the impact of ICT and RQC on EE in G20 countries. Column (1) regresses EE on control variables, i.e., REC, U\_Rate, Eco\_Opn, and Ind\_Value, whereas Column (2) includes ICT and RQC as independent variables. The moderating effect of RQC on ICT is examined in Column (3).

The findings in Table 5 indicate that ICT and RQC significantly positively impact EE within G20 economies. In terms of economic significance, the results suggest that even small improvements in ICT can substantially increase EE. Specifically, a 1% increase in ICT leads to approximately 1.5–1.6% improvement in EE across the models in Columns (2) and (3). This outcome highlights the critical role of digital infrastructure and the rapid expansion of ICT in optimizing energy usage. ICT facilitates substantial cost savings through improved operational efficiency, reduced energy waste, and better resource allocation. It suggests that investments in technologies like cloud computing, advanced analytics, and digital energy management systems can significantly optimize resource consumption and reduce energy costs. These findings align with the existing literature that emphasizes the transformative potential of ICT in reshaping traditional energy practices into more efficient and sustainable systems, particularly in technologically advanced economies [11,21,25,27,30]. Furthermore, G20 countries, with their well-established technological infrastructures, are uniquely positioned to leverage ICT for large-scale efficiency gains.

RQC shows a statistically significant and positive influence on EE. The findings indicate that a 1% improvement in RQC—through stricter regulations, better enforcement, or enhanced institutional transparency—can increase EE by 11–52% across the models in Columns (2) and (3). It highlights the fundamental role of robust governance structures in achieving meaningful EE improvements. In other words, effective RQC can decrease inefficiencies, halt unclear rules and regulations, and develop an environment that boosts investments in effectual technologies. In terms of economic significance, this decreases externalities associated with energy inefficiencies, such as environmental erosion and health costs, while affirming a more sustainable industrial base. Moreover, the interaction term of  $ICT \times RQC$  has a significant positive impact on EE in Column (3), which indicates a synergistic effect. It means that robust governance improves the efficiency of ICT. Shalov [25], Shah [27], and Elfara [30] support our findings. The results show that a 1% upsurge in  $ICT \times RQC$  leads to a 17.6% enhancement in EE, indicating the significance of combining technological and institutional support to maximize EE. Therefore, it is important to understand this synergy, specifically for G20 economies, where industrial actions and urbanization trends significantly impact energy use. Furthermore, effective governance ensures that ICT's economic benefits are maximized while mitigating potential disadvantages, like inequities in technology access.

**Table 5.** Influence of ICT and Regulatory Quality on Energy Efficiency.

Variable	Energy Efficiency	Energy Efficiency	Energy Efficiency
	(1)	(2)	(3)
ICT	- -	0.015 ** (0.006)	0.016 ** (0.007)
RQC	- -	0.112 *** (0.015)	0.520 *** (0.113)
ICT × RQC	- -	- -	0.176 *** (0.021)
REC	0.033 *** (0.008)	0.048 *** (0.007)	0.064 *** (0.009)
U_Rate	−0.007 * (0.004)	−0.003 (0.004)	−0.004 (0.004)
Eco_Opn	−0.059 *** (0.017)	0.061 *** (0.020)	0.061 *** (0.020)
Ind_Value	0.167 *** (0.040)	−0.107 ** (0.051)	−0.081 (0.051)
Cont.	0.222 *** (0.036)	0.199 *** (0.046)	0.236 *** (0.046)
R <sup>2</sup>	0.921	0.906	0.907
Chi_Square	13,524.11 ***	14,114.14 ***	14,245.07 ***
Country and Year Effect	Yes	Yes	Yes

\*\*\*, \*\*, and \* show the statistically significant levels at 1%, 5%, and 10%, respectively. The parentheses show the standard error of variables. All variables' measures are presented in Table 1.

Moreover, EE trends reveal significant disparities in performance across G20 economies, with countries such as Australia demonstrating higher efficiency levels due to strong governance frameworks. Conversely, countries like the Russian Federation exhibit lower efficiency scores driven by structural inefficiencies, reliance on non-renewable energy, and weaker governance mechanisms. These findings underscore the need for targeted policy interventions to address inefficiencies in energy-intensive economies. The findings suggest that for high-performing countries, sustaining EE improvements will require continuous investment in advanced technologies, such as smart grids and energy-efficient industrial practices, alongside robust regulatory oversight. For low-performing countries, policymakers should prioritize diversifying energy sources, enhancing governance quality, and incentivizing renewable energy adoption. Providing subsidies for clean energy technologies, implementing stricter emissions regulations, and fostering public-private partnerships could significantly improve EE outcomes. The interaction between ICT and RQC further highlights the critical role of institutional capacity in amplifying the benefits of digital infrastructure. Countries with strong governance frameworks, such as the European Union, exhibit a synergistic effect where ICT adoption significantly enhances EE. In contrast, in nations with weaker governance, the positive impact of ICT remains limited. Policymakers in such regions must focus on strengthening institutional capacity by enhancing transparency, accountability, and regulatory enforcement to maximize the effectiveness of ICT-driven energy solutions.

The control proxies' outcomes are also aligned with the existing literature. REC has a consistently significant positive impact on EE, indicating its dual economic and environmental advantages. The findings suggest that greater investment in renewable energy infrastructure could yield substantial efficiency gains. This is because a shift toward renewable energy decreases dependency on fuel markets and reduces greenhouse gas

emissions. In the context of economic significance, it reduces volatility in energy costs and alleviates risks from supply chain disruptions, leading to a strong energy infrastructure. Variations in REC adoption among G20 economies highlight its potential to shape EE outcomes. For instance, nations with higher shares of renewable energy in their energy mix tend to exhibit better EE performance. This is primarily because renewables, such as solar and wind energy, provide cleaner and more efficient alternatives to traditional energy sources, reducing the energy intensity of production and consumption processes. However, the transition to renewables is not uniform across G20 economies, with some nations facing significant barriers, such as high costs of renewable energy infrastructure, intermittency issues, and resistance from established fossil fuel industries. For example, countries like the Russian Federation, which have energy systems heavily reliant on fossil fuels, face challenges in scaling up renewable energy adoption, potentially limiting their improvements in EE. Policymakers should focus on promoting REC through incentives such as subsidies, tax benefits, and research funding for innovative renewable technologies. By addressing barriers to adoption, G20 economies can accelerate their progress toward sustainability and improve their EE performance.

Moreover, the findings highlight the importance of integrated energy strategies that combine ICT progress, strong governance, and renewable energy elevation to achieve energy security, decreased emissions, and SDGs. *Eco\_Opn* positively impacts EE, suggesting effective practices for enhancing EE. The effect of *U\_Rate* and *Ind\_Value* is mixed, indicating the struggle to balance economic growth with EE. The *U\_Rate* findings suggest that although energy systems are under pressure when the infrastructure is insufficient, it creates new technological opportunities. The *Ind\_Value* finding shows that effective approaches to sectoral energy challenges with the use of relevant technologies are important. Overall, the results show the importance of both ICT and RQC towards the improvement of EE in G20 nations and indicate that a small increase in ICT and RQC will bring a significant improvement in EE, which, in turn, will provide cost savings, enhance industrial competitiveness, and offer greater environmental sustainability. In other words, the results highlight the implication of an integrated framework that combines technological investments, regulatory developments, and the promotion of renewable energy.

## 6. Robustness Tests

In this section, we perform three different tests to support the main results: First, we apply the GMM to address endogeneity. Second, we use PCSE to account for heteroskedasticity. Third, we employ FGLS to correct for cross-sectional dependence.

Earlier studies indicate the potential for endogeneity among ICT, RQC, and EE [11,21,25,26,35,50]. Such issues may arise from omitted proxy bias, measurement errors, or reverse causality, where EE could influence ICT and RQC rather than the reverse. To overcome these issues, we employ GMM, a robust and flexible approach for mitigating endogeneity in panel data analysis [90]. GMM utilizes lagged values of endogenous proxies to correct for dynamic panel bias, ensuring consistent and reliable estimates [58,91]. The association between ICT, RQC, and EE is inherently dynamic, with past levels of EE potentially influencing current ICT adoption and governance improvements, while ICT and RQC simultaneously enhance EE over time. Furthermore, it addresses unobserved heterogeneity by accounting for country-specific characteristics that may not be directly measured but could affect ICT, RQC, and EE. Therefore, we incorporate a one-year lag of EE as an endogenous variable, treating ICT and RQC as instrumented control variables following Baum [90] and Wintoki [91]. Additionally, PCSE and FGLS address heteroskedasticity, cross-sectional dependence, and autocorrelation, which are common in panel data involving interconnected economies [92]. These methods provide robust standard error estimates,

improving the reliability and accuracy of the results. They are particularly effective for validating the main findings by delivering efficient estimates even when the error structure exhibits non-constant variance or time-dependent correlation. The findings in Table 6 confirm that ICT and RQC positively impact EE, aligning with the main results. It validates that ICT, RQC, and their interaction term collectively contribute to higher EE in G20 economies, emphasizing the consistency and reliability of this study's conclusions.

**Table 6.** Robustness Tests.

Variable	Energy Efficiency	Energy Efficiency	Energy Efficiency	Energy Efficiency	Energy Efficiency
	GMM	PCES	FGLS	PCSE	FGLS
	(1)	(2)	(3)	(4)	(5)
L.EE	0.916 *** (0.028)	- -	- -	- -	- -
ICT	0.015 ** (0.007)	0.026 *** (0.003)	0.015 ** (0.006)	0.022 *** (0.003)	0.002 (0.007)
RQC	0.028 ** (0.008)	0.050 *** (0.016)	0.112 *** (0.015)	0.225 *** (0.084)	0.520 *** (0.111)
ICT × RQC	0.033 *** (0.009)	- -	- -	0.032 ** (0.014)	0.076 *** (0.021)
REC	0.011 ** (0.004)	0.029 *** (0.005)	0.048 *** (0.007)	0.033 *** (0.006)	0.064 *** (0.009)
U_Rate	-0.001 (0.002)	0.001 (0.001)	-0.003 (0.004)	0.000 (0.001)	-0.004 (0.004)
Eco_Opn	0.026 ** (0.011)	0.050 *** (0.019)	0.061 *** (0.020)	0.059 *** (0.020)	0.061 *** (0.020)
Ind_Value	-0.027 (0.073)	-0.105 *** (0.034)	-0.107 ** (0.050)	-0.114 *** (0.034)	-0.081 (0.051)
Cont.	0.082 ** (0.022)	0.147 *** (0.029)	0.199 *** (0.045)	0.170 *** (0.029)	0.236 *** (0.046)
R <sup>2</sup>	-	0.892	-	0.892	-
Chi_Square	-	5,668,211.25	14,559.44	3,913,166.60	14,704.59
Arellano-Bond (AR-1)	-2.890 **	-	-	-	-
Arellano-Bond (AR-2)	-1.310	-	-	-	-
Hansen Test (Chi-Square)	17.44	-	-	-	-
Country Effect	-	Yes	Yes	Yes	Yes
Year Effect	Yes	Yes	Yes	Yes	Yes

\*\*\* and \*\* show the statistically significant levels at 1% and 5%, respectively. The parentheses show the standard error of variables. All variables' measures are presented in Table 1.

## 7. Conclusions and Implications

### 7.1. Conclusions

This study offers new insights into the relationship between EE and ICT, emphasizing the moderating role of regulatory quality across G20 economies. It employs the DEA Super-SBM model to assess EE using an input-output framework. Additionally, it utilizes GLS models to analyze the relationship between EE, ICT, and regulatory quality. The findings show that the average EE is 0.855, indicating a potential for an improvement of 14.50% throughout the sampling period. Argentina, South Africa, the United States, Saudi Arabia, Australia, and the United Kingdom achieved the highest EE among the G20 nations, reflecting their proximity to the efficient frontier. Moreover, the results show that EE has a significant positive relation with ICT. Regulatory quality positively moderates their relationship, implying that ICT development and governance quality improve resource allocation and real-time monitoring and reduce energy wastage. These results highlight

the transformative potential of ICT, particularly in economies where industrial processes and energy consumption are closely related.

The findings further show that governance is essential in driving maximum EE. Strong regulatory quality frameworks ensure significant improvements in EE by ICT adoption. It provides the right policy guidelines, strong mechanisms for enforcement, and relevant inducements that create an enabling environment where technology would result in substantial benefits. It points out that the synergy mechanism between ICT and regulatory quality calls for proper technological advancement matched by institutional capacity. These outcomes emphasize the transformative potential of integrating ICT with governance to enhance EE. Policymakers must adapt strategies to their unique national contexts, focusing on institutional reforms in regions where governance weaknesses impede ICT's impact. Additionally, global energy strategies should prioritize collaborative efforts to bridge digital infrastructure gaps, particularly in countries with low ICT penetration. These insights contribute to shaping policies that support sustainable energy transitions and align with global climate goals. For instance, nations with strong rules and regulations and effective policies are better positioned to link digital improvements for sustainable energy outcomes. In contrast, the most cutting-edge technologies cannot realize their full potential whenever the level of governance in a country is too low. The results are more relevant to G20 nations, which host a huge share of global energy use and carbon dioxide emissions. The G20 economies hold the key to industrial production and economic action; their role is unique and needs to pave the way for other emerging economies toward sustainable energy paradigms. The results suggest that G20 nations can achieve substantial EE developments by investing in ICT infrastructure and strengthening their governance structures. This study offers a strategic blueprint to enhance EE and supports the world community's move toward a low-carbon economy and environmental sustainability. The results are robust after considering different estimation approaches like GMM, PCSE, and FGLS.

While ICT holds significant potential to improve EE by enabling real-time monitoring, resource optimization, and automation, its implementation is challenging, particularly in less developed economies. Digital infrastructure gaps, such as inadequate internet connectivity, limited access to advanced technologies, and insufficient power grid stability, can hinder the effective placement of ICT-based solutions. These gaps create a digital divide, preventing less developed economies from gaining the full benefits of ICT-driven EE initiatives. Furthermore, the high initial costs of establishing digital infrastructure, including smart grids and IoT-enabled energy systems, pose a financial barrier for many countries. Governments in less developed regions may also face challenges in formulating and enforcing policies that promote ICT adoption, particularly when regulatory frameworks are weak or inconsistent. Additionally, low levels of digital literacy among consumers and policymakers can reduce the effectiveness of ICT-driven strategies as individuals may lack the skills to fully utilize or support such technologies. Addressing these challenges requires targeted investments in digital infrastructure, capacity building, and policy support. International cooperation, such as technology transfer initiatives and financial assistance, can also play a pivotal role in enabling less developed economies to bridge the digital divide and enhance their EE performance through ICT adoption.

## 7.2. Implications

This study's results deliver significant insights into integrating ICT with strong regulatory frameworks to enhance EE and achieve sustainable economic growth. To maximize the synergistic effects of ICT and governance quality, policymakers should prioritize investments in digital infrastructure, such as smart energy technologies, while fostering public-private partnerships to drive innovation in energy management systems. In parallel,

transparent regulatory frameworks with incentives like subsidies and tax benefits can encourage the adoption of energy-efficient practices. Capacity-building initiatives, including digital literacy programs and training for regulatory bodies, are vital to ensure effective implementation. Collaboration between energy providers, ICT companies, and regulators should be encouraged to align efforts with national energy goals. Additionally, global knowledge-sharing and technology transfer initiatives can help less developed economies adopt advanced ICT solutions, contributing to global energy sustainability and closing the digital divide. These strategies collectively enable policymakers to leverage ICT's full potential to drive EE and achieve sustainable energy targets. Moreover, policymakers can achieve better resource allocation, reduce waste, and have significant EE gains by improving the level of investment in basic ICT infrastructure, such as real-time energy monitoring systems or other digital platforms that enable better resource management. Simultaneously, they should strengthen regulatory quality to create an environment conducive to achieving ICT's full potential. They have to focus more on the demand side by enhancing transparency, using appropriate energy policies, and creating incentives to enhance the acceptance of energy-efficient technologies. Policymakers should also work to improve EE by reducing energy consumption, labor, capital, and carbon emissions without negatively affecting GDP growth. Reducing energy dependence on imports while increasing renewable energy generation is critical for long-term sustainability. Additionally, economies should prioritize advancing energy technologies through research and development or collaborating with other nations to close the technological growth rate gap. Improving technological capabilities to reach the efficient frontier in energy productivity growth and enhancing the efficiency of the energy conversion process are vital areas of focus.

The main economic sectors, including industry, transportation, and residential sectors, will benefit from the synergy between ICT and governance by accepting advanced technologies to reduce operational costs and increase EE. The industrial sector is often the largest energy consumer, making it a focal point for EE initiatives. Investments in energy-efficient machinery, adopting smart manufacturing practices, and incorporating renewable energy sources into production processes can significantly reduce energy consumption and carbon emissions. For example, energy-intensive industries, such as steel and cement, have the potential to achieve substantial efficiency gains through innovations like waste heat recovery systems and advanced material technologies. The transportation sector also holds considerable potential for EE improvements through the electrification of vehicles, optimization of logistics networks, and use of alternative fuels. Urbanization trends amplify the need for efficient transportation systems, making this sector a key contributor to sustainable energy use. Similarly, the residential and commercial sectors can improve EE by adopting smart technologies, energy-efficient building designs, and increased awareness of sustainable energy practices. For instance, smart meters, automated energy management systems, and insulation technologies can reduce energy consumption while maintaining comfort and convenience. Recognizing the contributions of these sectors to EE improvements emphasizes the need for sector-specific strategies tailored to their unique challenges and opportunities. These industries should also collaborate with regulatory authorities to maintain compliance while realizing maximum energy gain. Collaboration in integrating renewable energy and ICT offers a promising avenue for greater efficiency and sustainability, leading to cost reductions and environmental benefits.

Moreover, the relationship between ICT, regulatory quality, and EE is not solely influenced by technological and regulatory factors; social and cultural influences also play a critical role. Social attitudes toward technology adoption, digital literacy, and cultural openness to change can significantly impact the speed and scale at which ICT solutions are integrated into energy management systems. For example, societies with high levels of

digital literacy and technological awareness may exhibit faster and more efficient adoption of ICT, thereby enhancing EE outcomes. In addition, cultural factors, such as trust in institutions, political stability, and public perceptions of governance, play a critical role in determining the effectiveness of governance frameworks in driving ICT-enabled EE improvements. Countries with high levels of public trust and a strong culture of compliance may experience greater success in leveraging ICT and governance for sustainable energy outcomes. Conversely, the ICT- regulatory quality - EE synergy may be weaker in societies with lower trust or cultural resistance to policy enforcement.

Although this study focuses on G20 economies, the findings hold important implications for other nations and global energy strategies. Non-G20 nations, particularly those in developing and least developed categories, face limited access to advanced technologies, weaker governance structures, and financial constraints. These challenges may limit their ability to replicate the EE gains observed in G20 economies. However, this study's insights into the synergistic effects of ICT and governance quality provide a roadmap for other nations to design policies prioritizing foundational digital infrastructure and institutional capacity improvements. For example, non-G20 nations could leverage international partnerships and technology transfer initiatives to access ICT-based energy management tools. Similarly, strengthening governance frameworks by enhancing transparency, regulatory enforcement, and public sector accountability could amplify the impact of ICT adoption on EE. These strategies would improve national EE and contribute to global sustainability goals, including those outlined in the United Nations' SDGs. At a global level, this study emphasizes the need for coordinated energy strategies that integrate ICT and governance reforms. International organizations and policymakers could use the findings to inform global initiatives to reduce energy inefficiencies and promote sustainable energy transitions across developed and developing regions. This study contextualizes these findings within a broader framework, bridging the gap between G20-focused analyses and the global need for inclusive and scalable energy solutions.

Despite its significant contributions, this study is based on aggregate data at the national level; thus, regional and sector-specific deviations may not be captured. Future research should, therefore, bridge these gaps by including low-income countries, hence offering a diversified context. This is because the outcomes might differ for low-income countries owing to their unique challenges, including limited technological penetration, weaker institutional frameworks, or financial constraints that hinder the effective implementation of EE measures. In these nations, the lack of robust ICT infrastructure may limit the capacity to achieve significant improvements in EE through digitalization. Moreover, weaker regulatory quality and governance mechanisms could delay ICT's effective placement and scaling for EE purposes. The synergy between ICT and governance observed in G20 economies may be less pronounced in these countries, where resource allocation and monitoring capabilities are often underdeveloped. Factors such as inadequate regulatory oversight, lack of investment in technological development, and dependence on non-renewable energy sources could restrict their ability to achieve similar efficiency gains. In addition, cultural and political factors, such as differences in policy priorities, administrative capacity, and public acceptance of energy-efficient technologies, could further influence these outcomes. Future research can consider these contexts along with digital literacy indices, trust in institutions, and cultural dimensions that might influence the relationship between ICT, regulatory quality, and EE. Such studies could provide a better understanding of how tailored strategies might address the technological and institutional gaps in low-income countries, thereby fostering sustainable energy transitions on a global scale.

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