Economic and Technological Efficiency of Renewable Energy Technologies Implementation

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Abstract: Recent trends prove that energy production is shifting from traditional fossil fuel combustion technologies to renewable energy-based technologies. To estimate the economic efficiency of renewable energy technology implementation, the data for the EU-27 member states during the 2012–2021 period were collected; additionally, technological efficiency was analyzed based on a critical literature review. Breusch and Pagan Lagrangian multiplier tests were employed to select the most suitable econometric model. The results suggest that an increase in the share of renewable energy sources by one percentage point (1) decreased CO$_2$ emissions by 0.137 metric tons per capita (technological efficiency) and (2) decreased greenhouse gases by 13 g per EUR, in terms of GDP (economic efficiency). Regarding the Kyoto Protocol implementation, it was found for EU-27 that an increase in the share of renewable energy sources by one percentage point was related to a decrease of one percentage point in the greenhouse gases index. GDP per capita appeared to be an insignificant driver for reductions in per capita CO$_2$ emissions, while it proved to be important for economic efficiency models. Thus, increasing GDP per capita by 1000 USD reduces greenhouse gases by 7.1 g per EUR of GDP in EU-27. This paper also confirmed that a unit of electricity (1 kWh) generated by traditional energy plants is seven to nineteen times more environmentally costly than renewable energy generation. This paper thus concludes that digital transformations and additive manufacturing brought about the significant dematerialization of industrial production and the promotion of renewable energy on industrial and household levels.

Keywords: renewable energy; greenhouse gases; energy consumption; households; economic drivers; quasi-viral phenomenon

1. Introduction

The current energy challenge is related to the critical overproduction of energy from fossil fuels, which is leading to climate change and the destruction of the planet’s energy system. Thus, there is an urgent need to transition to methods of obtaining energy that do not create/release additional amounts of energy on the planet but only redistribute energy that arrives on Earth from space. Renewable sources can solve such issues.

A distinctive feature of renewable energy sources is their relative cost-effectiveness, because renewable energy generation costs approach zero.

An additional advantage of renewable energy sources is their distributed nature. Unlike fossil fuels, which are owned by individual entities, renewable energy sources are available to most of the inhabitants on the planet. Moreover, this applies not only to the ubiquitous physical presence of the energy sources themselves (sun, wind, geothermal heat, etc.) but also to the economic possibilities of energy generation itself.

For example, today, many households in the EU can afford to have their own electricity/energy generation plant that meets their energy needs. Moreover, the renewable energy share in the EU (%) is growing year by year (Figure 1).
which are related to improving climate-responsive life. Therefore, this paper aims to replace nine keywords (e.g., plural to singular, synonyms, etc.). The minimum number of occurrences of a keyword was five. Of 3593 keywords, 122 met the threshold.

Recently, the European Commission has adopted several legislative proposals laying out plans to achieve climate neutrality by 2050, setting the intermediate target of a 55% net reduction in greenhouse gas emissions by 2030 [1].

One of the important targets of the EU is the transition to sustainable development. For achieving sustainable development goals, it is necessary not only to estimate the influence of separate drivers on social and economic achievements but also to find drivers which are related to improving climate-responsive life. Therefore, this paper aims to investigate the economic and technological efficiency of renewable energy implementation as a holistic process.

The remainder of this study is set out as follows. Section 2 analyzes relevant scientific works. Section 3 shows the data and methods utilized. Section 4 provides the empirical results and the related discussion. Section 5 encompasses the conclusions and policy recommendations.

2. Literature Review
2.1. Bibliographical Analysis and Theoretical Background

A co-occurrence analysis was performed to explore the economic efficiency of renewable energy. The dataset contains 326 journal articles in English indexed by Scopus and was searched using the terms “economic efficiency” and “renewable energy”. The results were limited to six subject areas, namely energy; environmental science; social sciences; business management and accounting; economics, econometrics, and finance; and multidisciplinary fields. The publication dates covered 1992 to 2023. VOSviewer was used to visualize the co-occurrence network. A thesaurus was used to exclude 46 irrelevant keywords, including the names of countries, the names of methods and models, and common article keywords (e.g., “article”, “integrated approach”, etc.), as well as to replace nine keywords (e.g., plural to singular, synonyms, etc.). The minimum number of occurrences of a keyword was five. Of 3593 keywords, 122 met the threshold.

As shown in Figure 2, the “economic efficiency–renewable energy” co-occurrence network formed three clusters.

Figure 1. Dynamics of renewable energy levels in the EU in 2005–2021. Source: compiled by authors based on EURstat data.
Within this paper, we will expand the literature through the discussion of environmental drivers, which, together with renewable energy, can help researchers to improve the environment and increase the greenhouse gases’ economic efficiency (e.g., more GDP is produced when emitting the same or lower amounts of greenhouse gases).

The first cluster (red) includes 51 items with the main keyword “renewable energy”, focusing on renewable and alternative energies, energy efficiency, renewable resources, and sustainable development issues.

The second cluster (green) contains 45 items with the main keyword “wind power”, focusing on power generation, energy transmission, and energy storage (including electricity) using solar, wind, and hydro power.

The third cluster (blue) contains 26 items with the main keyword “economic efficiency”, focusing on the economic efficiency of renewable energy resources, energy policy, investment, power markets, and commerce.

The performed co-occurrence analysis proved the scientific and practical significance of results related to the “economic efficiency–renewable energy” field. The above-mentioned three clusters showed the most popular research directions during the last thirty years. Within this paper, we will expand the literature through the discussion of environmental drivers, which, together with renewable energy, can help researchers to improve the environment and increase the greenhouse gases’ economic efficiency (e.g., more GDP is produced when emitting the same or lower amounts of greenhouse gases).

The empirical results for G-7 economies in the 1990–2020 period suggest that research and development, as well as renewable energy consumption, improve environmental stability by decreasing CO₂ emissions [2]. Similarly for the OBOR region, using the data for 2004 to 2019, it was found that renewable energy sources reduce CO₂ emissions both in the long and short term [3]. In Morocco, energy productivity and renewable energy were found to be the key drivers for reducing CO₂ emissions in both the short term and long term, based on data for 1990–2020 [4].

Many studies deal with the analyses of the energy efficiency of economic sectors, as well as their dependency on economic and technological factors. For example, Wolniak et al. (2020) [5], focusing on the energy efficiency of the steel sector in Poland, stated that there is a link between investment in new technologies and energy efficiency in steel production. Gajdzik, Sroka, and Vveinhardt (2021) [6] argued that increasing the technological investment in electric steel plants results in an energy consumption decrease in steel electric furnaces produced. Surya et al. (2021) [7] found that economic growth, energy consumption savings, the availability of transportation infrastructure, and renewable energy have a significant effect on environmental quality, as well as on city sustainability. The empirical papers proved the theoretical concept that renewable energy production generates almost...
zero greenhouse gas emissions during its usage phase and that emissions only appear during the construction/liquidation phases of the renewable equipment itself.

There is a list of other drivers, which together with renewable energy, determine the CO$_2$ emissions and productivity of economic systems regarding pollution. Thus, it is expected that the energy consumption of households would, in general, increase CO$_2$ emissions [8,9], since the critical point for renewable energy generation has not been reached. The influence of GDP per capita on CO$_2$ emissions is different for different countries, and it is expected that for low and middle-income countries, economic growth contributes to the growth of CO$_2$ emissions [10,11], while for high-income economies, economic growth should improve the environmental situation [12]. The proportion of industry in GDP had a significantly positive impact on the CO$_2$ emissions of 44 sub-Saharan African countries over the period of 2000–2015 [13].

Recent studies also found a link between CO$_2$ emissions and monetary and fiscal policy. For example, Qingquan et al. (2020) [14] found a significant long-term positive relationship between expansionary monetary policy and CO$_2$ emissions in selected Asian economies from 1990–2014. Yulean et al. (2019) [15] argued that fiscal policy instruments, as well as the GDP and energy consumption, significantly increase environmental degradation in the long run in China. Halkos and Paizanos (2016) [16] stated that the implementation of expansionary fiscal spending provides an alleviating effect on emissions from production- and consumption-generated CO$_2$ emissions, whereas deficit-financed tax cuts are associated with an increase in consumption-generated CO$_2$ emissions in the U.S.

Additionally, the authors argued that developed and developing countries have different determinants of CO$_2$ emissions as well as energy consumption per household. For example, Bletsas et al. (2022) [17] found out that the main determinants of gas emissions in developing countries are economic growth, government expenses, and central bank independence, whereas in developed countries, these are economic growth, government efficiency, and central bank transparency and independence. Dokas et al. (2022) [18] argued that the main determinants of energy consumption in developing countries are economic growth, investment, and winter temperature, whereas in developed countries, the determinants are trade openness, corruption, and innovation. The significant positive impact of the economic growth and trade openness on energy consumption was also confirmed by Nasreen and Anwar (2014) [19], based on the data of 15 Asian countries in 1980–2011. Moreover, authors found a bidirectional causality between economic growth and energy consumption and trade openness and energy consumption. Ugursal (2014) [20] discussed the existence of a connection between energy consumption, wealth, and human development, as well as the impact of this connection on the future of energy demand and supply, considering the forecasted increase in population. Fredriksson et al. (2004) [21] stated that corruption and industry sector size influence energy policy outcomes. Their evidence is based on the testing of an energy intensity dataset of 11 sectors in 12 OECD countries from 1982 to 1996.

The general tendency toward fast technological transformations could create the expectations that CO$_2$ emissions would be reduced on a global level and the consequences of climate change would be mitigated. However, the speed of the development of these technological transformations (such as renewable energy) must be examined in detail and whether those processes are sufficient to improve the environmental situation must be evaluated.

2.2. The Technological Transformations and Splash of Digital Human Activity

During the last few decades, the technological transformation process dynamics have revealed signs of a quasi-viral phenomenon, and the main features of this are related to the digitalization of production/consumption activities [22]. Within economic systems, innovation can be considered as a virus—“infecting” different areas—and subsequently, the system often has insufficient time to develop an “antidote” to neutralize the virus. The fast changes are the most important indicators that determine the nature of the functioning
of current socio-economic systems and can provided a basis for the comparison of the spread of technological innovations with the process of infection during pandemics. These indicators primarily include:

- The number of personal computer users;
- The number of mobile phone users;
- The number of internet users;
- The share of energy produced by renewable sources;
- Energy storage (accumulation) capacity;
- The number of 3D printers used;
- The number of devices connected to the internet of things;
- The number of industrial and household robots;
- The number of remote workers;
- The amount of information produced;
- The number of payments made over the internet.

All these indicators are signs of a new, “cleaner” production based on renewable energy and additive manufacturing (such as 3D-printing technics in industrial production to make lighter, stronger parts and systems with almost no waste in the direct production stage). The patterns of these indicators spread similarly to viral infection cases spreading during the initial stages of a pandemic. However, the time scale for innovation is longer. Table 1 shows the dynamics of essential indicators characterizing the contemporary transformation processes, where most changes show an exponential pattern.

### Table 1. Exponential nature of socio-economic indicators during recent and future decades (composed by authors with data from [23–45]).

<table>
<thead>
<tr>
<th>No.</th>
<th>Indicator</th>
<th>Year/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2000</td>
</tr>
<tr>
<td>1</td>
<td>PC users (millions) [23]</td>
<td>140</td>
</tr>
<tr>
<td>2</td>
<td>Unique mobile phone users (millions) [24]</td>
<td>110</td>
</tr>
<tr>
<td>3</td>
<td>Internet users (millions) [25]</td>
<td>415</td>
</tr>
<tr>
<td>4</td>
<td>Social media users (millions) [26]</td>
<td>&lt;1</td>
</tr>
<tr>
<td>5</td>
<td>Share of renewable energy, excluding hydropower (%) [27–29]</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>LCOE of PV energy (USD/MWh) [30–32]</td>
<td>900</td>
</tr>
<tr>
<td>7</td>
<td>Global energy storage capacity (GW/GWh) [30,33,34]</td>
<td>&lt;1/1</td>
</tr>
<tr>
<td>8</td>
<td>The global number of electric cars (10^3 units) [35–37]</td>
<td>0.5</td>
</tr>
<tr>
<td>9</td>
<td>3D printers (10^3 units) [38–40]</td>
<td>0.5</td>
</tr>
<tr>
<td>10</td>
<td>Global IoT-connected devices (units)</td>
<td>6</td>
</tr>
<tr>
<td>11</td>
<td>Industrial robots (10^3 units) [41–43]</td>
<td>742</td>
</tr>
<tr>
<td>12</td>
<td>Share of digital information (%) [44]</td>
<td>&lt;50</td>
</tr>
<tr>
<td>13</td>
<td>Cost of information storage (USD/TB) [45]</td>
<td>12,000</td>
</tr>
</tbody>
</table>
The COVID-19 pandemic has been catalytic for intensifying digital communications. Epidemiological constraints have highlighted the necessity of dematerializing communication channels and developing new communication systems to replace direct material relations with information networks. The COVID-19 pandemic boosted the transformation of supply chains with increased digitalization, automatization, real-time tracking, and cost-efficiency [46]. Better innovative and digital infrastructure development contributes to better country economic, environmental, and energy sustainability [47]. Wireless power transfer technologies have been gaining more attention during the pandemic and the subsequent conditions of global instability [48].

It has been argued that the post-pandemic recovery strategy of a country’s socio-economic system should involve the consideration of ecological effects, encompassing the reduction in environmental damage and energy dependency [49,50].

A phase transition in economic systems occurs when the basic structures of the old and new systems must exist together, supporting different technological principles, production cycles, and various industrial facilities during a transition period [51]. The latter aspect could be illustrated through the development of the energy sector when two different technologies compete (e.g., traditional fossil fuel combustion plants vs. alternative renewable energy systems) within the rising environmental restrictions. Reference [52] provides a detailed justification of ways to transform the national economy into a circular system, proposing a method of selecting relevant tools through the characteristics of each cluster in order to reduce anthropological damage to the environment.

To conclude the Section 2, it must be pointed out that renewable energy has a strong potential to change the environmental efficiency of current economic systems. Therefore, it is necessary to estimate the final empirical results of the implementation of renewable and nonrenewable technologies and develop policy recommendations to improve the environmental situation.

3. Methods and Data

To estimate the economic and technological efficiency of the implementation of renewable energy technologies, the statistical data of the EU-27 states were collected from the last available period at Eurostat (2012–2021).

The dataset used in this paper consists of three blocks: (i) the renewable energy and environmental efficiency block, (ii) the digital and social block, and (iii) the income block.

The renewable energy and environmental efficiency block includes data on renewable energy sources in electricity (percentage), renewable energy sources (percentage), carbon dioxide emissions (tons), CO2 emissions (metric tons per capita), greenhouse gases (index 1990 = 100), air pollutants and greenhouse gases (CO2, N2O in CO2 equivalent, CH4 in CO2 equivalent, HFC in CO2 equivalent, PFC in CO2 equivalent, SF6 in CO2 equivalent, and NF3 in CO2 equivalent measured as grams per EUR), and energy consumption in households (equivalent to per capita kilograms of oil).

The digital and social block includes data on mobile cellular subscriptions (per 100 people), high technology exports (percentage of manufactured exports), and the population of each country in the sample.

The income block includes data on GDP (current USD); GNI, Atlas method (current USD); GNI, PPP (current international dollars); GNI per capita, PPP (current international dollars); GDP growth (annual %); industry value added (% of GDP); exports of goods and services (% of GDP); imports of goods and services (% of GDP); gross capital formation (% of GDP); personal remittances received (current US dollars); foreign direct investment, net inflows (BoP, current USD); GDP (constant 2015 US dollars); and GDP per capita (current USD).

To identify the statistical properties of the panel data and find the possible outliers, we plotted a graph showing the leverage versus the squared residuals for the current sample (Figure 3).
For our methodology, we began by estimating the ordinary least square regression, and then the lvr2plot option in Stata 16.0 was used to plot the graph showing the leverage versus the squared residuals, and the mlabel option was used to show the two-letter abbreviations for each EU member state. Several sample outliers can be seen in Figure 3 (ID 15 and ID 8). In order to not reduce the size of the sample, the robust regression was used when outliers or high-leverage data points were found. Robust regression is useful when the data are not data entry errors but are also not from different samples; therefore, there is no specific need to exclude data from the sample. Robust regression is a good strategy since it is a compromise between excluding these points entirely from the analysis and including all the data points and treating all of them equally in regression [53].

Within this research, three indicators, namely CO₂ emissions (metric tons per capita), air pollutants and greenhouse gases (grams per EUR), and greenhouse gases (index 1990 = 100), were selected as the dependent variables. The main explanatory variables for consideration in this paper were renewable energy sources in electricity (percent) and renewable energy sources (percentage) in total energy balances. Both explanatory variables are structural and their influence on CO₂ emissions (metric tons per capita) and the greenhouse gases index (Kyoto base index) should prove the technological efficiency of renewable energy technology implementation, while their influence on air pollutants and greenhouse gases (grams per EUR) should prove the economic efficiency of renewable energy technology implementation.

The methodological point analysis of EU-27 data during 2021–2021 can be presented in liner and matrix notations:

\[ \{y_{jt}; X_{jt}\}, j = 1, 2, 3, 4 \ldots , t = 1, 2, 3 \ldots , T \]  \hspace{1cm} (1)

where \(x_1, \ldots , x_n\) is the set of explanatory variables of the general least square (GLS) regression, \(j\) is number of explanatory variables used, and \(t\) is time (years).

The empirical representation of the model (1) is identified via the following equation:

\[ y_{it} = \beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n + \epsilon_{it} \] \hspace{1cm} (2)

where \(\beta_0\) is the constant term; \(\beta_1, \ldots , \beta_n\) is the set of regression coefficients; and \(\epsilon\) is the disturbance term.
The GLS estimators possess a similar covariance structure. \( y_i \) \((T \times 1)\) is a matrix of observations for dependent variables, and \( X_i \) \((T \times k)\) is a matrix of explanatory variables.

\[
Y = \begin{pmatrix}
y_1 \\
y_2 \\
y_3 \\
\vdots \\
x_n
\end{pmatrix},
X = \begin{pmatrix}
x_1 \\
x_2 \\
x_3 \\
\vdots \\
x_n
\end{pmatrix},
v = \begin{pmatrix}
u_1 \\
u_2 \\
u_3 \\
\vdots \\
u_n
\end{pmatrix}
\]

(3)

The covariance matrix (CM) for the disturbance terms is calculated as follows:

\[
\Omega = E(u'v) = \begin{pmatrix}
\sum & \cdots & 0 \\
\vdots & \ddots & \vdots \\
0 & \cdots & \sum
\end{pmatrix}
\]

(4)

Having estimated the CM of error terms, it is possible to estimate the GLS coefficients:

\[
\hat{\beta}_{GLS} = \left( X' \Omega^{-1} X \right)^{-1} X' \Omega^{-1} Y
\]

(5)

Below, the theoretical concept is presented, which is constructed for the quantification of \( \text{CO}_2 \) emissions (metric tons per capita):

\[
\text{CO}_2 \text{ pct} = F(\text{REt}, \text{ECT}, \text{GDPpct}, \text{IST}, \text{GCFt}, \text{MCSt}, \text{HTE})
\]

(6)

where: \( \text{REt} \)—renewable energy sources (%); \( \text{ECT} \)—energy consumption of household (kg of oil equivalent per capita); \( \text{GDPpct} \)—GDP per capita in current (USD); \( \text{IST} \)—industry share (%); \( \text{GCFt} \)—gross capital formation (% of GDP); \( \text{MCSt} \)—mobile cellular subscriptions; and \( \text{HTE} \)—high technology exports (%).

A similar model and logic are applied for air pollutants (grams per EUR) and greenhouse gases (index 1990 = 100).

4. Results and Discussion

Before running econometric regressions, all dependent and independent variables were confirmed regarding stationarity using the unit root test with the Levin, Lin, and Chu (LLC) approach [54]. The empirical results of the panel stationary tests are available in Appendix A. The Ho hypothesis that the panels contain unit roots was rejected for all analyzed variables and the data are stationary.

The Breusch and Pagan Lagrangian multiplier test for random effects was employed to select either the random-effects regression or the OLS regression. The results of the test were in favor of random-effects GLS regression (Appendix B). Consequently, below, we present the results for the economic and technological efficiency of renewable energy technology implementation (Table 2).

The results prove that an increase in renewable energy sources by one percentage point in energy balance on average in a EU-27 member sample during the 2012–2021 period leads to (1) a decrease in \( \text{CO}_2 \) emissions of 0.137 metric tons per capita (Model 1); (2) decrease in air pollutants and greenhouse gases of 13 g per EUR (Model 2); and (3) improvement in greenhouse gases (index 1990 = 100) of one percentage point (Model 3). According to Model 3, renewable energy sources are the key drivers of efficient implementation of the Kyoto Protocol (committing industrialized countries and economies in transition to limit and reduce greenhouse gases (GHG) emissions) and the Paris Climate Agreement (which aimed to reduce “the increase in the global average temperature to well below 2 °C above pre-industrial levels”). The obtained results for the EU-27 are in line with other empirical papers. Thus, Guo et al. (2022) [55] found that a 1% increase in renewable energy consumption led to a decrease in carbon emission balance of 5.8%. For G7 countries, it
was proven that hydroelectric and renewable energy production was able to reduce CO\textsubscript{2} emissions in all regression models [56].

Table 2. Climate and environmental efficiency drivers in the EU-27 in 2012–2021.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Model 1 CO\textsubscript{2} Emissions (Metric Tons Per Capita)</th>
<th>Model 2 Air Pollutants and Greenhouse Gases (Grams Per EUR)</th>
<th>Model 3 Greenhouse Gases (Index 1990 = 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable energy sources (%)</td>
<td>−0.137***</td>
<td>−13.05***</td>
<td>−1.028***</td>
</tr>
<tr>
<td></td>
<td>(0.0271)</td>
<td>(3.546)</td>
<td>(0.239)</td>
</tr>
<tr>
<td>Energy consumption by household (kg of oil equivalent)</td>
<td>0.00327***</td>
<td>−0.0491</td>
<td>0.00572</td>
</tr>
<tr>
<td></td>
<td>(0.00109)</td>
<td>(0.103)</td>
<td>(0.0175)</td>
</tr>
<tr>
<td>GDP pc current (USD)</td>
<td>7.99 × 10\textsuperscript{−6}</td>
<td>−0.00719***</td>
<td>0.000162</td>
</tr>
<tr>
<td></td>
<td>(1.54 × 10\textsuperscript{−5})</td>
<td>(0.00227)</td>
<td>(0.000160)</td>
</tr>
<tr>
<td>Industry share (%)</td>
<td>0.109*</td>
<td>25.22**</td>
<td>0.362</td>
</tr>
<tr>
<td></td>
<td>(0.0563)</td>
<td>(10.49)</td>
<td>(0.340)</td>
</tr>
<tr>
<td>Gross capital formation (% of GDP)</td>
<td>−0.0396</td>
<td>−6.271</td>
<td>−0.117</td>
</tr>
<tr>
<td></td>
<td>(0.0314)</td>
<td>(4.104)</td>
<td>(0.308)</td>
</tr>
<tr>
<td>Mobile cellular subscriptions</td>
<td>−0.00494</td>
<td>1.802 *</td>
<td>−0.197**</td>
</tr>
<tr>
<td></td>
<td>(0.00700)</td>
<td>(0.987)</td>
<td>(0.0987)</td>
</tr>
<tr>
<td>High technology exports (%)</td>
<td>0.0570***</td>
<td>−2.838</td>
<td>0.494</td>
</tr>
<tr>
<td></td>
<td>(0.0213)</td>
<td>(4.156)</td>
<td>(0.467)</td>
</tr>
<tr>
<td>Constant</td>
<td>5.088***</td>
<td>356.7**</td>
<td>104.1***</td>
</tr>
<tr>
<td></td>
<td>(1.237)</td>
<td>(162.2)</td>
<td>(17.63)</td>
</tr>
<tr>
<td>Observations</td>
<td>265</td>
<td>265</td>
<td>265</td>
</tr>
<tr>
<td>Number of IDs</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
</tbody>
</table>

Robust standard errors in parentheses *** p < 0.01, ** p < 0.05, * p < 0.1.

GDP per capita appeared to be an insignificant factor for the first and third models, while it proved to be statistically significant for the model on air pollutants and greenhouse gases (grams per EUR) when an increase in GDP per capita of 1000 USD is associated with a reduction in greenhouse gases of 7.1 g per EUR. It is worth noting that an increase in energy use (kg of oil equivalent per capita) in households leads to an increase in CO\textsubscript{2} emissions (tons per capita) throughout the whole of society. EU-27 economies are still industrial societies, and an increase in industry share (% of GDP) by one percent leads to a 100 kg increase in CO\textsubscript{2} emissions per capita. The relationships between renewable energy sources and environmental efficiency can be also seen in the following figures (Figures 4 and 5).

Both figures prove that an increase in renewable energy sources in the energy balance in a sample of EU-27 states during the 2012–2021 period is associated with climate change and environmental efficiency improvements. Still, it is necessary to note that renewable energy sources are still related to greenhouse gas emissions at the production and utilization stages, and one can expect the rebound effect of the reduction in expected gains from new technologies to increase the efficiency of resource use because of behavioral or other systemic responses. At certain critical points, renewable energy sources in energy balances could start to increase greenhouse gas emissions. The results are presented in Appendices C and D. A rebound effect between renewable energy sources, climate, and environmental efficiency increases was not found, since the regression coefficients for “Renewable energy sources (%) SQUARE” appeared to be statistically insignificant.
Figure 4. The relationships between renewable energy sources and air pollutants and greenhouse gases (grams per EUR).

Figure 5. The relationships between renewable energy sources and air pollutants and greenhouse gases (index 1990 = 100).

Both figures prove that an increase in renewable energy sources in the energy balance in a sample of EU-27 states during the 2012–2021 period is associated with climate change and environmental efficiency improvements. Still, it is necessary to note that renewable energy sources are still related to greenhouse gas emissions at the production stage.
Our next step would be to compare the technological efficiency of renewable and fossil fuel energy generation. Since thermal energy production reached its improvement limits, those ratios are the same worldwide. The fundamental difference between traditional energy sources (e.g., coal, gas, oil) and renewable ones (e.g., sun, wind) is the limited direct impact of renewable-based energy power plants on the environment [57,58]. The thermal energy environmental losses structure is as follows: direct damages are 80% and the indirect specific damages per unit of output are 20% [59]. Table 3 shows an assessment of the environmental performance of various power plants in Ukraine, highlighting the differences between traditional and renewable-based energy plants.

Table 3. Environmental parameters of power plants operation (source: based on [60]).

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Air Emissions (m³/MWh)</th>
<th>Freshwater Input (m³/MWh)</th>
<th>Wastewater Discharge (m³/MWh)</th>
<th>Solid Wastes (g/MWh)</th>
<th>Environmental Protection Costs (% of General Costs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>-</td>
<td>-</td>
<td>0.02</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wind</td>
<td>-</td>
<td>20</td>
<td>0.2</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>Biogas</td>
<td>2–10</td>
<td>40–60</td>
<td>0.5</td>
<td>200–500</td>
<td>30</td>
</tr>
<tr>
<td>Coal</td>
<td>20–35</td>
<td>2–5</td>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
</tr>
<tr>
<td>Gas</td>
<td>2–15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The positive side of Table 3 is that it allows considering different environmental loads concerning other energy generation sources. The negative side of these results is that it does not allow an estimate of the actual environmental damage since the polluters are depicted as averages. Therefore, it is necessary to consider specific pollutants, which would enable the estimation and comparison of energy generation efficiency between traditional and renewable energy sources. Based on data from [28,61], Table 4 shows the differences between the indicators of damage to the environment for traditional and alternative energy sources in terms of air pollution.

Table 4. Life cycle emissions (CO₂) from various energy sources (source: based on [28,61,62]).

<table>
<thead>
<tr>
<th>Energy Sources</th>
<th>Gas Emissions (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal (best practice)</td>
<td>950</td>
</tr>
<tr>
<td>Coal (NO₃) and FGD</td>
<td>987</td>
</tr>
<tr>
<td>Oil (best practice)</td>
<td>818</td>
</tr>
<tr>
<td>Natural gas (CCGT)</td>
<td>350</td>
</tr>
<tr>
<td>Diesel</td>
<td>772</td>
</tr>
<tr>
<td>Wind</td>
<td>3–22</td>
</tr>
<tr>
<td>Solar photovoltaic</td>
<td>60–150</td>
</tr>
<tr>
<td>Solar thermal electric</td>
<td>26–38</td>
</tr>
</tbody>
</table>

Life cycle emissions in Table 4 includes all related carbon dioxide gas emissions (g/kWh), starting from the production stage of equipment that will generate electricity. Therefore, the abovementioned table considers emissions related to the production stage of electricity generation equipment, as well as the installation and operational performance of that equipment.

Coal and oil have the worst indicators regarding environmental efficiency, while wind and solar technologies are environmentally friendly. Environmental innovations are considered to be a crucial determinant of traditional energy production vitality in
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competition with the renewable energy industry [63,64]. Solar energy is often considered to be a panacea for electricity generation in developing countries [65,66]. In the 2013–2019 period, the production of wind and solar energy in Ukraine increased from 0.1% to 0.5% of total energy production and the ratio of biofuels and waste energy production increased from 1.6% to 3.8% [67].

The levelized cost of electricity has dropped significantly in many developing countries, with current levels of USD 0.29/kWh in Uganda and USD 0.27/kWh in Indonesia, for example [68]. The operating lifetime of photovoltaic panels is estimated at 15–20 years in Australia; after which, waste management must be enforced [69]. However, to reach zero fossil fuel usage by 2050, renewable energy generation is to be increased by up to six-fold (if the energy is frozen at the 2020 level) or by up to eight-fold (if energy demand increases by 50% from the 2020 level) [70].

Policy uncertainty and an underprepared transmission grid are factors that undermine the development of renewable energy sources in households in developing countries [71–74]. Knowing the structure of electricity generation energy sources in the world makes it possible to calculate weighted average traditional and renewable energy environmental costs.

Total specific greenhouse gas emissions at coal power plants and gas power plants equal 950 g/kWh and 350 g/kWh, respectively (Table 4). The share of electricity generation produced by coal and gas power plants in total world electricity production is 36% for coal and 22% for gas [75].

The weighted average world indicator of the specific greenhouse gas emissions from coal and gas power plants may be calculated as follows:

\[
(950 \times 0.36 + 350 \times 0.22)/(0.41 + 0.22) \approx 722 \text{ g/kWh}
\]  

The share of electricity generation from wind and solar power plants in the total world electricity production is 4.5% and 7.5%, respectively [75].

The specific greenhouse gas emissions from wind power plants vary from 3 to 22 g/kWh (Table 4). The specific greenhouse gas emissions from solar (PV) power plants are between 60 and 150 g/kWh (Table 4).

The weighted average world indication of the specific greenhouse gas emissions from wind and solar power plants may be calculated as follows:

- for the minimum value:

\[
(3 \times 0.045 + 60 \times 0.075)/(0.045 + 0.075) \approx 38.6 \text{ g/kWh}
\]  

- for the maximum value:

\[
(22 \times 0.045 + 150 \times 0.075)/(0.045 + 0.075) \approx 102 \text{ g/kWh}
\]  

Thus, the ratio between the specific greenhouse gas emissions for the traditional energy sector (coal and gas) and the renewable the energy sector (wind and solar) on life cycles can be calculated by dividing the value of Formula (7) by the values of Formulas (9) and (8) for minimum and maximum values, respectively:

- for the minimum value:

\[
722/102 \approx 7
\]  

- for the maximum value:

\[
722/38.6 \approx 19
\]

Calculations prove that a unit of electricity (1 kWh) generated by traditional energy plants is seven to nineteen times more environmentally costly than that of renewable energy generation plants.
5. Conclusions

Humanity has entered the next transition phase of the three modern industrial revolutions (i.e., Industries 3.0, 4.0, and 5.0). At the same time, energy generation from renewable sources and additive methods (3D printing) for processing substances are promising for the achievement of sustainability on different levels. The fast change in the most important parameters of economic systems allows the use of “the quasi-viral nature of the ongoing technological transformations” terminology. Some key parameters (the share of renewable energy, the capacity of energy storage, number of electric cars, number of 3D printers, etc.) have changed dramatically several times over the past ten years, sometimes even by an order of magnitude represented by the spread of a virus.

The obtained results suggested that relative damages from air pollution due to the production of 1 kWh of electricity from fossil fuels are from seven to nineteen times larger than renewable electricity generation-related damages. Using econometric modeling and graphical mapping, it has been found that an increase in the share of renewable energy sources in the EU-27 sample in 2012–2021 is associated with climate and environmental efficiency improvements.

The empirical models prove that the rebound effect, which is related to the reduction in gains (e.g., increases in resource efficiency/productivity) from new technology use due to the more intensive usage of such resources, is not confirmed for the renewable energy source promotion in the EU. Moreover, the promotion of renewable energy sources has a unidirectional influence on greenhouse gases, reducing its total per capita and EUR indicators.

Renewable energy generation proved to be a driver in the Kyoto Protocol’s efficient implementation; therefore, the European Commission has implemented challenging plans for changing energy generation balances from fossil fuels to renewable energy (concentrating mainly on households). In the European Green Deal, it is planned for the EU to become the world’s first climate-neutral continent by 2050.

GDP per capita appears to be an insignificant driver for the generation of CO₂ emissions (metric tons per capita) in the EU.

The policy implications of this paper are to motivate households to reduce energy consumption and stimulate renewable energy generation at accelerating rates. One of the limitations of this study is that it does not consider the influence of digitalization on the economic and technological efficiency of renewable energy technology implementation but only discusses it as a theoretical concept. Therefore, the perspectives of future research could be related to the empirical estimations of digital competencies on change in environmental situations and the environmental efficiency of industries and households. The performed analyses conclude that the new principles of production and consumption are more environmentally effective than their previous traditional counterparts.


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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. The results of the Levin, Lin, and Chu unit root test.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Adjusted t</th>
<th>p-Value</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions (metric tons per capita)</td>
<td>−6.4875</td>
<td>0.0000</td>
<td>Stationary</td>
</tr>
<tr>
<td>Air pollutants and greenhouse gases (grams per EUR)</td>
<td>−8.7965</td>
<td>0.0000</td>
<td>Stationary</td>
</tr>
<tr>
<td>Greenhouse gases (index 1990 = 100)</td>
<td>−7.8719</td>
<td>0.0000</td>
<td>Stationary</td>
</tr>
<tr>
<td>Renewable energy sources(%)</td>
<td>−4.8915</td>
<td>0.0000</td>
<td>Stationary</td>
</tr>
<tr>
<td>Energy consumption HH (kg of oil equivalent, pc)</td>
<td>−15.9059</td>
<td>0.0000</td>
<td>Stationary</td>
</tr>
<tr>
<td>GDP pc current (USD)</td>
<td>−5.9962</td>
<td>0.0000</td>
<td>Stationary</td>
</tr>
<tr>
<td>Industry share (%)</td>
<td>−10.5190</td>
<td>0.0000</td>
<td>Stationary</td>
</tr>
<tr>
<td>Gross capital formation (% of GDP)</td>
<td>−5.6406</td>
<td>0.0000</td>
<td>Stationary</td>
</tr>
<tr>
<td>Mobile cellular subscriptions</td>
<td>−5.1013</td>
<td>0.0000</td>
<td>Stationary</td>
</tr>
<tr>
<td>High technology exports (%)</td>
<td>−10.7444</td>
<td>0.0000</td>
<td>Stationary</td>
</tr>
</tbody>
</table>

Appendix B

Breusch and Pagan Lagrangian multiplier test for random effects against OLS

Source | SS df MS F(9, 260) = 28.41
Model | 1966.302928 9 107.366992 Prob > F = 0.0000
Residual | 982.706507 260 3.77964041 R-squared = 0.4958
Total | 1949.00944 269 7.24538824 Root MSE = 1.9441

co2emissionsmetric~a | Coef. Std. Err. t P>|t| [95% Conf. Interval]
renewableenergysou~e | −0.0749662 0.0125482 −5.97 0.000 −0.0996753 −0.0502571
energyconsumptioni~c | 0.0059053 0.0009454 6.25 0.000 0.0040436 0.0077669
gdpercapitacurrent~d | −9.62 × 10⁻⁶ 0.0000189 −5.51 0.612 −0.0000469 0.0000276
gdpercapitasaquare~d | 3.41 × 10⁻¹⁰ 1.54 × 10⁻¹⁰ 2.21 0.028 3.78 × 10⁻¹₁ 6.45 × 10⁻¹⁰
mobilecellularsub~a | −10.053523 0.0090105 5.94 0.000 0.0357801 0.0712658
hightechnologyexpo~u | 0.0248395 0.0218838 1.14 0.257 −0.0182526 0.0679315
foreigndirectives~w | −1.76 × 10⁻¹³ 2.28 × 10⁻¹² −0.08 0.938 −4.66 × 10⁻¹² 4.31 × 10⁻¹²
grosscapitalformat~t | −0.0447673 0.0387426 −1.16 0.249 −0.1210566 0.0315219
industryincludingc~l | −0.0199792 0.0270739 0.74 0.461 −0.0333329 0.0732913
_cons | −2.345446 1.328057 −1.77 0.079 −4.960563 0.269671

Random-effects GLS regression Number of obs = 270
Group variable: Number of ID groups = 27
R-sq: Obs per group:
within = 0.3351 min = 10
between = 0.0874 avg = 10.0
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overall = 0.0999 max = 10
Wald chi2(7) = .
corr(u_i, X) = 0 (assumed) Prob > chi2 = .

co2emissionsmetric~a | Coef. Std. Err. z P>|z| [95% Conf. Interval]
-----------------------+------------------------------------------------------
renewableenergysou~e | -0.1395363 0.0175055 -7.97 0.000 -0.1738464 -0.1052261
energyconsumptioni~c | 0.0033043 0.0011941 2.77 0.006 0.0009639 0.0056474
gdppercapitacurren~d | -4.92 × 10^{-6} 0.0000267 -18 0.854 -0.0000572 0.0000474
 gdppercapita_squared | 1.732 × 10^{-13} 1.87 × 10^{-10} 0.00 0.997 -3.65 × 10^{-10} 3.67 × 10^{-10}
mobilecellularsub~10 | -0.0050593 0.006184 -0.82 0.413 -0.0171797 0.0070612
hightechnologyexpo~u | 0.0582125 0.0321386 1.26 0.209 0.0323959 0.1583770
foreigndirectinves~w | -9.36 × 10^{-13} 8.98 × 10^{-13} -1.04 0.297 -2.70 × 10^{-12} 8.24 × 10^{-13}
grosscapitalformat~1 | -0.024057 0.0192846 -1.26 0.209 -0.0620028 0.0135914
 industryincludingc~l | 0.0953865 0.0321386 2.97 0.003 0.0323959 0.1583770
 _cons | 5.55009 1.383418 4.01 0.000 2.838641 8.261547

sigma_u | 2.1128657
sigma_e | 0.6821353
rho | 0.9056075 (fraction of variance due to u_i)

Breusch and Pagan Lagrangian multiplier test for random effects
co2emissionsmetrictonspercapita[id, t] = Xb + u[id] + e[id, t]
Estimated results:
<table>
<thead>
<tr>
<th>Var sd = sqrt(Var)</th>
</tr>
</thead>
<tbody>
<tr>
<td>co2emissionsmetric</td>
</tr>
<tr>
<td>e</td>
</tr>
<tr>
<td>u</td>
</tr>
</tbody>
</table>
Test: Var(u) = 0
chibar2(01) = 736.89
Prob > chibar2 = 0.0000
Note: the evidence of a group-wise effect is enough to switch from pooled OLS to xt RE.

Appendix C

Table A2. The estimation of the rebound effect between renewable energy sources climate/environmental efficiency increases.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Model 1 CO2 Emissions (Metric Tons Per Capita)</th>
<th>Model 2 Air Pollutants And Greenhouse Gases (Grams Per EUR)</th>
<th>Model 3 Greenhouse Gases (Index 1990 = 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable energy sources (%)</td>
<td>-0.138 ***</td>
<td>-16.58 ***</td>
<td>-1.797 ***</td>
</tr>
<tr>
<td></td>
<td>(0.0418)</td>
<td>(4.556)</td>
<td>(0.472)</td>
</tr>
<tr>
<td>Renewable energy sources (%)_SQUARED</td>
<td>4.29 × 10^{-5}</td>
<td>0.0681</td>
<td>0.0152 *</td>
</tr>
<tr>
<td></td>
<td>(0.00103)</td>
<td>(0.0977)</td>
<td>(0.00867)</td>
</tr>
<tr>
<td>Energy consumption HH (kg pc)</td>
<td>0.00330 ***</td>
<td>-0.0558</td>
<td>0.00510</td>
</tr>
<tr>
<td></td>
<td>(0.00112)</td>
<td>(0.109)</td>
<td>(0.0168)</td>
</tr>
<tr>
<td>GDP pc current (USD)</td>
<td>8.45 × 10^{-6}</td>
<td>-0.00717 ***</td>
<td>0.000170</td>
</tr>
<tr>
<td></td>
<td>(1.56 × 10^{-5})</td>
<td>(0.00227)</td>
<td>(0.000162)</td>
</tr>
<tr>
<td>Industry share (%)</td>
<td>0.109 *</td>
<td>25.40 **</td>
<td>0.382</td>
</tr>
<tr>
<td></td>
<td>(0.0559)</td>
<td>(10.53)</td>
<td>(0.336)</td>
</tr>
<tr>
<td>Gross capital formation (% of GDP)</td>
<td>-0.0399</td>
<td>-6.054</td>
<td>-0.0700</td>
</tr>
</tbody>
</table>
Table A2. Cont.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Model 1 CO₂ Emissions (Metric Tons Per Capita)</th>
<th>Model 2 Air Pollutants And Greenhouse Gases (Grams Per EUR)</th>
<th>Model 3 Greenhouse Gases (Index 1990 = 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile cellular subscriptions</td>
<td>(0.0321)</td>
<td>(4.084)</td>
<td>(0.294)</td>
</tr>
<tr>
<td></td>
<td>−0.00473</td>
<td>1.889 *</td>
<td>−0.175 *</td>
</tr>
<tr>
<td>High technology exports (%)</td>
<td>(0.00713)</td>
<td>(1.018)</td>
<td>(0.0947)</td>
</tr>
<tr>
<td></td>
<td>0.0568 ***</td>
<td>−2.763</td>
<td>0.516</td>
</tr>
<tr>
<td></td>
<td>(0.0212)</td>
<td>(4.045)</td>
<td>(0.432)</td>
</tr>
<tr>
<td>Constant</td>
<td>5.056 ***</td>
<td>373.8 **</td>
<td>107.0 ***</td>
</tr>
<tr>
<td></td>
<td>(1.254)</td>
<td>(162.0)</td>
<td>(18.27)</td>
</tr>
<tr>
<td>Observations</td>
<td>265</td>
<td>265</td>
<td>265</td>
</tr>
<tr>
<td>Number of IDs</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
</tbody>
</table>

Robust standard errors in parentheses *** p < 0.01, ** p < 0.05, * p < 0.1.

Appendix D

Table A3. The reduced model for estimation of the rebound effect between renewable energy sources and climate/environmental efficiency.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Model 1 CO₂ Emissions (Metric Tons Per Capita)</th>
<th>Model 2 Air Pollutants And Greenhouse Gases (Grams Per EUR)</th>
<th>Model 3 Greenhouse Gases (Index 1990 = 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable energy sources (%)</td>
<td>−0.154 ***</td>
<td>−18.66 ***</td>
<td>−1.774 ***</td>
</tr>
<tr>
<td></td>
<td>(0.0459)</td>
<td>(5.870)</td>
<td>(0.550)</td>
</tr>
<tr>
<td>Renewable energy sources (%)_SQUARED</td>
<td>4.62 × 10⁻⁵</td>
<td>0.0404</td>
<td>0.0163</td>
</tr>
<tr>
<td></td>
<td>(0.000955)</td>
<td>(0.127)</td>
<td>(0.0111)</td>
</tr>
<tr>
<td>Constant</td>
<td>9.351 ***</td>
<td>787.3 ***</td>
<td>107.4 ***</td>
</tr>
<tr>
<td></td>
<td>(0.934)</td>
<td>(132.8)</td>
<td>(8.005)</td>
</tr>
<tr>
<td>Observations</td>
<td>270</td>
<td>270</td>
<td>270</td>
</tr>
<tr>
<td>Number of IDs</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
</tbody>
</table>

Robust standard errors in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1.

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