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Article

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MARKET CHANGES IN THE ENERGY AND GREEN ENERGY SECTOR DURING THE COVID-19 CRISIS: A GLOBAL PERSPECTIVE

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Abstract
The objective of this study was to examine the effects of the COVID-19 pandemic on the energy and electricity industry, with a particular focus on green energy sources such as wind and solar energy. The analysis provided a global perspective, based on a panel of 45 countries that represent more than 90% of the world's GDP. The analysis was structured in two steps: a counterfactual analysis based on the mean and variance of the country data sample for the 14 indicators and the 45 countries in the panel and a counterfactual analysis that looked at the statistical significance of the difference of mean between the data sets referring to the time of the pandemic and before the time of the pandemic using the t-student test of 2 samples assuming unequal variances between samples. For the pandemic time, the analysis took into consideration two years (2020 and 2021), and the benchmark year was 2019. The counterfactual analysis included a short-term perspective based on a comparative analysis with the dynamic of the year before the crisis (2019/2018 dynamic) and a long-term perspective based on a comparative analysis with the multiannual average dynamic (2019/2015 – 5 years). The study results indicated that the COVID-19 pandemic has led to a decline in global energy and electricity production, a partial reduction in global greenhouse gas emissions, a partial improvement in the global trade balance with energy and electricity, a decrease in global energy and electricity consumption, and a partial increase in global green energy and electricity production and intensity.

Keywords: COVID-19 crisis, global economy, energy, green energy, sustainable development.

JEL Classification: F01, N70, Q01, Q58

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Introduction

This article aims to investigate the impact of the COVID-19 pandemic on the energy and electricity industries, which is considered a critical event in the current decade. The academic discourse on this topic remains ongoing and no definitive conclusions have been reached. Our analysis will contribute to this discourse, which is fundamental in defining the approach to one of the most critical challenges facing human society in the near future: climate change and the natural environment. The subject of energy and its relationship to the environment received considerable attention during and after the pandemic crisis, with scholars providing different perspectives and explanations for the changes in the market. Despite its significant impact, efforts to transition to clean energy intensified following the crisis.

This research aims to examine the influence of the COVID-19 crisis on the energy market, including production, consumption, and energy intensity, with a specific focus on changes in green electricity resulting from this unusual situation. The study uses empirical data on the energy and electricity markets of selected countries around the world, offering a global perspective of the impact of the crisis. To capture this impact, the study develops five research hypotheses. The results are statistically significant and consistent with recent literature, indicating that the COVID-19 crisis has played a role in the current disruptions of the energy market.

The emergence of the COVID-19 pandemic in 2020 has presented one of the most pressing challenges for humanity in the past decade. This global health crisis has challenged the political and economic systems and forced most countries to develop new approaches to dealing with unexpected and significant events. The COVID-19 pandemic can be classified as a *black swan* event, as it was a low probability event despite previous warnings, such as SARS or MERS-COV. The COVID-19 pandemic has resulted in the loss of 5.975 million lives worldwide, according to Nigam et al. (2022, p.1).

Some observers suggest that the emergence of the COVID-19 pandemic can be attributed to climate change and the significant difficulties that the natural environment poses to human society due to the profound transformations it is undergoing.

The emergence of COVID-19 has presented unprecedented challenges due to its rapid spread and high mobility. To contain the spread of the virus and prevent the overwhelming of healthcare systems, numerous countries, including China, implemented unprecedented lockdown measures. These policies immediately and profoundly affected the mobility and economic activity of citizens. In addition, confinement of individuals to restricted areas significantly reduced their carbon footprint. This sudden and drastic decrease in pollution was mainly due to reduced air travel and fuel consumption from automobiles.

1. Literature review

Due to the specific nature and rapid global spread of the COVID-19 crisis, there has been a significant increase in the economic literature studying its impact on the social and economic environment and challenging governments and public policies around the world. These studies can be broadly categorised into several distinct areas, including studies on the impact of the crisis on economic growth and development, studies on the effects of COVID-19 measures and public policies, studies on the environmental impact of the crisis, studies analysing the impact on various industries and sectors (including the energy and green energy sectors), and studies examining the social impact, including poverty, inequality, and access to medical services.

The COVID-19 pandemic caused varying levels of disruption in global markets. The energy sector was not spared and was affected in different ways, depending on the region. The impact of COVID-19 on the energy market can be categorised into several areas: (i) its effect on pollution levels, which influences public policies and strategies; (ii) its impact on energy production; (iii) its effect on energy consumption; (iv) its impact on the production and intensity; and (v) the geopolitical implications of COVID-19, which results in significant changes in the global energy market. Following extensive analysis, it can be concluded that the global energy sector is one of the hardest hit industries due to the effects of the pandemic on energy supply and demand and pricing mechanisms, resulting in significant uncertainty (Bashir et al., 2021).

However, some studies suggest that lockdowns have led to the emergence of other forms of pollution. Janardhanan (2020) noted that the crisis generated by COVID-19 posed a dual global challenge. The reduction in social mobility has led to increased door-to-door services by the food and retail industries. Additionally, with individuals confined to their homes, telework has increased, resulting in increased residential consumption of utilities, goods, and services. As stated in a report by the European Commission, the environmental impacts of COVID-19 are more complex than anticipated (European Commission, 2022). Atoufi, Lampert and Sillanpää (2021) observed that COVID-19 had been a double-edged sword for the environment. Although it has helped reduce air pollution, greenhouse gas emissions, noise pollution, and human exposure to the environment, it has increased the generation of solid waste microplastics. This negative impact has also been highlighted by Soubry, Rosen and Tsioumani (2021).

Lockdowns and mobility barriers have had a significant impact on economic activities by affecting the production and consumption of final and intermediate goods and services. This reaction has led to the temporary closure of many factories and manufacturing facilities around the world and the introduction of numerous regional and international trade barriers, causing supply chain disruptions and significant problems in various industries. Adjustments in demand and supply in different markets have resulted in significant price changes. Such second-wave effects have also affected the economic and social behaviour of individuals and entities, resulting in higher prices for certain goods and services. Furthermore, the current turbulent economic and political environment presents unprecedented challenges, exacerbated by the Russian invasion of Ukraine, which has brought massive disruptions to the international market and necessitated new approaches to international policy coordination. Furthermore, COVID-19-related lockdowns, disruptions of global supply chains, and national support measures to keep food and fuel prices affordable have contributed to the lasting changes associated with COVID-19. These changes are particularly evident in the transport sector, including aviation, less office work, and altered commuting habits, which will likely result in the use of transport energy never again reaching 2019 levels, according to Alvik and Irvine (2020).

The implementation of COVID-19 lockdown measures resulted in a significant decrease in weekly electricity demand by 10-35% in affected regions, as reported by the International Energy Agency (IEA, 2020). Restrictive measures such as travel bans, border closures, remote learning, and work have led to a reduction in personal vehicle use and other forms of transportation (Hoang et al., 2021). The World Health Organisation (WHO) has revealed that 733 million people do not have access to electricity, while 2.4 billion people still use harmful fuels to cook. This implies that 670 million people will continue to be without electricity by 2030 (WHO, 2022). According to current models, the pandemic is expected to result in an

8% reduction in energy demand by 2050, with energy demand projected to reach the 2018 level, according to the research by Alvik and Irvine (2020). In 2020, the IEA predicted a decline of 13% in net additions of renewable power capacity compared to 2019 due to supply chain disruptions, lockdown measures, social distancing guidelines, and financing challenges. However, the installed global renewable power capacity still increased by 6%, surpassing the combined size of power systems in North America and Europe (IEA, 2020). Lu et al. (2021) confirmed that during the COVID-19 crisis, clean energy consumption replaced conventional energy consumption, supply chain shortages increased, and unemployment increased.

In the context of a global transition to a greener economy, COVID-19 has introduced significant challenges and uncertainties. The pandemic has occurred during a period of significant restructuring in energy markets, which have been at the forefront of addressing global warming by reducing the consumption of fossil fuels. Although traditional energy sources have been abandoned in favour of renewable energy, gas has been viewed as a transition choice. However, Gaucher et al. (2022) argue that policies that discourage the use of fossil fuels are also necessary for climate change mitigation.

The pandemic crisis has resulted in a decrease in energy and electricity demand due to various causes, such as reduced transportation and industrial production, declining car sales, and changes in climate conditions. The oil market has been strongly coupled with the renewable energy market, and changes in the production structure reflect expected changes in global environmental protection (Horky, Mutascu and Fidrmuc, 2022). Priya, Cuce and Sudhakar (2021) suggest that COVID-19 lockdown measures have significantly reduced energy use as people cut back on driving and travelling, and businesses and factories reduce operations to protect workers' health.

The current situation of uncertainty regarding the greening of the economy has placed decision-makers in a challenging predicament. Specifically, they must weigh the potential benefits of accelerating the transition process in the midst of economic disruption caused by the COVID-19 pandemic against the potential risks and challenges posed by such an approach.

As cited by Selby and Kagawa (2020), Clark noted that the shutdown of industrial activity, limited flights, reduced road traffic, and clearer skies have resulted in reduced greenhouse gas emissions and pollution levels, providing a glimpse of a different world. As such, the question arises whether the COVID-19 pandemic would lead to the abandonment of ambitious pollution reduction targets or, conversely, present an opportunity to push even further. Blondeel, Van De Graaf and Haesebrouck (2020) have highlighted the need to ensure a structural decline in greenhouse gas emissions aligned with the Paris Agreement despite the drop in economic activity leading to a significant reduction in emissions.

Divergent viewpoints exist regarding the economic implications of environmental policies and policy makers are wary of provoking political and social upheaval. Bianchi et al. (2020) observed that several populist parties in Europe are exploiting these concerns by advancing a reactionary narrative. Therefore, political leaders must persuade the general populace to support the *greening* agenda; otherwise, the environmental agenda may be jeopardised. Pantuliano (cited in Selby and Kagawa, 2020, p. 22) asserted that returning to pre-pandemic *normal* policies would exacerbate the environmental crisis, arguing, "We won't go back to normal because normal was the problem."

Furthermore, returning to pre-pandemic policy measures is likely to exacerbate the environmental crisis, as indicated by research findings that reveal the short-term and unsustainable nature of improvements in air quality in most regions. According to Zhang et al. (2022), the concentration of NO_2 increased rapidly with the resumption of production, indicating the insustainability of improvements in air quality following the COVID-19 pandemic. Many activists propose that continuing the deep restructuring posed by the pandemic is the most optimistic agenda, as it offers opportunities for transformative policies that simultaneously address sustainability and prosperity (Bianchi, 2020). However, whether political decision makers around the world will adopt and follow such an agenda remains to be seen. The pandemic has been regarded as a test or exercise in the process of addressing policy measures necessary for a more radical approach to addressing global warming, and activists believe that the speed and extent of the global response to the virus signify that global mobilisation on policy issues is possible, even when it requires significant economic disruption (Brannen, Haig and Schmidt, 2020).

According to Hoang et al. (2021), the increasing development of new technologies such as renewable energy systems (e.g., wind and photovoltaic), energy storage and hydrogen technologies has led to a steady rise in renewable energy demand, with the United States, China, Japan, Southeast Asia, and Africa contributing a significant portion of renewable energy generation. However, achieving a sustainable energy balance in the future is not guaranteed and requires faster solutions for energy security and new energy management systems. In response to lower overall demand, energy production has been significantly reduced, leading to a decrease in natural gas demand by up to 2%, particularly in China, Europe and the US, as well as a notable reduction in global demand for coal and oil.

According to several studies, the negative impacts of the pandemic, such as a 9% reduction in world GDP by 2050 compared to pre-pandemic forecasts, are likely to persist (Alvik and Irvine, 2020). Furthermore, there is an increasing dependence on renewables and the production of biofuels, which can come at the expense of food crops. The cost of financing and securing measures to combat climate change to support adaptation, loss, and damage is also expected to increase. Large corporations have taken advantage of an inflationary environment to increase their profits and dividends, particularly in the food and energy sectors, where monopolies are prevalent. The wealth of billionaires in these sectors has increased by $453 billion in the past two years, equivalent to $1 billion every two days (Oxfam, 2022). However, lower energy demand has led to a rise in the share of renewable energy consumption worldwide (Sadiq et al., 2022). Many countries have intensified their efforts to implement policies that increase the share of renewables in their energy mix during and after the pandemic crisis (Sultan et al., 2021).

The COVID-19 pandemic has hindered progress toward universal energy access, resulting in a 2.5% global reduction in electricity demand in 2020, with a double impact during the lockdown period (Elavarasan et al., 2020). This evolution has led to a growing interest in increasing the importance of green energy in reducing energy self-dependence (Anderson et al., 2020). The pandemic has also affected progress toward achieving Sustainable Development Goal 7 of ensuring universal access to affordable, reliable, sustainable, and modern energy by 2030 (WHO, 2022). However, the pandemic has also led to the implementation of green stimulus plans as part of the economic recovery and energy transition process, prioritising transportation, heating, and electricity (Tian et al., 2022).

These stimulus plans are considered real opportunities for market players and are being implemented by many countries (Tian et al., 2022).

This article aims to contribute to the ongoing discussion on the economic and social implications of the pandemic on a global scale. Therefore, the collective findings of these studies unequivocally indicate that the impact of COVID-19 on the energy industry was more adverse than in other sectors, preventing progress toward recovery. Furthermore, COVID-19 has substantially transformed the global energy landscape in terms of production and consumption, exerting a profound impact on public policies that promote economic development and growth through the energy sector.

2. Research methodology and design

This research investigates the impact that the COVID-19 crisis has had on the energy sector, including green energy (renewable energy, wind and solar, etc.). Following this research objective, we propose five research hypotheses on the impact of the COVID-19 crisis:

• *H1: The COVID-19 crisis had a negative impact on energy and electricity production.* In our opinion, the determinant factors that could explain this research hypothesis are the economic and social restrictions imposed on the population and the business sector that temporarily closed the production of goods and services and that generated important disruptions in the main global supply channels with spare parts and components. These factors caused significant problems in the production of energy and electricity and could explain the presumed reduction in it at the global level.

• *H2: The COVID-19 crisis had a positive impact on greenhouse gas emissions.* Among the determinant factors that could explain this positive impact (the reduction of green-gas) are: the significant economic contraction due to the restriction applied in the pandemic time, the social imposed distance, and the limitation of the social life and activities that reduced the activity volume in the transportation sector.

• *H3: The COVID-19 crisis had a negative impact on energy and electricity consumption.* The short-term influence on the consumption of energy can be explained by the restrictions applied to the population and the imposed social distancing policies (limited working time, limited time for shopping, very restrictive conditions for travel and shopping, etc.). Long-term influence could be explained by the introduction of new technologies and innovations that reduce the amount of energy consumed by machines and equipment in the production processes or reduce the consumption of energy of the population (electric cars, for example).

• *H4: The COVID-19 crisis had a positive impact on trade balance (difference between imports and exports).* The determinant factor that could explain the presumed improvement of the commercial balance with energy is the reduction of consumption that decreased the export volume (for exporting countries) and decreased the needs for imports (for importing countries). Practically, lower energy demand decreased dependence on imports and significantly limited the volume of exports for a while.

• *H5: The COVID-19 crisis had a positive impact on the production of green energy (renewable, wind, and solar) and the importance of green energy in the production of total energy / electricity.* The determining factor that could explain this research hypothesis took into account the reduction of costs and the higher efficiency in energy production and

consumption. The technological progress of today allows for the replacement of the classical energy sources by green ones and opens new perspectives in this direction. Green energy became a viable alternative to the traditional way of producing energy. A crisis is always considered a good opportunity to invest in capital saved from consumption. The crisis is seen as the time to prepare for the next boom by investing in more production or greater efficiency. Green energy improves economic efficiency due to the availability and sustainability of the energy source.

Table no. 1. Research hypotheses and selected indicators

Hypothesis	Indicators used in the empirical analysis
H1: The impact on the energy production	• Total energy production (*Mtoe*); • Electricity production (*TWh*); • Energy intensity of GDP at constant purchasing power parities (*koe/$15p*).
H2: The impact on the greenhouse gas emissions	• CO_2 intensity at constant purchasing power parities (*kCO_2/$15p*); • Average CO_2 emission factor (*tCO_2/toe*).
H3: The impact on the energy consumption	• Total energy consumption (*Mtoe*); • Electricity domestic consumption (*TWh*); • Share of electricity in total final energy consumption (*%*).
H4: The impact on the balance of energy trade	• Energy balance of trade (*Mtoe*); • Electricity balance of trade (*TWh*).
H5: The impact on green energy/electricity production and intensity	• Renewable electricity production (*TWh*); • Wind and Solar electricity production (*TWh*); • Share renewables in total electricity (*%*); • Share wind and solar in total electricity (*%*).

Source: own representation

The global data source is the database provided by *Enerdata* (online access to the database: https://www.enerdata.net). The database covers the following regions: Europe (14 countries), CIS (4 countries), North America (2 countries), Asia (8 countries), the Pacific (2 countries), Africa (4 countries), and the Middle East (4 countries). The following forty-five countries are included in the dataset (in alphabetical order): Algeria, Argentina, Australia, Belgium, Brazil, Canada, Chile, China, Colombia, Czech Republic, Egypt, France, Germany, India, Indonesia, Iran, Italy, New Zealand, Nigeria, Norway, Netherlands, Poland, Portugal, Romania, Spain, Sweden, United Kingdom, Turkey, Kazakhstan, Russia, Ukraine, Uzbekistan, United States, Mexico, Japan, Malaysia, South Korea, Taiwan, Thailand, South Africa, Kuwait, Saudi Arabia, United Arab Emirates. Since the 45 selected countries account for more than 90% of the world's GDP, our research is relevant to provide a global perspective. The choice of this panel was imposed by the condition to use a complete data panel (with country data for all countries and for all years included in the study).

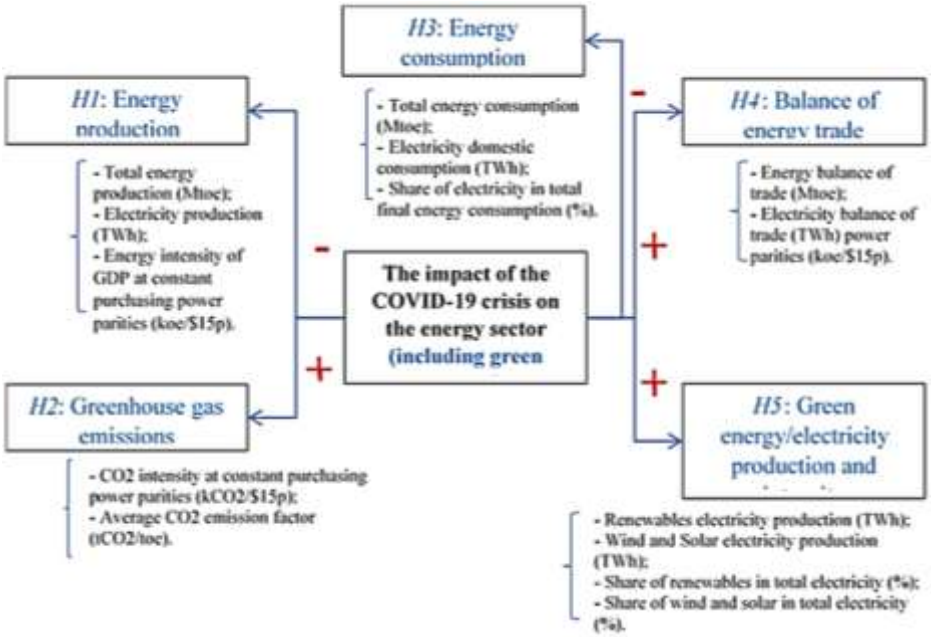

Figure no. 1. Map of research hypotheses, indicators, and estimated impact

Based on the data collected for the selected indicators for each hypothesis (see Table no. 1 and Figure 1), we calculated the following growth rates based on log values – $Log[V_1/V_0]$:

- $Log[V_{2020}/V_{2019}]$ estimates the evolution of selected variables in the first year of the COVID-19 crisis;
- $Log[V_{2021}/V_{2019}]$ estimates the evolution of selected variables in the second year of the COVID-19 crisis, taking into consideration the year before the crisis too;
- $Log[V_{2019}/V_{2018}]$ estimates the evolution of the selected variables one year before the COVID-19 crisis (for the short-term impact);
- $Log[V_{2019}/V_{2015}]$ estimates the evolution of the selected variables in the last five years before the COVID-19 crisis (for the long-term impact).

As it could be noticed, the analysis uses two data sets for the period before the crisis: a data set that refers to the dynamic for a single year, the year before the crisis – 2019/2018 (for the short-term impact) and a data set that refers to a multi-annual average dynamic – 5 years, 2019/2015 (for the long-term impact). Using this multiannual average dynamic before the crisis, we could better observe the importance of the influence of this COVID-19 crisis on the dynamic of the energy sector.

Regarding the time of the pandemic, we decided to include in the analysis two relevant years that are associated with it: 2020 and 2021, the first year being considered more severe in terms of its social and economic impact. For the second year of COVID-19, we also used the dynamic of the year before the crisis (2019/2018) and not the previous year (2020), considering that this is more relevant for the impact assessment on the selected variables.

Our research was designed in two subsequent stages: (i) a counterfactual analysis based on the mean and variance of the 14 selected indicators corresponding to these five research hypotheses, and (ii) a counterfactual analysis based on the t-test to test the statistical significance of the differences between the data sets corresponding to the pandemic time and before the pandemic time (short-term and long-term perspective). This methodological option (mean analysis, variance analysis and 2 sample t-test assuming unequal variances) is argued by the nature of the proposed analysis, a counterfactual analysis focused on the impact of an event that generated a lot of social and economic effects at global and regional level. This analysis had no specific goal of determining the exact impact of COVID-19 on the consumption or production of energy or the structural changes of the market, but was primarily focused on observing whether COVID-19 significantly changed or not the dynamic of the energy sector by looking at its main components (production, consumption, and green energy).

The empirical analysis started with the mean and variance analysis of the data sets that describes the dynamic of the 14 indicators selected according to the research hypothesis (Table 1). We estimated, based on the dynamic for each country, the following logarithmic values: $Log[V_{2020}/V_{2019}]$ – for the first year of pandemic crisis, $Log[V_{2021}/V_{2019}]$ – for the second year of pandemic crisis, $Log[V_{2019}/V_{2018}]$ – for the short term perspective (the first year before crisis dynamic) and $Log[V_{2019}/V_{2015}$ – for the long term perspective (5 years average dynamic). All these logarithmic values were calculated for all countries and for all indicators and were observed for two years of pandemic and two periods before the pandemic crisis. In this stage of the analysis, we look at the differences in terms of mean and variance during the pandemic time and before the crisis and analyse the significant changes by comparing them with the research hypotheses.

In the second stage of our analysis, for the robustness of the results, we considered it important to add to the counterfactual analysis a parametric test (2 samples t-test assuming unequal variances) of the differences between the data sets before crisis (short-term perspective and long-term perspective) and pandemic time (first- and second-year dynamics). This parametric test allowed us to test whether the unknown means of the two samples are equal and to see if the differences before and during the COVID-19 crisis are statistically significant. In the case where these differences between *before* and *during the* crisis were statistically relevant, we could emphasise the conclusion that COVID-19 had a strong and clear impact and, moreover, the research hypotheses are better validated.

3. Results and discussion

The energy sector is a key sector for economic development and for the sustainability of development. Depending on its nature, the crisis could have a more or less important impact on various sectors (for instance, a financial crisis is expected to affect more the banking sector and the small and medium enterprises). The COVID-19 crisis was a very complex one, considering its various and unexpected effects. The solutions applied by governments as a response to this pandemic crisis generated significant changes in production and consumption, one of the most affected sectors being the energy sector (not only production and consumption were affected, but also their structure, including green energy).

The first test focused on the first two hypotheses: the influence of COVID-19 on energy / electricity production (*H1*) and greenhouse gas emissions at the global level (*H2*).

Table no. 2. Mean and variance for the impact of COVID-19 on the production of energy/electricity and greenhouse gas emissions (short-term and long-term perspective)

First-year COVID-19 impact	Mean		Variance	
	t_0	t_1	t_0	t_1
Total energy production	0.005	-0.025	0.001	0.001
Electricity production	0.001	-0.005	0.000	0.000
Energy intensity of GDP	-0.021	-0.006	0.005	0.000
CO_2 Intensity	-0.024	-0.010	0.005	0.000
Average CO_2 Emission Factor	-0.004	-0.003	0.000	0.000
Second-year COVID-19 impact	**Mean**		**Variance**	
	t_0	t_1	t_0	t_1
Total energy production	0.005	-0.012	0.001	0.001
Electricity production	0.001	0.012	0.000	0.001
Energy intensity of GDP	-0.021	-0.010	0.005	0.000
CO_2 Intensity	-0.024	-0.014	0.005	0.001
Average CO_2 Emission Factor	-0.004	-0.004	0.000	0.001
Long-term impact of the first year	**Mean**		**Variance**	
	t_0	t_1	t_0	t_1
Total energy production	0.020	-0.025	0.004	0.001
Electricity production	0.026	-0.005	0.002	0.000
Energy intensity of GDP	-0.035	-0.006	0.006	0.000
CO_2 Intensity	-0.052	-0.010	0.006	0.000
Average CO_2 Emission Factor	-0.016	-0.003	0.001	0.000
Long-term impact of second year	**Mean**		**Variance**	
	t_0	t_1	t_0	t_1
Total energy production	0.020	-0.012	0.004	0.001
Electricity production	0.026	0.012	0.002	0.001
Energy intensity of GDP	-0.035	-0.010	0.006	0.000
CO_2 Intensity	-0.052	-0.014	0.006	0.001
Average CO_2 Emission Factor	-0.016	-0.004	0.001	0.001

Note: t_0 – before COVID-19 and t_1 – during COVID 19.

Source: own estimations based on Enerdata time series.

Analysis of mean and variance (Table 2) revealed the following: (i) The short-term perspective: the production of energy decreased, for both pandemic years, the production of electricity decreased in the first year of crisis but in the second year of crisis increased, the decrease of the energy intensity of GDP continued during the pandemic crisis (both years) but decelerated (especially in the second year), the decrease of CO_2 and the average CO_2 emission factor also decelerated (especially in the first year of crisis and especially for CO_2 intensity; (ii) The long-term perspective: the total production of energy and electricity continues to decrease but with less intensity during the pandemic years (therefore, we concluded that this is a long-term trend but decelerated by COVID-19 crisis). The same is true in the case of GDP energy intensity, CO_2 intensity (significantly decelerated in both pandemic years), and the average CO_2 emission factor (decelerated more in the second year of crisis).

Based on this mean and variance analysis, we can conclude that H1 is confirmed in both perspectives (short-term and long-term) and H2 is partially confirmed because the

COVID-19 crisis was simply a decelerator of the short-term and long-term trend for CO_2 emissions and intensity.

Table no. 3. T-stat outputs for the influence of COVID-19 on the production of energy/electricity and greenhouse gas emissions (short-term and long-term perspectives)

First-year COVID-19 impact	t-stat	P(T<=t) one-tail	t critic one-tail	P(T<=t) two-tail	t critic two-tail
Total energy production	4.455	0.000	1.663	0.000	1.989
Electricity production	1.427	0.079	1.665	0.158	1.991
Energy intensity of GDP	-1.346	0.093	1.679	0.185	2.013
CO_2 Intensity	-1.329	0.095	1.677	0.190	2.010
Average CO_2 Emission Factor	-0.107	0.458	1.667	0.915	1.994
Second-year COVID-19 impact	**t-stat**	**P(T<=t) one-tail**	**t critic one-tail**	**P(T<=t) two-tail**	**t critic two-tail**
Total energy production	2.359	0.010	1.663	0.021	1.989
Electricity production	-2.366	0.010	1.663	0.020	1.989
Energy intensity of GDP	-0.969	0.169	1.677	0.337	2.010
CO_2 Intensity	-0.896	0.187	1.672	0.374	2.002
Average CO_2 Emission Factor	0.025	0.490	1.669	0.980	1.998
Long-term impact of the first year	**t-stat**	**P(T<=t) one-tail**	**t critic one-tail**	**P(T<=t) two-tail**	**t critic two-tail**
Total energy production	4.043	0.000	1.671	0.000	2.000
Electricity production	4.781	0.000	1.672	0.000	2.002
Energy intensity of GDP	-2.426	0.010	1.679	0.019	2.014
CO_2 Intensity	-3.517	0.000	1.677	0.001	2.011
Average CO_2 Emission Factor	-2.679	0.004	1.664	0.009	1.990
Long-term impact of second year	**t-stat**	**P(T<=t) one-tail**	**t critic one-tail**	**P(T<=t) two-tail**	**t critic two-tail**
Total energy production	2.802	0.003	1.669	0.007	1.998
Electricity production	1.918	0.030	1.668	0.059	1.995
Energy intensity of GDP	-2.074	0.022	1.677	0.043	2.011
CO_2 Intensity	-3.033	0.002	1.673	0.004	2.004
Average CO_2 Emission Factor	-2.422	0.009	1.663	0.018	1.989

*Note: * 5% significance; ** 10% significance.*

Source: own estimations based on Enerdata time series.

Considering the t-stat results, we can see that the short-term influence (compared to the year before the crisis average) is less significant than the long-term impact (compared to the five-year average). The short-term impact is statistically significant only for energy/electricity production. Therefore, the t-stat analysis revealed that *H1* is confirmed, but *H2* is not confirmed from a short-term perspective. The long-term perspective confirms both hypotheses (*H1* and *H2*). However, in the case of *H2*, the estimated impact is different from that expected because the evolution of GDP and consumption in the formula decreased faster than the decarbonisation of the global economy.

In the next section, we analyse the impact of COVID-19 on the consumption of energy/electricity – *H3* and on the trade balance (the difference between imports and exports of energy/electricity) – *H4*. The results are presented in Table no. 4 (analysis of mean and variance) and Table no. 5 (t-stat analysis).

Table no. 4. Mean and variance for the impact of the COVID-19 crisis on the consumption of energy/electricity and the trade balance (short-term and long-term perspectives)

First-year COVID-19 impact	Mean		Variance	
	t_0	t_1	t_0	t_1
Total energy consumption	0.002	-0.024	0.000	0.000
Electricity consumption	0.002	-0.006	0.000	0.000
Share of electricity in total energy consumption	-0.003	0.014	0.000	0.000
Balance of trade – energy	0.061	-0.038	0.704	0.372
Balance of trade – electricity	-0.312	-13.622	1.020	6399.360
Second-year COVID-19 impact	**Mean**		**Variance**	
	t_0	t_1	t_0	t_1
Total energy consumption	0.002	-0.006	0.000	0.000
Electricity consumption	0.002	0.012	0.000	0.000
Share of electricity in total energy consumption	-0.003	0.013	0.000	0.001
Balance of trade - energy	0.061	0.043	0.704	0.389
Balance of trade - electricity	-0.312	-11.685	1.020	4724.588
Long-term impact of the first year	**Mean**		**Variance**	
	t_0	t_1	t_0	t_1
Total energy consumption	0.022	-0.024	0.002	0.000
Electricity consumption	0.032	-0.006	0.001	0.000
Share of electricity in total energy consumption	0.009	0.013	0.001	0.001
Balance of trade – energy	-0.567	-0.038	12.982	0.372
Balance of trade – electricity	-5.521	-13.622	1217.510	6399.360
Long-term impact of second year	**Mean**		**Variance**	
	t_0	t_1	t_0	t_1
Total energy consumption	0.022	-0.006	0.002	0.000
Electricity consumption	0.032	0.012	0.001	0.000
Share of electricity in total energy consumption	0.009	0.014	0.001	0.000
Balance of trade – energy	-0.567	0.043	12.982	0.389
Balance of trade – electricity	-5.521	-11.685	1217.510	4724.588

Note: t_0 – before COVID-19 and t_1 – during COVID-19

Source: own estimations based on Enerdata time series.

The mean and variance analysis confirmed the following results with respect to the research hypotheses H3 and H4: (i) The short-term perspective: the energy and electricity consumption decreased (electricity consumption only in the first year of COVID-19, in the second year we can see a deceleration of its previous growth rate), the share of electricity in total energy consumption increased in both pandemic years, the commercial balance with energy and electricity was improved in the two pandemic years (the positive impact was more consistent for the balance of electricity trade and more consistent for the second pandemic year). (ii) Comparison with the multi-year (5-year) average revealed that the pandemic crisis significantly changed the trend of consumption of energy / electricity from an increasing situation to a decreasing situation (both years). The share of electricity in total energy consumption increased significantly during the pandemic crisis compared to the previous long-term trend, which means that COVID-19 accelerated this change in the structure of energy consumption, in favour of electricity. The balance of trade with energy and electricity improved significantly during the pandemic period (both years) compared to the long-term

situation. In conclusion, the mean & variance analysis confirmed both the H3 and H4 research hypotheses, both perspectives (short-term and long term).

Table no. 5. T-stat outputs for the impact of COVID-19 on energy / electricity consumption and trade balance (short-term and long-term perspectives)

First year COVID-19 impact	t-stat	P(T<=t) one-tail	t critic one-tail	P(T<=t) two-tail	t critic two-tail
Total energy consumption	6.942	0.000	1.664	0.000	1.990
Electricity consumption	2.822	0.003	1.663	0.006	1.989
Share of electricity in total energy consumption	-4.432	0.000	1.665	0.000	1.991
Balance of trade - energy	0.625	0.267	1.665	0.533	1.991
Balance of trade - electricity	0.970	0.170	1.692	0.339	2.035
Second year COVID-19 impact	**t-stat**	**P(T<=t) one-tail**	**t critic one-tail**	**P(T<=t) two-tail**	**t critic two-tail**
Total energy consumption	1.789	0.039	1.666	0.078	1.993
Electricity consumption	-2.641	0.005	1.666	0.010	1.993
Share of electricity in total energy consumption	-3.544	0.000	1.668	0.001	1.995
Balance of trade - energy	0.116	0.454	1.665	0.908	1.991
Balance of trade - electricity	0.965	0.171	1.692	0.342	2.035
Long-term impact of first year	**t-stat**	**P(T<=t) one-tail**	**t critic one-tail**	**P(T<=t) two-tail**	**t critic two-tail**
Total energy consumption	6.788	0.000	1.671	0.000	2.000
Electricity consumption	6.281	0.000	1.675	0.000	2.007
Share of electricity in total energy consumption	-0.623	0.268	1.664	0.535	1.990
Balance of trade - energy	-0.950	0.174	1.680	0.347	2.015
Balance of trade - electricity	0.541	0.296	1.679	0.591	2.014
Long-term impact of second year	**t-stat**	**P(T<=t) one-tail**	**t critic one-tail**	**P(T<=t) two-tail**	**t critic two-tail**
Total energy consumption	3.935	0.000	1.668	0.000	1.997
Electricity consumption	3.056	0.002	1.669	0.003	1.997
Share of electricity in total energy consumption	-0.822	0.207	1.667	0.414	1.994
Balance of trade - energy	-1.094	0.140	1.679	0.280	2.014
Balance of trade - electricity	0.466	0.322	1.677	0.643	2.010

Source: own estimations based on Enerdata time series

The t-statistical analysis indicated that the COVID-19 crisis significantly negatively affected energy and electricity consumption (at a 5% confidence level). However, the positive impact on the share of electricity in total final energy consumption was only significant in the short-term perspective (comparing the two crisis years to the year before the crisis), not in the long-term perspective (comparing the two crisis years to the average value of five years). The effect of the pandemic on the trade balance was not statistically significant for energy or electricity. Thus, our study supports the hypothesis that the COVID-19 crisis had a negative impact on energy and electricity consumption (H3). In contrast, the positive impact on the trade balance is revealed but is not statistically significant (H4).

The final section of our analysis deals with the impact of COVID-19 on the production and intensity of green energy (*H5*). The results are presented in Table no. 6 (mean and variance analysis) and Table no. 7 (t-stat analysis).

Table no. 6. Mean and variance for the influence of COVID-19 on green energy production and intensity (short-term and long-term perspectives)

First-year COVID-19 Impact	Mean		Variance	
	t_0	t1	t_0	t1
Renewables electricity production	0.049	0.023	0.012	0.003
Wind and solar electricity production	0.132	0.076	0.021	0.007
Share renewables in total electricity	0.048	0.028	0.012	0.003
Share of wind and solar in total electricity	0.131	0.081	0.022	0.007
Second-year COVID-19 impact	**Mean**		**Variance**	
	t_0	t_1	t_0	t_1
Renewables electricity production	0.049	0.046	0.012	0.009
Wind and solar electricity production	0.374	0.076	0.082	0.007
Share renewables in total electricity	0.048	0.033	0.012	0.010
Share of wind and solar in total electricity	0.131	0.124	0.022	0.016
Long-term impact of first-year	**Mean**		**Variance**	
	t_0	t_1	t_0	t_1
Renewables electricity production	0.178	0.023	0.062	0.003
Wind and solar electricity production	0.374	0.132	0.082	0.021
Share renewables in total electricity	0.152	0.028	0.058	0.003
Share of wind and solar in total electricity	0.349	0.081	0.076	0.007
Long-term impact of second-year	**Mean**		**Variance**	
	t_0	t_1	t_0	t_1
Renewables electricity production	0.178	0.046	0.062	0.009
Wind and solar electricity production	0.374	0.136	0.082	0.018
Share renewables in total electricity	0.152	0.033	0.058	0.010
Share of wind and solar in total electricity	0.349	0.124	0.076	0.016

Note: t_0 – before COVID-19 and t_1 – during COVID 19

Source: own estimations based on Enerdata time series.

The mean & variance analysis of the influence of COVID-19 on the production and importance of green energy was carried out to the following conclusions:

- The short-term perspective: we observed that the production of energy from regenerable sources increased during COVID-19 (both years) but with a decelerated growth rate. The same is true in the case of wind & solar energy (the decelerating impact is higher in this case). A similar situation exists in the case of the share of this total energy production of *green* energy. It is clear that COVID-19 significantly altered the dynamic of these indicators by countries. However, because the production of electricity decreased in the pandemic time (both years) we can state that COVID-19 also had a replacement impact in the case of green energy: the production of electricity continued to be greener than in previous years. Taking into account these results, we can conclude that H5 is partially confirmed from a short-term perspective.

- The long-term perspective: the mean and variance comparison with the multi-year values revealed the same situation. The COVID-19 (both years) mean is lower than the multi-year mean (the positive value suggested an increasing situation) but is still positive for all indicators in this section. Therefore, we can state that COVID-19 was actioned merely as a decelerator rather than as a determinant factor, generating a significant deceleration of the dynamic of the green energy sector. Anyway, because the production of electricity decreased (short-term and long-term perspective), the continuous growth (even decelerated) suggests that the replacing

situation (green energy replaces traditional energy sources) is still present and was accelerated by COVID-19. H5 is also partially confirmed from a long-term perspective.

In conclusion, the mean and variance analysis partially confirmed the research hypothesis H5.

Table no. 7. T-stat outputs for the influence of COVID-19 on green energy production and intensity (short-term and long-term perspectives)

First-year COVID-19 impact	t-stat	P(T<=t) one-tail	t critic one-tail	P(T<=t) two-tail	t critic two-tail
Renewables electricity production	1.406	0.082	1.670	0.165	2.000
Wind and solar electricity production	2.155	0.017	1.668	0.035	1.997
Share of renewables in total electricity	1.081	0.142	1.669	0.284	1.998
Share of wind and solar in total electricity	1.922	0.030	1.669	0.059	1.998
Second-year COVID-19 impact	**t-stat**	**P(T<=t) one-tail**	**t critic one-tail**	**P(T<=t) two-tail**	**t critic two-tail**
Renewables electricity production	0.167	0.434	1.664	0.868	1.990
Wind and solar electricity production	6.474	0.000	1.677	0.000	2.011
Share of renewables in total electricity	0.679	0.249	1.663	0.499	1.989
Share of wind and solar in total electricity	0.247	0.403	1.664	0.805	1.990
Long-term impact of first-year	**t-stat**	**P(T<=t) one-tail**	**t critic one-tail**	**P(T<=t) two-tail**	**t critic two-tail**
Renewables electricity production	3.988	0.000	1.679	0.000	2.013
Wind and solar electricity production	4.883	0.000	1.670	0.000	2.000
Share of renewables in total electricity	3.279	0.001	1.678	0.002	2.012
Share of wind and solar in total electricity	6.038	0.000	1.677	0.000	2.011
Long-term impact of second year	**t-stat**	**P(T<=t) one-tail**	**t critic one-tail**	**P(T<=t) two-tail**	**t critic two-tail**
Renewables electricity production	3.264	0.001	1.674	0.002	2.006
Wind and solar electricity production	4.872	0.000	1.672	0.000	2.002
Share of renewables in total electricity	2.991	0.002	1.673	0.004	2.003
Share of wind and solar in total electricity	4.794	0.000	1.672	0.000	2.002

*Note: * 5% significance; ** 10%* significance.

Source: own estimations based on Enerdata time series.

The t-stat analysis of country data samples before and during the COVID-19 crisis indicates that the short-term impact is statistically significant for wind and solar energy only, but not for all renewables (as shown in Table 7). In the second year of the crisis, the impact is statistically significant only for wind and solar electricity production, but not for its intensity. However, the findings are consistent from a long-term perspective for both years of the COVID-19 crisis. Based on these results, hypothesis H5 is partially confirmed (only with long-term impact), suggesting that the COVID-19 crisis has positively impacted global green energy production and intensity.

Conclusions and remarks

Analysis of mean and variance revealed that on COVID-19 had the following short-term influence on the energy sector: the production of total energy and electricity continued to decrease but with a decelerated rate, the energy intensity of GDP continued to decrease but with a decelerated rate (especially due to the drop in GDP), the CO_2 intensity and average CO_2 emission factor continued to decrease but with a decelerated rate too (H1 and H2 are

partially confirmed on a short-run); the total consumption of energy and electricity decreased and COVID-19 clearly reversed the short-run trend (before crisis consumption increased) strongly confirming H3, the COVID-19 increased the share of electricity in the total consumption of electricity, improved the balance of trade with energy and electricity (lower imports than exports) confirming H4, the production of green energy (from renewables sources, from solar, from wind) continued to increase but with lower rates (COVID-19 actioned as a decelerator for this production but accelerated the replacement effect) and the share of green energy increased (but with a lower rate) during the pandemic crisis, partially confirming H5. The long-term perspective (the comparison with the multiannual 5-year mean) provided conclusions similar to those of the short-term perspective. Therefore, we can clearly state that, for production, emissions, and green energy, COVID-19 merely had a decelerating influence rather than a direct and strong impact. The direct and strong impact was confirmed for consumption and for the balance of trade.

The analysis of the statistical significance of the difference in terms of means and variance between the two samples (before and during the COVID-19 crisis, both years) confirmed the following: (i) The short-term perspective: differences that were statistically significant were registered in the case of energy production (both years), electricity production (only the second COVID-19 year), energy consumption and electricity (both years), the share of electricity in total energy consumption (both years), the production of solar & wind energy, the share of solar & wind energy in total electricity consumption (both years). (ii) Long-term perspective: the counterfactual analysis based on the parametric test of t-stat revealed that the differences between the considered samples (before and during the crisis) are statistically significant in the case of production of energy and electricity (both years), energy intensity of GDP, CO_2 intensity (both years), average CO_2 emission factor (both years), consumption of energy and electricity (both years), share of electricity in total energy consumption (both years), green energy production (both years) and share of green energy in total electricity production (both years). The long-term influence of COVID-19 is clearly greater than the short-term impact.

In conclusion, the results obtained by this research fully confirmed the H1 research hypothesis (energy production decreased during COVID-19 and the dynamic changed radically from positive to negative rate, for both perspectives – short and long-run), the H2 research hypothesis was partially confirmed (only for long-term and there is a decelerating influence of COVID-19 on the decreasing rate for CO_2 intensity and emissions), the H3 is fully confirmed (the COVID-19 decreased the consumption of energy and electricity and radically changed the dynamic of global consumption from positive to negative) for both perspectives (short and long-term perspective), partially confirmed H4 (there is an improvement of the balance of trade with energy and electricity due to the COVID-19 crisis, but the differences between samples are not statistically significant for both perspectives – short and long-term) and partially confirmed H5 (the production of green energy increased, the differences between samples are statistically significant for long-run only, there is a decelerating impact of COVID-19, and there is a clear accelerated replacement effect in favour of green energy from renewable energy from wind and solar).

These findings provide valuable contributions to the ongoing international debate on the impact of the COVID-19 pandemic on the environment. This debate is highly controversial and the results are often ambiguous (Janardhanan, 2020; Atoufi, Lampert and Sillanpää, 2021; Soubry, Rosen and Tsioumani, 2021; Gaucher et al., 2022). Our study supports previous conclusions that the COVID-19 crisis has led to an increase in clean energy production and consumption, while the demand for other types of energy has declined (Lu et

al., 2021). Our research also confirms that both years of the COVID-19 crisis severely affected energy price mechanisms, energy demand, and energy supply, resulting in a significant disruption of the global energy market (Bashir et al., 2021). Additionally, our study confirms that the production of electricity from renewable sources was less affected by the COVID-19 crisis compared to traditional electricity sources (Akrofi and Antwi, 2020; Siddique et al., 2021). Our research has identified that the COVID-19 pandemic has had a significant impact on the development of renewable energy, a finding consistent with the conclusion reached by Peng et al. (2022).

In terms of limitations, our research was restricted by several factors, including a limited number of indicators used to test our hypotheses, a restricted set of variables to represent pollution problems and the green energy sector, and a limited selection of countries (only 45 countries, although they represent more than 90% of the world's GDP, excluding very small and impoverished countries). Moving forward, we plan to expand the number of indicators used to assess the green energy/electricity sector, as well as the number of indicators measuring CO_2 and greenhouse gas emissions. Additionally, our objective is to introduce control variables such as the size of a country's population and economic potential and development, and to broaden our analysis to include research on sustainable development.

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