

Article

Carbon Dioxide, Nitrous Oxide, and Methane: What Types of Greenhouse Gases Are Most Affected by Green Investments and Renewable Energy Development?

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Abstract: The article aims to analyze the impact of green investments and the development of renewable energy on greenhouse gas emissions based on 223 countries in 2011–2021. The information base is the International Renewable Energy Agency, Our World in Data, Climate Policy Initiative, and FTSE Russell. Correlation analysis was used to check the data multicollinearity, multivariate regression analysis with stepwise variable entry—to formalize functional relationships. All variables characterizing the dynamics of green investments and the development of alternative energy, the number of annual investments in off-grid renewable energy has the largest impact on the amount of CO₂ and N₂O. Thus, an annual investment increase of USD 1 million leads to a CO₂ emission increase of 4.5 kt and an N₂O emission increase of 0.272 kt. Simultaneously, the green economy's market capitalization level has the largest impact on the amount of CH₄. In this case, a capitalization increases of USD 1 trillion leads to a CH₄ emission increase of 129.53 kt. The dynamics of renewable energy development have a statistically significant effect on only one of the three studied greenhouse gases—CO₂ emissions. Here, 1 MW growth of an absolute increase in off-grid renewable energy capacity leads to a 1171.17 kt reduction of CO₂ emissions. Checking input data for lags confirmed a time lag of one year between the level of green investments and the level of greenhouse gas emissions. That is, the impact of green investments on the level of greenhouse gas emissions is delayed by one year. The results of regression models taking into account lags confirmed that an increase in the level of green investments has a positive effect on reducing the level of greenhouse gas emissions (an increase in off-grid renewable energy annual investments of USD 1 million leads to a decrease in CO₂ of 1.18 kt and N₂O of 1.102 kt; the increase in green economy market capitalization of USD 1 trillion leads to a decrease in CH₄ emissions of 0.64 kt).

Keywords: finance; renewable; greenhouse; carbon; emission; nitrous; methane; regression



Citation: Kwilinski, A.; Dobrovolska, O.; Wołowiec, T.; Cwynar, W.; Didenko, I.; Artyukhov, A.; Dluhopolskyi, O. Carbon Dioxide, Nitrous Oxide, and Methane: What Types of Greenhouse Gases Are Most Affected by Green Investments and Renewable Energy Development? *Energies* **2024**, *17*, 804. <https://doi.org/10.3390/en17040804>

Academic Editor: Constantine D. Rakopoulos

Received: 30 November 2023

Revised: 17 January 2024

Accepted: 6 February 2024

Published: 7 February 2024



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1. Introduction

In recent decades, the world community has faced several important tasks, the achievement of which should become a guarantee of sustainable development in society. These global tasks were outlined in “Transforming our world: the 2030 Agenda for Sustainable Development”, a resolution adopted by the United Nations General Assembly in the form

of the 17 Sustainable Development Goals [1]. This resolution singles out the need for countries to transition to clean energy and the introduction of energy-efficient technologies as Goal 7, and the importance of combating climate change and its consequences as Goal 13.

The need to combat climate change has been established in several international documents. Among such documents, one can single out the United Nations Framework Convention on Climate Change (UNFCCC), the purpose of which is to establish the need to stabilize the level of greenhouse gases in the atmosphere at a level that would prevent dangerous anthropogenic influence on the Earth's climate [2]. As part of the tasks set by the UNFCCC, the Kyoto Protocol was concluded in 1997, which was a legally formalized obligation of developed countries and countries with transition economies to reduce greenhouse gas emissions in 2008–2012 to the level of 1990 [3]. Also, within the framework of the UNFCCC in 2015, the Paris Agreement was concluded, which should replace the Kyoto Protocol. This agreement aims to regulate measures to reduce carbon dioxide emissions by 2020 [4]. Unlike the Kyoto Protocol, the Paris Agreement stipulates that all countries, regardless of their economic development, undertake to reduce greenhouse gas emissions into the atmosphere.

The annual increase in greenhouse gas emissions into the atmosphere causes global warming. The latter, in turn, provokes the melting of glaciers, coastal flooding, and weather changes in the Earth's climatic zones. The primary sources of greenhouse gas emissions are the energy industry, transport sector, manufacturing, and agriculture.

Also, tourist islands significantly contribute to the volume of greenhouse gas emissions due to the active use of air transport [5].

Humanity's concern for emerging climate problems, including human-induced ones, prompts politicians and scientists to search for effective mechanisms to reduce the harmful effects of atmospheric air pollution. According to the International Energy Agency (IEA), about two-thirds of greenhouse gas emissions in the world come from the energy industry. Meanwhile, the latter is 80% generated by fossil fuels, the main source of carbon dioxide emissions [6]. One of the ways to reduce greenhouse gas emissions is to develop energy-efficient technologies and an alternative energy industry that works with renewable energy sources [7].

Significant financial flows are directed specifically to the development of innovations aimed at reducing the negative effect of human activity on the biosphere. This ultimately aids in improving environmental quality. These financial flows themselves are called "green investments", as they are aimed at environmental goals such as preventing or reducing the level of environmental pollution and preserving the planet's natural resources and biodiversity [8]. Therefore, research on issues related to improving environmental quality and reducing negative human impact is important for the protection of the planet and the well-being of society.

2. Literature Review

The construction of a high-quality, safe environment requires a systematic approach to the development and implementation of an effective security policy in various sectors of the economy. This is why issues related to greenhouse gases, renewable energy, and green investments have often become important research objects in recent years. Accordingly, scholars consider such issues in the context of the impact of global changes on economic and environmental security [9,10], energy security [11], and ensuring sustainable development [12–14]. Alongside this, the studied concepts occupy a leading place in the development of a new economic model called the "circular economy". This model is based on the implementation of closed cycles in the processes of production, circulation, and consumption, which in the long run leads to a reduction in the negative impact on the environment [15,16]. In [17,18], authors reviewed publications on the subject of green finance and investments.

Nowadays, scientists highlight various aspects of the relationship between greenhouse gas emissions, in particular carbon dioxide, the development of renewable energy sources,

and green investments. Thus, author [19], using co-integration methods, the Granger causality model, and the data of Vietnam, empirically proved the existence of cointegration between such pairs of variables as consumption of renewable energy—CO₂ emissions, and environmental investments—CO₂ emissions. Another author [20], using Chinese data as an example, showed that green investments can reduce CO₂ emissions due to industrial optimization. The authors [21] believe the reduction of CO₂ emissions is possible due to the improvement of transport infrastructure and logistics operations. In [22], the author analyzed the role of energy efficiency and environmental technologies, using the Norwegian maritime industry as an example.

In addition, researchers study the issues related to the connection between green economic development and tourism. Their focus is on how renewable energy, urbanization, green investments, carbon emissions, and household incomes affect the tourism industry [23,24]. The relationship between energy and human health is also under discussion. Researchers investigate the impact of energy consumption [25], energy efficiency [26,27], renewable energy [28], and energy from waste incineration [29] on public health.

It is crucial, when making decisions about the expansion of renewable energy production and consumption, to study public opinion regarding the implementation of such initiatives [30]. In general, the study of various determinants of renewable energy development is principally for its qualitative analysis and forecasting [31]. Using the example of European countries, a group of scientists [32–34] studied the critical determinants of renewable energy and clean energy technologies as prospects for transforming the region's energy industry. The cumulative value of renewable energy for society as a whole is considered in work [35], and in work [36], a group of researchers focuses directly on the economic difficulties of Nigerians in solving energy supply issues. The authors [37] conducted a study on the efficiency of renewable energy production, taking into account investments from state financial institutions and the installed electricity capacity for renewable energy sources.

The issue of the relationship between green investments and green energy is quite relevant in the scientific community. Scientists use various economic and mathematical methods and models to investigate this connection, such as the Markov switching regression model [38], bibliometric analysis [39], and panel regression models [40,41]. Research shows that green bonds, as one of the instruments of green investments, are an effective method for promoting projects related to renewable energy sources and aimed at reducing CO₂ emissions in the long term [42,43]. In addition to green bonds, scientists consider the long-term impact of taxation on carbon emissions [44,45] and direct foreign investments for the deployment of the renewable energy sector. Over time, this should lead to a reduction in the rate of greenhouse gas emissions [46–48].

The author [49] investigated the impact of green investments on CO₂ emissions using empirical data and economic-mathematical modeling. This research showed that green investments, technological innovation, and corporate social responsibility contribute to ecological economic growth and provoke a reduction in CO₂ emissions. At the same time, income per capita and GDP per capita significantly increase CO₂ emissions.

Using regression analysis based on data from the BRICS countries, scientists [50] studied the impact of economic, demographic, and environmental factors on green investments. They found that renewable energy consumption, population, foreign direct investments, inflation, carbon dioxide emissions, technical corporation grants, research, and development play vital roles in terms of promoting environmental finance and mitigating the effects of climate change for the BRICS countries. This indicates that scientists do not simply investigate the impact of green investments on greenhouse gas emissions, but conversely, they also study the impact of renewable energy and emissions on green investments.

Another issue to analyze is the impact of COVID-19 on various sectors of the economy, in particular the energy sector [51] and the environment [52,53]. The corporate activity of economic stakeholders in forming and ensuring their green brand is also an integral part of developing an ecological society [54,55]. Thus, in work [56] on the example of energy management on railways, a model of market regulation and transition from the active use of

traditional energy sources to the use of ecologically clean resources is considered. Scientists search for ways to support the economy, which suffered because of pandemic restrictions, through environmental, energy, and political leverages [57–59]. Equally important is the analysis of the consequences of the energy crisis caused by the war between Russia and Ukraine for EU climate policy.

Currently, there are discussions on how to mitigate the effects of climate change by identifying ways to decarbonize the economy and ensure environmental sustainability [60,61]. One of the possible solutions is public-private investments, which should be aimed at the development of renewable energy and technological innovations in the field of increasing energy efficiency [62,63].

In the search for ways to neutralize environmental pollution, scientists have investigated the role of environmental finance and energy innovation in this process. Using the CS-ARDL (Cross-Sectional-Autoregressive-Distributed Lag) approach, they found that environmental pollution increases are associated with economic growth, urbanization, and natural resource rent. At the same time, it appeared that green investments, consumption of renewable energy, and energy innovation neutralize environmental pollution [64]. A fairly new approach to achieving energy efficiency is using artificial intelligence and blockchain in energy management systems [65].

Thus, the analysis of the literature has shown that studies on the connections between green investments, renewable energy, and greenhouse gas emissions open up a broad field of research. To study various aspects of these relationships, scientists use different methods, from theoretical analysis to empirical research using economic and mathematical modeling tools. Given the importance of the issue of reducing greenhouse gas emissions, the purpose of this study is to analyze the impact of green investments and renewable energy on the amount of CO₂, N₂O, and CH₄ emissions.

3. Materials and Methods

The study uses variables that characterize the state of renewable energy, the number of green investments, and the number of emissions of the main types of greenhouse gases. Quantitative values of variables at the global level were taken from the website Our World in Data [66,67], the International Renewable Energy Agency's yearbooks [68], the Climate Policy Initiative's reports [69], and the FTSE Russell Company [70] on the example of data from 223 countries in the world during 2011–2021. Table 1 shows the variables chosen for the study. The study covers the time from 2011 to 2021.

To define the connections between the selected variables, correlation analysis was used. This was necessary to determine the closeness of the relationship between the dependent variable and the independent variables, as well as the strength of the relationship between independent variables, to detect and eliminate such a phenomenon as multicollinearity. To identify the relationship and establish a quantitative relationship between dependent and independent variables, regression analysis was used based on the multivariate linear regression model. The general equation for multivariate linear regression is as follows (1):

$$Y = b_0 + b_1 * x_1 + b_2 * x_2 + \dots + b_n * x_n + e, \quad (1)$$

where Y —dependent variable; x_1, x_2, \dots, x_n —independent variables; $b_0, b_1, b_2, \dots, b_n$ —coefficients of equation; and e —a residual (error).

The purpose of this study is to identify and analyze the impact of renewable energy development and the amount of green investment on the main types of greenhouse gases at the global level. In accordance with this purpose, there are three assumptions that need to be tested:

- How renewable energy and green investments affect carbon dioxide emissions.
- How renewable energy and green investments affect nitrous oxide emissions.
- How renewable energy and green investments affect methane emissions.

Thus, the dependent variables are carbon dioxide emissions (CO_2), nitrous oxide emissions (N_2O), and methane emissions (CH_4); the remaining variables are independent ones. Variables that characterize renewable energy sources are re1–re6. Variables that characterize green investments are gf1–gf5 (Table 1).

According to the outlined assumptions, three models to estimate the impact of independent variables on the dependent variable were developed. The research was conducted using the statistical software Statistica 10.

Table 1. Definitions of the selected variables.

Designation of the Variable	Type of the Variable	Variable	Units	Source
CO_2	dependent	Carbon dioxide (CO_2) emissions	kt	Our World in Data, 2022
N_2O	dependent	Nitrous oxide (N_2O) emissions	kt	Our World in Data, 2023
CH_4	dependent	Methane (CH_4) emissions	kt	Our World in Data, 2023
re1	independent	Total capacity for renewable energy	MW	IRENA, 2023
re2	independent	Total production of renewable energy	GWh	IRENA, 2023
re3	independent	Off-grid capacity for renewable energy	MW	IRENA, 2023
re4	independent	Renewable energy share of electricity capacity	%MW	IRENA, 2023
re5	independent	Renewable energy share of electricity production	%GWh	IRENA, 2023
re6	independent	Installed renewable energy-generating capacity in developing countries	watts per capita	IRENA, 2023
gf1	independent	Public renewable energy finance flow	USD million	IRENA, 2023
gf2	independent	International financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems	USD million	IRENA, 2023
gf3	independent	Green economy market capitalization	USD trillion	FTSE Russell, 2023
gf4	independent	Total global climate finance flow	USD billion	CPI, 2022
gf5	independent	Annual investment in off-grid renewable energy	USD million	IRENA and CPI, 2023

Source: Based on [61–65].

4. Results

The examination of empirical data begins with determining the strength of the relationship between the studied variables based on correlation analysis. Table 2 presents the correlation matrix with pairwise correlation coefficients. According to the table, almost all independent variables have a very strong relationship with each other since the absolute value of the correlation coefficient is greater than 0.9. This testifies that there is a phenomenon of multicollinearity between independent variables. Therefore, in order to eliminate the correlation between independent variables, it was decided instead of working with the variables' initial data to work with their first differences. The first differences in variables re1–re6 were taken.

Hereafter, to distinguish initial data and first differences, letters f and d (first differences) will be added before variable designations. Variables gf1 and gf2 were excluded from further calculations as they have a weak relationship with dependent variables CO_2 , N_2O , and CH_4 (correlation coefficient < 0.3).

Table 2. Correlation matrix of initial data.

Var	CO ₂	N ₂ O	CH ₄	re1	re2	re3	re4	re5	re6	gf1	gf2	gf3	gf4	gf5
CO ₂	1.000	0.760	0.791	0.749	0.758	0.784	0.749	0.719	0.750	−0.054	0.262	0.610	0.738	0.806
N ₂ O		1.000	0.988	0.987	0.985	0.958	0.986	0.982	0.987	−0.180	0.181	0.943	0.968	0.946
CH ₄			1.000	0.992	0.993	0.981	0.991	0.986	0.993	−0.267	0.104	0.931	0.960	0.943
re1				1.000	0.999	0.985	0.999	0.997	1.000	−0.289	0.104	0.948	0.953	0.944
re2					1.000	0.987	0.999	0.997	0.999	−0.278	0.116	0.940	0.948	0.943
re3						1.000	0.986	0.979	0.986	−0.298	0.099	0.892	0.926	0.952
re4							1.000	0.997	0.999	−0.267	0.130	0.939	0.955	0.951
re5								1.000	0.997	−0.307	0.083	0.957	0.939	0.927
re6									1.000	−0.280	0.112	0.946	0.954	0.945
gf1										1.00	0.87	−0.41	−0.13	−0.07
gf2											1.000	−0.06	0.227	0.312
gf3												1.000	0.882	0.813
gf4													1.000	0.959
gf5														1.000

Source: Authors' results.

Table 3 shows a correlation matrix that includes correlation coefficients calculated on the basis of the first difference values for variables re1–re6. This table will be used later in the study to check that independent variables with a correlation greater than 0.7 are not included in the regression equation.

Table 3. Correlation matrix, including the first differences.

Var	CO ₂	N ₂ O	CH ₄	fd_re1	fd_re2	fd_re3	fd_re4	fd_re5	fd_re6	gf3	gf4	gf5
CO ₂	1.000	0.760	0.791	0.138	0.321	0.273	−0.175	0.406	−0.534	0.610	0.738	0.806
N ₂ O		1.000	0.988	0.589	0.091	0.774	0.346	0.887	−0.271	0.943	0.968	0.946
CH ₄			1.000	0.567	0.150	0.770	0.361	0.858	−0.397	0.931	0.960	0.943
fd_re1				1.000	0.026	0.583	0.820	0.696	0.126	0.662	0.525	0.453
fd_re2					1.000	−0.219	−0.179	0.047	−0.496	0.009	−0.016	0.140
fd_re3						1.000	0.643	0.884	−0.151	0.855	0.761	0.681
fd_re4							1.000	0.557	0.119	0.504	0.332	0.203
fd_re5								1.000	−0.094	0.897	0.848	0.783
fd_re6									1.000	−0.224	−0.281	−0.327
gf3										1.000	0.882	0.813
gf4											1.000	0.959
gf5												1.000

Source: Authors' results.

The next step in the research is a regression analysis, which is aimed at determining the presence of a stochastic relationship between the dependent variable and several independent variables. In our case, there are three dependent variables—CO₂, N₂O, and CH₄. Three regression models will be built, one for each dependent variable, respectively. The general form of the models is given in Equations (2)–(4).

Then, there will be testing of the assumptions about the impact of renewable energy and green investments on outcome variables. For this, a multivariate regression model

will be built by stepwise including variables in the regression model. This method makes it possible to include in the model those independent variables that increase its quality. Table 4 presents the result of the model evaluation. On this basis, the assumption that renewable energy and green investment variables affect carbon dioxide emissions will be tested.

Table 4. Multivariate linear regression for carbon dioxide (CO₂).

Multiple R	0.924206365					
Multiple R-squared	0.854157405					
Adjusted R-squared	0.791653436					
F(3,7)	13.66565061					
P	0.002596735					
Std. Err. of Estimate	397.7949549					
Durbin–Watson d	2.166173					
Variable	b *	Std. Err.	b	Std. Err.	t(7)	p-value
Intercept			36,054.86	501.4971	71.89445	0.000000
gf5	1.046439	0.207270	4.50	0.8923	5.04867	0.001482
fd_re3	−0.480110	0.198153	−1171.17	483.3709	−2.42292	0.045895
fd_re6	−0.264746	0.153562	−0.04	0.0233	−1.72404	0.128360

F-test (df₁, df₂)—Fisher’s test with degrees of freedom (i.e., df₁ and df₂) is a statistical test for assessing the significance of differences in the variances of two random samples; df₁ = m (m—number of independent variables); df₂ = n−m−1 (n—number of years); t-test (df)—Student’s *t*-test with degrees of freedom df of statistical hypothesis testing methods (statistical criteria) based on comparison with the Student’s distribution for checking the equality of mean values in two samples; df = m−N (N—number of samples). gf₅—Annual investment in off-grid renewable energy, USD million; fd_re₃—The first differences in off-grid capacity of renewable energy, MW; fd_re₆—The first differences in installed renewable energy-generating capacity in developing countries, watts per capita. * means standardized regression coefficients. Source: Authors’ results.

After analyzing the results of the modeling given in Table 4, there are the following conclusions:

- The coefficient of determination R-squared is 0.85, and the adjusted coefficient of determination adjusted R-squared is 0.79; therefore, the obtained model explains 79% of the change in the outcome variable, which is quite a high value.
- The calculated value of the F-test (Fisher’s test with degrees of freedom is a statistical test for assessing the significance of differences in the variances of two random samples). F(3,7) (df₁ = 3, df₂ = 11−3−1 = 7) is 13.67, and it is larger than the critical value, which is 4.3468. Therefore, the regression model is adequate with 95% confidence.
- The Durbin–Watson statistic is 2.166173, which testifies that the built model is stable.
- The intercept is statistically significant as its *p*-value is less than 0.05.
- The significance level of the *p*-value for variables gf₅ and fd_re₃ is less than 0.05. Therefore, these variables are statistically significant. Another proof of this is the value of the Student’s coefficient, which is greater than the table value of 2.2.
- A variable fd_re₆ with a significance level higher than 0.05 is not statistically significant. The Student’s coefficient also proves the statistical insignificance of this variable.

The regression equation for variable CO₂ looks as follows (2):

$$\text{CO}_2 = 36054.86 + 4.50 * \text{gf}_5 - 1171.17 * \text{fd_re}_3 - 0.04 * \text{fd_re}_6 \quad (2)$$

where:

CO₂—Carbon dioxide (CO₂) emissions, kt;

gf₅—Annual investment in off-grid renewable energy, USD million;

fd_re₃—The first differences in off-grid capacity of renewable energy, MW;

fd_re6—The first differences in installed renewable energy-generating capacity in developing countries, watts per capita.

Figure 1 shows a graphical representation of Equation (2).

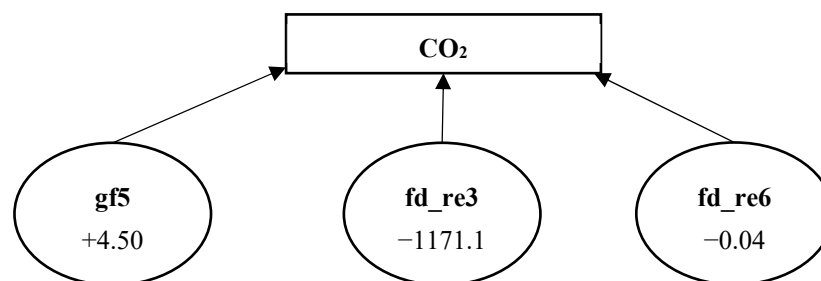


Figure 1. Graphical representation of the functional dependency of carbon dioxide on green investments and renewable energy development. CO₂—Carbon dioxide (CO₂) emissions, kt; gf₅—Annual investment in off-grid renewable energy, USD million; fd_re₃—The first differences in off-grid capacity of renewable energy, MW; fd_re₆—The first differences in installed renewable energy-generating capacity in developing countries, watts per capita. Source: Authors’ results.

Thus, carbon dioxide emissions were found to be affected by off-grid renewable energy capacity and investment in off-grid renewable energy. Based on regression Equation (5), with an increase in off-grid renewable energy annual investments of USD 1 million, the growth of carbon dioxide emissions is 4.5 kt. With this, 1 MW growth of an absolute increase in off-grid renewable energy capacity gives us a 1171.17 kt reduction in carbon dioxide emissions. Therefore, according to the results of the regression analysis, there are conclusions that renewable energy and green investments affect carbon dioxide emissions.

As the next step, there is testing of the assumption that renewable energy and green investment variables affect nitrous oxide emissions. The results of the model evaluation, on the basis of the assumption testing, are presented in Table 5.

Table 5. Multivariate linear regression for nitrous oxide (N₂O).

Multiple R	0.969094252					
Multiple R-squared	0.93914367					
Adjusted R-squared	0.913062385					
F(3,7)	36.00833666					
<i>p</i>	0.000126344					
Std. Err. of Estimate	21.19644855					
Durbin–Watson d	1.725938					
Variable	b *	Std. Err.	B	Std. Err.	t(7)	<i>p</i> -value
Intercept			2674.182	32.12214	83.25042	0.000000
gf5	0.765917	0.127892	0.272	0.04542	5.98879	0.000548
fd_re1	0.142845	0.115303	0.001	0.00010	1.23886	0.255325
fd_re3	0.168931	0.140332	33.992	28.23757	1.20380	0.267790

F-test (df₁, df₂)—Fisher’s test with degrees of freedom (i.e., df₁ and df₂) is a statistical test for assessing the significance of differences in the variances of two random samples; df₁ = *m* (*m*—number of independent variables); df₂ = *n* − *m* − 1 (*n*—number of years); *t*-test (df)—Student’s *t*-test with degrees of freedom df of statistical hypothesis testing methods (statistical criteria) based on comparison with the Student’s distribution for checking the equality of mean values in two samples, df = *m* − *N* (*N*—number of samples). Gf₅—Annual investment in off-grid renewable energy, USD million; fd_re₁—The first differences in total capacity renewable energy, MW; fd_re₃—Off-grid capacity of renewable energy, MW. * means standardized regression coefficients. Source: Authors’ results.

After analyzing the results of the model given in Table 5, there are the following conclusions:

- The coefficient of determination R-squared is 0.939, and the adjusted coefficient of determination adjusted R-squared is 0.913. Therefore, the obtained model explains 91.3% of the change in the outcome variable, which is quite a high value.
- The calculated value of the F-test ($F(3,7)$ ($df_1 = 3$, $df_2 = 11 - 3 - 1 = 7$)) is 36.01, whereas the critical value is 4.3468. Therefore, the regression model is adequate with 95% confidence, as the calculated value is larger than the critical one.
- The Durbin–Watson statistic is 1.725938, which testifies that the built model is stable.
- The intercept is statistically significant as its p -value is less than 0.05.
- A variable gf_5 with a significance level (p -value) that is less than 0.05 is statistically significant. The Student's coefficient also proves the statistical significance of this variable.
- The significance level p -value for variables fd_re1 and fd_re3 is higher than 0.05, therefore these variables are statistically insignificant. This is also confirmed by the Student's coefficient, which is less than the table value of 2.2.

The regression equation for variable N_2O is as follows (3):

$$N_2O = 2674.182 + 0.272*gf_5 - 0.001*fd_re1 - 33.992*fd_re3 \quad (3)$$

where:

N_2O —Nitrous oxide (N_2O) emissions, kt;

gf_5 —Annual investment in off-grid renewable energy, USD million;

fd_re1 —The first differences in total capacity renewable energy, MW;

fd_re3 —Off-grid capacity of renewable energy, MW.

Figure 2 demonstrates a graphical representation of Equation (3).

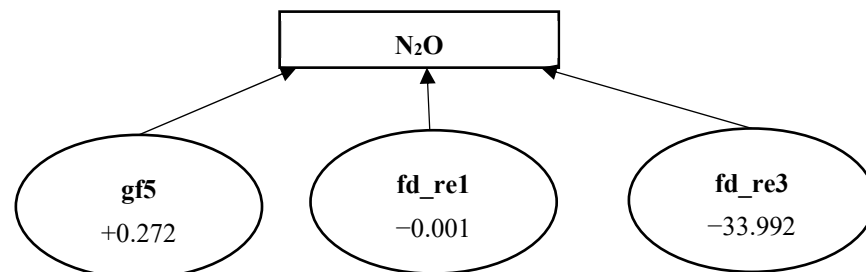


Figure 2. Graphical representation of the functional dependency of nitrous oxide on green investments and renewable energy development. N_2O —Nitrous oxide (N_2O) emissions, kt; gf_5 —Annual investment in off-grid renewable energy, USD million; fd_re1 —The first differences in total capacity renewable energy, MW; fd_re3 —Off-grid capacity of renewable energy, MW. Source: Authors' results.

Thus, nitrous oxide emissions are found to be affected by investments in off-grid renewable energy. In particular, an increase in off-grid renewable energy annual investments of USD 1 million leads to an increase in nitrous oxide emissions of 0.272 kt. The impact of renewable energy variables appeared to be statistically insignificant. Therefore, the results of the regression analysis demonstrate that green investments negatively affect nitrous oxide emissions. The second assumption is partially confirmed.

Table 6 shows the results of the model evaluation, on the basis of which there is the assumption that renewable energy and green investment variables affect methane emissions.

Table 6. Multivariate linear regression for methane (CH₄).

Multiple R	0.951152316					
Multiple R-squared	0.904690728					
Adjusted R-squared	0.88086341					
F(2,8)	37.96863434					
<i>p</i>	8.25165×10^5					
Std. Err. of Estimate	91.93346321					
Durbin–Watson d	0.9095813					
Variable	b *	Std. Err.	b	Std. Err.	t(8)	<i>p</i> -value
Intercept			9646.657	59.66288	161.6861	0.000000
gf3	0.886764	0.111993	129.530	16.35877	7.9181	0.000047
fd_re6	−0.198650	0.111993	−0.009	0.00520	−1.7738	0.114028

F-test (*df*₁, *df*₂)—Fisher’s test with degrees of freedom (i.e., *df*₁ and *df*₂) is a statistical test for assessing the significance of differences in the variances of two random samples; *df*₁ = *m* (*m*—number of independent variables); *df*₂ = *n* − *m* − 1 (*n*—number of years); *t*-test (*df*)—Student’s *t*-test with degrees of freedom *df* of statistical hypothesis testing methods (statistical criteria) based on comparison with the Student’s distribution for checking the equality of mean values in two samples; *df* = *m* − *N* (*N*—number of samples). gf₃—Green economy market capitalization, USD million; fd_re₆—The first differences in installed renewable energy-generating capacity in developing countries, watts per capita. * means standardized regression coefficients. Source: Authors’ results.

After analyzing the data given in Table 6, there are conclusions:

- The coefficient of determination R-squared is 0.905, and the adjusted coefficient of determination adjusted R-squared is 0.881. Therefore, the obtained model explains 88.1% of the change in the outcome variable, which is quite a high value.
- The calculated value of the F-test (F(2,8) (*df*₁ = 2, *df*₂ = 11 − 2 − 1 = 8)) is 37.97, whereas the critical value is 4.46. As the calculated value is larger than the critical one, the regression model is adequate with 95% confidence.
- The Durbin–Watson statistic is 0.9095813, which indicates that the built model is unstable. It has a positive autocorrelation with the residuals.
- The intercept is statistically significant as its *p*-value is less than 0.05.
- A variable gf₃ has a significance level (*p*-value) that is less than 0.05 and is statistically significant. The Student’s coefficient also proves the statistical significance of this variable.
- The significance level *p*-value for the fd_re₆ variable is higher than 0.05. This makes the fd_re₆ variable statistically insignificant. The Student’s coefficient, which is less than the table value of 2.2, also proves the statistical insignificance of this variable.

The regression equation for variable CH₄ looks as follows (4):

$$\text{CH}_4 = 9646.657 + 129.530 \cdot \text{gf}_3 - 0.009 \cdot \text{fd_re}_6 \quad (4)$$

where:

CH₄—Methane (CH₄) emissions, kt;

gf₃—Green economy market capitalization, USD million;

fd_re₆—The first difference between installed renewable energy-generating capacity in developing countries, watts per capita.

Figure 3 shows a graphical representation of Equation (3).

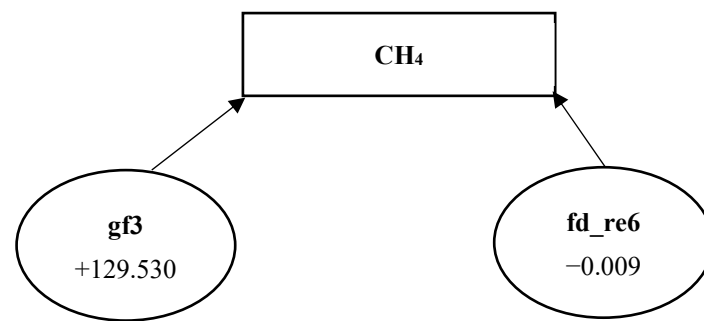


Figure 3. Graphical representation of the functional dependency of methane on green investments and renewable energy development. CH₄—Methane (CH₄) emissions, kt; gf₃—Green economy market capitalization, USD million; fd_re₆—The first differences in installed renewable energy-generating capacity in developing countries, watts per capita. Source: Authors’ results.

Thus, the results of the regression analysis show that methane emissions are affected by green economy market capitalization. The increase in green economy market capitalization of USD 1 trillion leads to an increase in methane emissions of 129.53 kt. The impact of renewable energy variables appeared to be statistically insignificant. Hence, there is a conclusion that only green investments affect methane emissions. The third assumption is only partially confirmed.

In general, it appears that green investments do not lead to a decrease in greenhouse gas emissions, but on the contrary, in our case, they cause an emission rise. The reason for this may be the presence of a time lag.

To confirm or refute this hypothesis regarding the presence of a time lag between the volume of green investments and greenhouse gas emissions, it is necessary to build models with a distributed lag for the following pairs of variables: CH₄ and gf₃; N₂O and gf₅; CO₂ and gf₅. The simulation results are presented in Tables 7–9.

Table 7. Results of the distributed lag model for a pair of variables CH₄ and gf₃.

Lag	Regression Coeff.	Standard Error	<i>t</i> -Test	<i>p</i> -Value
0	802.33	1785.72	1.81	0.08
1	−2296.02	1149.99	−4.00	0.01
2	−340.34	2205.68	−0.15	0.89
3	1086.83	2269.13	0.48	0.68
4	3534.50	2045.82	1.73	0.23

Lag—Lag value; Regression Coeff.—Regression coefficient at the lag value; Standard Error—The standard error of the regression coefficient; *t*-test—Student’s *t*-test of statistical hypothesis testing methods (statistical criteria) based on comparison with the Student’s distribution for checking the equality of mean values in two samples; *p*-value—probability of error. Source: Authors’ results.

Table 8. Results of the distributed lag model for a pair of variables N₂O and gf₅.

Lag	Regression Coeff.	Standard Error	<i>t</i> -Test	<i>p</i> -Value
0	7.99	2.32	3.44	0.07
1	−12.63	4.89	−2.98	0.04
2	−2.94	9.67	−0.30	0.78
3	−4.48	12.86	−0.35	0.74
4	0.07	8.43	0.01	0.99

Lag—Lag value; Regression Coeff.—Regression coefficient at the lag value; Standard Error—The standard error of the regression coefficient; *t*-test—Student’s *t*-test of statistical hypothesis testing methods (statistical criteria) based on comparison with the Student’s distribution for checking the equality of mean values in two samples; *p*-value—Probability of error. Source: Authors’ results.

Table 9. Results of the distributed lag model for a pair of variables CO₂ and gf₅.

Lag	Regression Coeff.	Standard Error	<i>t</i> -Test	<i>p</i> -Value
0	84.81	17.94	1.74	0.06
1	−104.87	26.59	−3.94	0.03
2	63.10	51.96	1.21	0.35
3	−131.38	61.52	−2.14	0.17
4	51.91	63.26	0.82	0.50

Lag—Lag value; Regression Coeff.—Regression coefficient at the lag value; Standard Error—The standard error of the regression coefficient; *t*-test—Student's *t*-test of statistical hypothesis testing methods (statistical criteria) based on comparison with the Student's distribution for checking the equality of mean values in two samples; *p*-value—Probability of error. Source: Authors' results.

Given the obtained results, there is a lag of one year between all three pairs of variables (the *p*-value for all three models is less than 0.05 at the lag value of 1). Thus, the assumption about a time lag between the volume of green investments and greenhouse gas emissions is confirmed. This fact must be considered when forming an investment plan for green investments.

As a result of the identified lags, it is necessary to re-evaluate the parameters of the regression models of the dependence of CO₂, N₂O, and CH₄ on the independent variables under study. Since the lag value for investment indicators is one year, it is necessary to build a new regression model with a new independent variable added, namely the values of the variables gf₃ and gf₅ shifted by one value (since the lag for these indicators corresponds to one year). As a result of such a procedure, the regression parameter near the lag variable is expected not to be statistically significant. Accordingly, the parameter near the initial variable should change its sign to the opposite and have a statistically significant value. The results of building regression models considering lag variables are presented in Tables 10–12.

Table 10. Multivariate linear regression for carbon dioxide (CO₂) with lags.

Multiple R	0.91093068					
Multiple R-squared	0.82979470					
Adjusted R-squared	0.69363046					
F(4,5)	6.0941					
<i>p</i>	0.03675					
Std. Err. of Estimate	439.77					
Durbin–Watson d	2.1246					
Variable	b *	Std. Err.	b	Std. Err.	t(5)	<i>p</i> -value
Intercept			36146.38	651.8312	55.45360	0.000000
gf ₅	−1.178294	0.629291	−4.87	2.6019	−5.87241	0.020041
gf ₅₋₁	−0.147483	0.674745	−0.62	2.8207	−0.21858	0.835622
fd_re3	−0.524687	0.254221	−1183.83	573.5900	−2.06390	0.033966
fd_re6	−0.243261	0.195830	−0.03	0.0280	−1.24220	0.269246

F-test (df₁, df₂)—Fisher's test with degrees of freedom (i.e., df₁ and df₂) is a statistical test for assessing the significance of differences in the variances of two random samples; df₁ = *m* (*m*—number of independent variables); df₂ = *n* − *m* − 1 (*n*—number of years); *t*-test (df)—Student's *t*-test with degrees of freedom df of statistical hypothesis testing methods (statistical criteria) based on comparison with the Student's distribution for checking the equality of mean values in two samples, df = *m* − *N* (*N*—number of samples). gf₅—Annual investment in off-grid renewable energy, USD million; fd_re₃—The first differences in off-grid capacity of renewable energy, MW; fd_re₆—The first differences in installed renewable energy-generating capacity in developing countries, watts per capita. * means standardized regression coefficients. Source: Authors' results.

Table 11. Multivariate linear regression for nitrous oxide (N₂O) with lags.

Multiple R	0.97234647					
Multiple R-squared	0.94545765					
Adjusted R-squared	0.90182377					
F(4,5)	21.668					
<i>p</i>	0.00234					
Std. Err. of Estimate	21.338					
Durbin–Watson d	1.688					
Variable	b *	Std. Err.	B	Std. Err.	t(5)	<i>p</i> -value
Intercept			2641.413	46.74539	56.50639	0.000000
gf5	−1.102162	0.440947	−0.391	−0.15627	−5.49953	0.044521
gf5 _{−1}	−0.483850	0.519316	−0.173	0.18608	−0.93171	0.394254
fd_re1	0.384655	0.215290	0.000	0.00016	1.78668	0.134036
fd_re3	0.099473	0.158635	19.237	30.67822	0.62705	0.558140

F-test (df₁, df₂)—Fisher’s test with degrees of freedom (i.e., df₁ and df₂) is a statistical test for assessing the significance of differences in the variances of two random samples; df₁ = m (m—number of independent variables); df₂ = n−m−1 (n—number of years); *t*-test (df)—Student’s *t*-test with degrees of freedom df of statistical hypothesis testing methods (statistical criteria) based on comparison with the Student’s distribution for checking the equality of mean values in two samples, df = m−N (N—number of samples). gf₅—Annual investment in off-grid renewable energy, USD million; fd_re₁—The first differences in total capacity renewable energy, MW; fd_re₃—Off-grid capacity of renewable energy, MW. * means standardized regression coefficients. Source: Authors’ results.

Table 12. Multivariate linear regression for methane (CH₄) with lags.

Multiple R	0.94732032					
Multiple R-squared	0.89741578					
Adjusted R-squared	0.84612367					
F(3,6)	17.496					
<i>p</i>	0.00227					
Std. Err. of Estimate	97.731					
Durbin–Watson d	2.816					
Variable	b *	Std. Err.	b	Std. Err.	t(6)	<i>p</i> -value
Intercept			9645.437	80.91318	119.2073	0.000000
gf3	−0.639780	0.514148	−87.820	70.57499	−5.2443	0.025977
gf3 _{−1}	0.285243	0.519901	53.757	97.97999	0.5486	0.603047
fd_re6	−0.142183	0.137881	−0.006	0.00618	−1.0312	0.342207

F-test (df₁, df₂)—Fisher’s test with degrees of freedom (i.e., df₁ and df₂) is a statistical test for assessing the significance of differences in the variances of two random samples; df₁ = m (m—number of independent variables); df₂ = n−m−1 (n—number of years); *t*-test (df)—Student’s *t*-test with degrees of freedom df of statistical hypothesis testing methods (statistical criteria) based on comparison with the Student’s distribution for checking the equality of mean values in two samples, df = m−N (N—number of samples). gf₃—Green economy market capitalization, USD million; fd_re₆—The first differences in installed renewable energy-generating capacity in developing countries, watts per capita. * means standardized regression coefficients. Source: Authors’ results.

As can be seen from the results in Tables 10–12, the new regression parameters near the variables gf3 and gf5, taking into account the lags, have changed their sign to the opposite, and now the influence of green investments contributes to the reduction of greenhouse gas emissions, namely:

- With an increase in off-grid renewable energy annual investments of USD 1 million, the reduction of carbon dioxide emissions to 1.18 kt.

- An increase in off-grid renewable energy annual investments of USD 1 million leads to a decrease in nitrous oxide emissions of 1.102 kt.
- The increase in green economy market capitalization of USD 1 trillion leads to a decrease in methane emissions of 0.64 kt.

5. Discussion

The importance of the problem of greenhouse gas emissions is confirmed by the concern about this issue at the international level, as evidenced by the conclusion of various international documents, protocols, and agreements and the creation of international organizations dealing with climate change risk assessment. An important place among such organizations is the Intergovernmental Panel on Climate Change (IPCC) (an organ of the United Nations), which conducts regular assessments of the scientific basis of climate change and looks for options for adaptation and mitigation of the consequences of these changes. In addition, its goal is to provide governments at all levels with scientific information that they can use to develop climate policy. In 2023, the organization completed the sixth summary assessment report on climate change, which indicated that the planet could warm by 3.2 degrees Celsius by the end of the century. Even if all countries meet the conditions specified in the Paris Agreement, more than these efforts will be needed to limit the increase in temperature to 1.5 degrees Celsius. For such a limitation, it is necessary to reduce harmful emissions into the atmosphere by a factor of two by the mid-2030s [71].

The European Union (EU) is just a little behind in developing strategies and goals for climate action under the European Green Deal. In particular, the European Climate Law, which envisages the legal establishment of climate neutrality by 2050 in EU legislation, is currently under discussion. In 2020, the European Climate Pact aimed at involving society in climate action was adopted, and in 2021, the new EU strategy for adaptation to climate change was adopted. In addition, the EU plans to allocate 1.8 trillion euros to finance the European Green Deal, which aims to reduce net greenhouse gas emissions by 55% by 2030. Thus, the issue of climate change is highly relevant from the point of view of solving the problem of greenhouse gas emissions.

Researchers [42,43] have found that financing environmental projects is beneficial only in the long term. It is safe to say that countries nowadays are in a transition period from the use of traditional technologies, which lead to significant emissions of greenhouse gases, to implementing new processes and technologies designed to reduce such emissions. For example, in the process of such a transition, the increase in emissions may be associated with the construction of alternative power plants. In addition, such a transition period is characterized by a time gap between an investment and the final result of such an investment.

This research analyzes relationships at the global level, so the results may not coincide with the results of other works, as the latter were conducted based on the data from a separate country or several countries: for E7 economies [49], N-11 and BRICS countries [50], MINT economies [64], EU countries [72], and Asian countries [73]. Surely, the study of the issue at the microlevel gives more accurate results regarding the effectiveness of the influence of a certain phenomenon. Nevertheless, the given analysis, based on global trends, makes it possible to evaluate the overall benefits for the planet from the implementation (or non-implementation) of environmental innovations, taking into account the combined efforts of all countries.

6. Conclusions

The main purpose of this study was to identify general trends in the impact of renewable energy source development and green investments on CO₂, N₂O, and CH₄ greenhouse gas emissions at the global level. The main sources of carbon dioxide emissions are power plants, the transport sector, and some types of industrial processes (production of steel, cement, etc.). Nitrous oxide emissions occur due to the use of fertilizers. Methane is released during the extraction and production of oil and gas, the use of coal, industrial processes and

landfills, and agriculture (cattle breeding). For this research, there are 14 statistical variables that characterize greenhouse gases, renewable energy, and green investments for the period from 2011 to 2021. In accordance with the set purpose, using correlation-regression analysis, it was established that:

- Green investments contribute to greenhouse gas emissions. In particular, an increase in off-grid renewable energy investments of USD 1 million leads to an increase in CO₂ emissions of 4.5 kt and N₂O emissions of 0.272 kt. At the same time, a USD 1 trillion increase in green economy market capitalization leads to an increase in methane emissions of 129,530 Mt.
- The development of renewable energy leads to a reduction in carbon dioxide emissions, as 1 MW growth of an absolute increase in off-grid renewable energy capacity leads to a 1171.17 Mt decrease in CO₂ emissions.
- There is no statistically significant impact of renewable energy on N₂O and CH₄ emissions.

During the research, there was a time lag of one year between the level of green investments and the level of greenhouse gas emissions. The results of the regression models, taking into account the time lag, showed the following results: An increase in off-grid renewable energy annual investments of USD 1 million leads to a decrease in CO₂ of 1.18 kt and N₂O of 1.102 kt; an increase in green economy market capitalization of USD 1 trillion leads to a decrease in CH₄ emissions of 0.64 kt.

Thus, the conscious choice of households and enterprises to abandon the use of traditional energy and independently switch to the use of energy from renewable sources should reduce the negative consequences of climate change caused by greenhouse gases. In general, research within a single country or several countries gives a narrowly focused evaluation of the impact of renewable energy and green investments. It may differ for each country and depend on a country's contribution and its policy regarding the transition to energy-saving technologies, renewable energy development, and the number of green investments. On the contrary, the study of greenhouse gases at the global level makes it possible to assess the general trends of their emissions and the global influence of green energy and green investments.

This study has certain limitations that can be used to guide future research. Further research could examine the impact of renewable energy and green investments at the regional or country level. In addition, if the research period is increased, it is necessary to analyze the lag level between the impact of green investments and greenhouse gas emissions. Furthermore, the list of variables can be expanded by adding new factors of an economic, demographic, and energy nature. For now, the list of variables that would characterize green investments is very narrow, so in the future, when more data appears at the global and regional levels and the list of variables expands, further research in this direction will deserve development.

Author Contributions: Conceptualization, A.K., I.D., O.D. (Olena Dobrovol'ska) and A.A.; methodology, A.K., T.W., O.D. (Oleksandr Dluhopolskyi) and W.C.; software, A.K., I.D., W.C. and A.A.; validation, T.W. and W.C.; formal analysis, A.K., I.D., O.D. (Olena Dobrovol'ska) and A.A.; investigation, A.K., I.D., O.D. (Olena Dobrovol'ska) and A.A.; resources, T.W. and W.C.; data curation, W.C. and O.D. (Oleksandr Dluhopolskyi); writing—original draft preparation, A.K., I.D., O.D. (Olena Dobrovol'ska) and A.A.; writing—review and editing, A.K., O.D. (Oleksandr Dluhopolskyi), T.W., I.D., A.A., O.D. (Oleksandr Dluhopolskyi) and W.C.; visualization, A.K., I.D., T.W. and W.C.; supervision, A.K., I.D. and O.D. (Olena Dobrovol'ska); project administration, T.W. and W.C.; funding acquisition, T.W. and W.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

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

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