Collision of Environmental Expectations when Assessing the Supply Versus the Consumption of Electrical Energy

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Abstract

The use of energy supplies for economic activities is a major global concern due to its environmental impact. Mitigating this problem involves the adoption of clean energies, so it is not trivial to assess those that can fit into this category, particularly the part corresponding to electrical energy. While the consumption of the latter is often perceived as more environmentally friendly than other sources, its production process raises significant questions, hence the core motivation to evaluate the behavior of the main inputs for electrical energy production over 50 years and its correlation with the world Gross Domestic Product (GDP), confirming a prominent dependence on fossil fuels, a situation that seems to differ from the expectations set forth through the Paris Agreement and the United Nations Conference of the Parties. On the other hand, even though the production of electrical energy is consistent with the behavior of the world GDP, it shows heterogeneous annual percentage changes.

Keywords: Clean energy, environment, electric energy, fossil fuels, renewable resources.

1. Introduction

Concern for protecting the environment due to expectations regarding global temperature change attributed to so-called greenhouse gases is frequently encountered in the global community (National Oceanic and Atmospheric Administration, n.d) [1]. This has led to the organization of international summits, which have become visible through the Paris Agreement (United Nations Framework Convention on Climate Change, n.d.) [2] and the recurring Conferences of the Parties (United Nations 2023) [3] under the United Nations Framework Convention on Climate Change. It is assumed that energy supplies play a significant role in the increase in global temperature, so it is considered relevant to promote the use of clean energy, including electrical energy. According to the International Energy Agency [4], the use of "electric vehicles, electrification in buildings, industry, and international maritime transport" is considered part of clean energy. Therefore, the assessment of the generation process of this type of energy from a consumption perspective must be seen separately from the production process addressed in this

document, as the latter only partially meets this condition when produced with some renewable resources.

Global Electricity Production

The extensive efforts to mitigate global warming resulting from human economic activities are evident, as confirmed by the Paris Agreement and the periodic Conferences of the Parties on climate change, which establish ambitious goals for the world. To achieve this, controlling greenhouse gases, which are attributed to the unbalanced increase in global temperatures, is intended.

It is encouraging to know that many nations intend to contribute through various international forums to address the problem of climate change. However, this effort is still limited (United Nations, n.d.) [5], as the situation remains unresolved and concerning in terms of temperature increase, according to the World Meteorological Organization (2024) [6]. Illustrative cases of the above abound in different regions of the world, such as record-high temperatures exceeding historical levels and the consequences in areas such as Antarctica (National Snow and Ice Data Center, n.d.) [7]. Also, widespread flooding in various nations has caused immense human and material impacts, such as in southern Brazil in May 2024 (Defesa Civil Atualiza Balanço das Enchentes no RS - 8/5, 12h, 2024) [8], where it is estimated that more than 1.5 million people were affected. The effects of climate change may worsen as global temperatures and sea levels rise, in addition to wildfires as in Canada (Environmental Protection Agency) [9], to name a few.

It is assumed that thermal retention gases show imbalance due to various energy production processes (Government of Canada, n.d.) [10], so it is deemed advisable to use clean energy. However, reality seems to contradict what is expected of climate change in the coming years regarding the amount of CO2 (carbon dioxide) on the planet. Likewise, when referring to so-called clean energies, it is necessary to analyze how environmentally friendly they are from the perspective of electrical energy addressed in this document. Even though the description of technical elements related to the production process is beyond the scope of this paper, it is necessary to remember that to obtain electrical energy involves two substantial mechanisms [11]. The first involves rotating a turbine, which requires one or more inputs to achieve it, such as the use of fossil fuels, nuclear energy, wind, and renewable resources, while the second involves generating a photovoltaic process, which requires solar energy.

The use of fossil fuels such as coal, natural gas, fuel oil, and nuclear energy, among others, draws attention due to their impact on the environment [12], so it is always necessary to ask the following question: How clean is electrical energy? From the consumption perspective, electricity is considered clean energy when used; however, the production process, whose cleanliness depends on the type of inputs used for its production, presents a different situation. To contextualize the level of concern this represents, it is advisable to assess the specific weight of each set of inputs on electricity generation. The results of this analysis are presented in the following paragraphs.

2. Results

During the global study period from 1971 to 2021, only nuclear energy shows a practically horizontal behavior, unlike fossil fuels and the use of renewable resources, which reflect a positive trend.

Through figure (Fig.) 1, we seek to evaluate the participation of each input in total global electricity generation during this time.

As shown in the Fig. 1, the main inputs used for electricity production are grouped into three major categories: fossil fuels, nuclear energy, and renewable resources.

In Fig. 2 , the enormous dependence of electrical energy on fossil fuels is evident, and although a slight decrease is observed over time, in the last year, the contribution exceeds 60%.

It is difficult to expect that the decline in the use of fossil energy will continue in the future when observing the data from the research period.

Although there have been reductions in their contribution by only a few percentage points, these have been recovered, and even a level close to the end of the observation period is appreciated, compared to the levels reached in the mid-1990s of the last century.

It is illustrative to observe in Fig. 3, the decisiveness shown regarding the contribution of fossil fuels, which accounts for 67% on average in electricity production during the observation period.

This is of the utmost importance since fossil fuels are considered a determining element in global climate change, which is consistent with the analysis presented in the Global Status Report (Climate Action Tracker, 2023) [14], where their use predominates in electricity production.

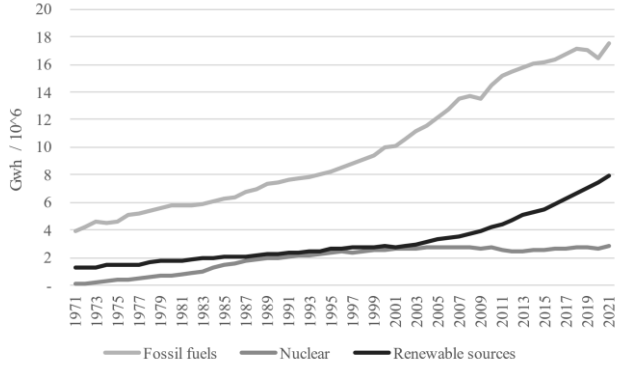

Figure 1. Global Trend of Relevant Inputs for Electricity Production. Based on data provided by the International Energy Agency (IEA), n.d.) [13].

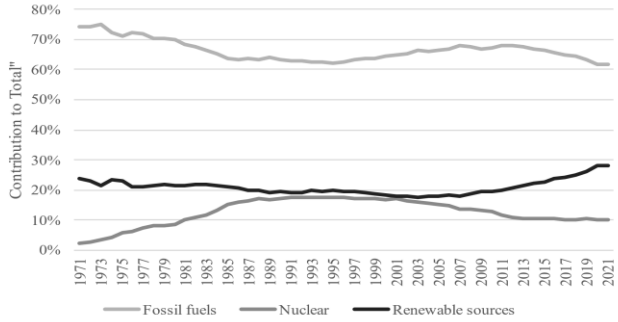

Figure 2. Contribution to Total Electricity Production Worldwide. Based on data provided by the International Energy Agency (IEA), n.d.) [13].

From an environmental protection perspective, it is positive that the world can move towards intelligent processes in the distribution network of electrical energy (REN21, 2023) [15]. However, a central element to address is the type of inputs used for its production.

To illustrate the relationship between electricity production and economic growth, Fig. 4, shows the evolution of electricity production and the global gross domestic product (GDP) from 1971 to 2021, revealing an upward trend in both areas, although the second shows a steeper upward slope.

Furthermore, when assessing the dependence of electricity production concerning the behavior of the global GDP, it is confirmed that there is a direct relationship between the variables when running a regression model, with the coefficient R^2 approaching 1, as can be seen in Table 1.

The relationship between the variables seems consistent with the expectation that can be had about energy production, as there are changes in wealth creation in the world, measured through the GDP. The model is reinforced by observing both the critical value of f and the probability, which are below 0.05.

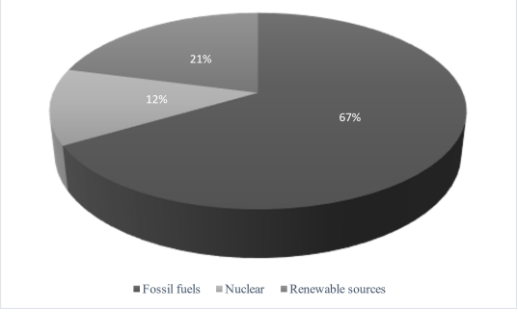

Figure 3. Worldwide electric power 1971-2021 average contribution. Based on data provided by the International Energy Agency (IEA), n.d.) [13].

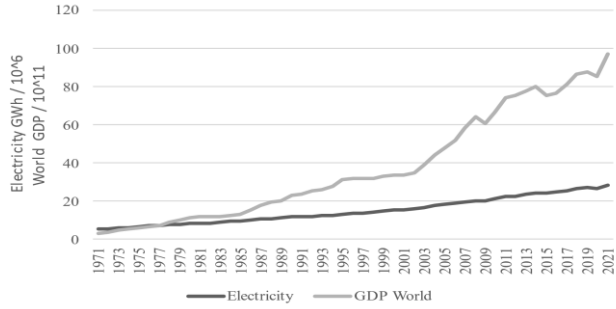

Figure 4. Electric Power - World GDP Trend. Based on data provided by the International Energy Agency (IEA), n.d.) [13] and the World Bank [16].

To further examine the possible dependence between electricity production and the global GDP, a regression has been run by separately considering that derived from the use of fossil fuels, confirming a direct relationship as is the case with total generation. As the independent variable increases, so does the dependent variable, as observed in the results shown in Table II, where the coefficient R^2 is equal to 0.98, very close to 1.

However, this dependence relationship does not seem to be as significant when running the model and comparing it against nuclear energy, where the coefficient R^2 barely reaches 0.61, with a critical value of f and probability lower than 0.05, which reinforce the model, as seen in Table III.

To complete the analysis, renewable resources have now been used as the dependent variable for electricity generation concerning the world's GDP.

In this case, there is again a direct relationship between the variables, with an R^2 coefficient reaching 0.92, as shown in Table IV.

Table 1. Comparative GDP against global electricity production. Based on data provided by the International Energy Agency (IEA), n.d.) [13] and the World Bank [16].

Summary output

Regression Statistics	
Multiple R	0.993373972
R Square	0.986791849
Adjusted R Sq	0.986516679
Standard Error	0.777599863
Observations	50

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2168.388547	2168.388547	3586.119476	9.163E-47
Residual	48	29.02375422	0.604661546		
Total	49	2197.412302			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	6.112563336	0.187190323	32.65426998	1.94964E-34	5.736191967
3.32304E+12	2.36578E-13	3.95059E-15	59.88421725	9.163E-47	2.28635E-13

In Figure 4, an upward trend is observed between electricity production and the global GDP; however, the rate at which they do so is different.

Table II. Comparative GDP against global electricity production with fossil fuels. Based on data provided by the International Energy Agency (IEA), n.d.) [13] and the World Bank [16].

Summary output

Regression Statistics	
Multiple R	0.994176418
R Square	0.988386749
Adjusted R Square	0.988144807
Standard Error	0.467453636
Observations	50

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	892.6710303	892.6710303	4085.209724	4.17237E-48
Residual	48	10.48861928	0.218512902		
Total	49	903.1596495			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	4.145846301	0.112529337	36.84235963	7.39927E-37	3.919590905
3.32304E+12	1.51793E-13	2.37489E-15	63.91564538	4.17237E-48	1.47018E-13

To delve into this, the annual percentage changes between the variables in the same period from 1971 to 2021 have been compared, with the result shown in Figure 5.

At first glance, a discrepancy in intensity between the growth levels in each year is observed, confirming that percentage changes are pronounced in gross domestic product levels, while in general, those related to electricity production seem much smoother, even though in the long term, both show an increase, according to previous graphs and regression models.

Given the above, it can be assumed again that even though there may be a direct relationship between both variables, the production for the global GDP is met by electrical energy but also by other sources globally.

A regression model has been run considering the variables from Figure 5, with total electricity production remaining dependent.

When comparing annual changes, the one corresponding to electricity production with fossil fuels has been considered separately, as shown in Figure 6.

Table III. Comparative GDP against global electricity production with nuclear energy. Based on data provided by the International Energy Agency (IEA), n.d.) [13] and the World Bank [16].

Summary output

Regression Statistics	
Multiple R	0.783071911
R Square	0.613201618
Adjusted R Square	0.605143318
Standard Error	0.549953127
Observations	50

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	23.01501343	23.01501343	76.09565867	1.81788E-11
Residual	48	14.51752523	0.302448442		
Total	49	37.53253865			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	1.026586042	0.132389302	7.754297539	5.18757E-10	0.760399509
3.32304E+12	2.43731E-14	2.79403E-15	8.723282563	1.81788E-11	1.87554E-14

Table IV. Comparative GDP against global electricity production with renewable resources. Based on data provided by the International Energy Agency (IEA), n.d.) [13] and the World Bank [16].

Summary output

Regression Statistics	
Multiple R	0.960018438
R Square	0.921635402
Adjusted R Square	0.920002806
Standard Error	0.488841353
Observations	50

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	134.9013673	134.9013673	564.5214873	3.42705E-28
Residual	48	11.47036167	0.238965868		
Total	49	146.3717289			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	0.94604809	0.117677967	8.039296719	1.92086E-10	0.70944068
3.32304E+12	5.90084E-14	2.48355E-15	23.75966093	3.42705E-28	5.40149E-14

As observed, the annual growth levels between the variables do not occur with the same intensity.

This observation is supported by running a regression model with both, using the world GDP as the independent variable. The R^2 coefficient reaches 0.24, as shown in Table VI.

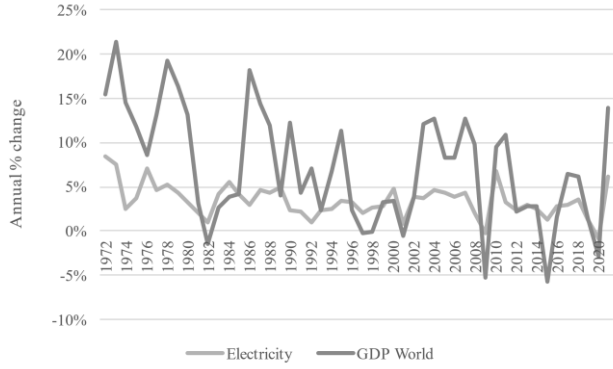

Figure 5. Comparative Annual Percentage Change. Based on data provided by the International Energy Agency (IEA), n.d.) [13] and the World Bank [16].

Table V. Comparative Annual Percentage Change, GDP versus global electricity production. Based on data provided by the International Energy Agency (IEA), n.d.) [13] and the World Bank [16].

Summary output

Regression Statistics	
Multiple R	0.62097213
R Square	0.385606387
Adjusted R Square	0.372534182
Standard Error	0.013849969
Observations	49

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.005658392	0.005658392	29.49819104	1.93128E-06
Residual	47	0.009015617	0.000191822		
Total	48	0.014674009			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	0.021490135	0.002962999	7.252833524	3.38413E-09	0.015529351
0.154152736	0.171075204	0.031498464	5.431223715	1.93128E-06	0.107708468

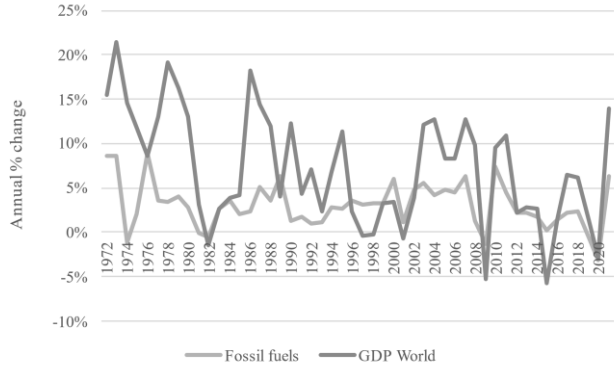

Figure 6. Comparative Annual Percentage Change. Based on data provided by the International Energy Agency (IEA), n.d.) [13] and the World Bank [16].

This confirms the previously observed, with an R^2 coefficient reaching 0.38, indicating that the degrees of intensity of annual changes are different among the variables under observation, as shown in Table 5.

Now, the comparison is made with electricity production using nuclear energy, as shown in Fig. 7.

Table VI. Comparative Annual Percentage Change, GDP versus electricity production with fossil fuels. Based on data provided by the International Energy Agency (IEA), n.d.) [13] and the World Bank [16].

Summary output

Regression Statistics	
Multiple R	0.495313524
R Square	0.245335487
Adjusted R Square	0.229278795
Standard Error	0.021782612
Observations	49

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.00724977	0.00724977	15.27932968	0.000296407
Residual	47	0.022300663	0.000474482		
Total	48	0.029550433			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	0.016117023	0.004660072	3.458535521	0.001164399	0.006742168
0.154152736	0.193643389	0.049539375	3.908878314	0.000296407	0.093983021

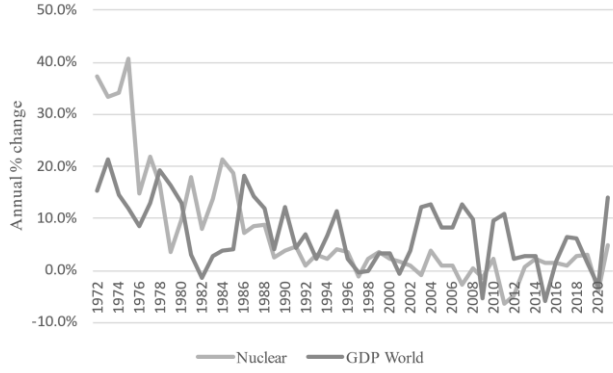

Figure 7. Comparative Annual Percentage Change. Based on data provided by the International Energy Agency (IEA), n.d.) [13] and the World Bank [16].

Table VII. Comparative Annual Percentage Change, GDP versus global electricity production generated with nuclear energy. Based on data provided by the International Energy Agency (IEA), n.d.) [13] and the World Bank [16].

Summary output

Regression Statistics	
Multiple R	0.407927109
R Square	0.166404526
Adjusted R Square	0.148668452
Standard Error	0.092167139
Observations	49

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.079700282	0.079700282	9.382263904	0.003620063
Residual	47	0.39925473	0.008494781		
Total	48	0.478955011			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	0.020475377	0.019717813	1.03842029	0.304387363	-0.019191746
0.154152736	0.642052431	0.209612256	3.063048139	0.003620063	0.220366963

Although there appears to be a less abrupt situation when comparing annualized percentage changes, the difference persists, confirmed by observing the R^2 coefficient at 0.16 in Table VII.

To complete the analysis, Fig. 8 is presented to compare annual growth with respect to electricity generation from renewable resources and the world GDP.

The difference between the percentage changes is pronounced and is also confirmed by consistently running the regression model with the world GDP as the independent variable. An R^2 coefficient of 0.01 is observed in Table VIII.

According to the model, annual percentage changes are not significant when renewable resources are used as inputs for electricity production, as observed as well to those derived from nuclear energy and fossil fuels.

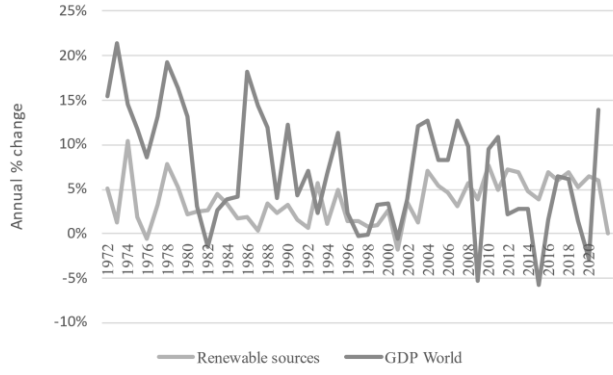

Figure 8. Comparative Annual Percentage Change. Based on data provided by the International Energy Agency (IEA), n.d.) [13] and the World Bank [16].

Table VIII. Comparative Annual Percentage Change, GDP versus global electricity production through renewable resources. Based on data provided by the International Energy Agency (IEA), n.d.) [13] and the World Bank [16].

Summary output

Regression Statistics	
Multiple R	0.103252582
R Square	0.010661096
Adjusted R Square	-0.010388668
Standard Error	0.025664236
Observations	49

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.000333589	0.000333589	0.506471036	0.480188117
Residual	47	0.030956692	0.000658653		
Total	48	0.03129028			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	0.034970931	0.005490488	6.369366262	7.41313E-08	0.023925494
0.154152736	0.041538061	0.058367207	0.711667785	0.480188117	-0.075881613

To enhance the results, it is valuable to analyze the situation that prevails regarding electrical energy from the perspective of consumption, as illustrated in Fig. 9.

On average, during the last five decades, 58.7% of the world's energy was met with fossil fuels, followed by electrical energy with 14.6%. In 2021, 55.6% of energy consumption came again from fossil fuels and electrical energy consumption reached one-fifth of the total. The use of renewable resources barely exceeded 10% of the total.

3. Discussion

While the use of electricity for various means of transportation, urban infrastructure, and industry can be considered clean, encouraging its consumption for these purposes can have adverse impacts on the environment, given that the main input for its production comes from fossil fuels, which significantly contribute to the increase in greenhouse gases.

Encouraging electricity consumption must be accompanied by efforts to reduce the use of fossil fuels in electricity production and increase the use of renewable resources such as solar energy.

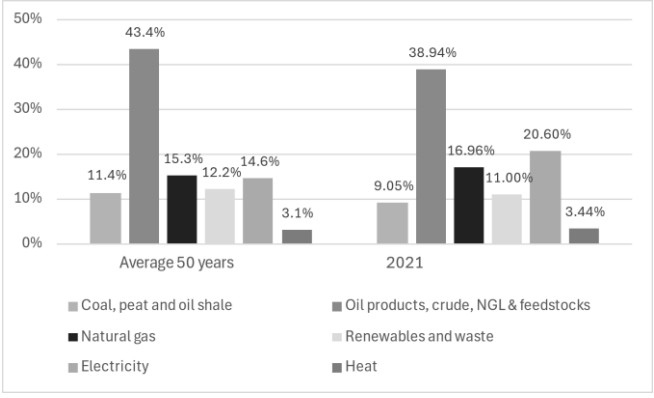

Figure 9. Contribution to Total Consumption in the World (Petajoules (PJ)). Based on data provided by the International Energy Agency (IEA), n.d.) [13].

It is necessary to assess how long and at what cost the available capacity of the world's electrical infrastructure could replace energy obtained from other sources, considering that its contribution to the global total appears secondary. In other words, a deeper analysis of the material reasons leading to the prevailing situation in the industry is needed.

It is advisable to conduct research on the economic incentives that favor the consumption of fossil fuels over more environmentally friendly renewable resources.

In addition to electricity generation, every variable related to human activity that may impact the environment needs to be analyzed, given the current levels of Earth's temperature.

4. Conclusion

Electricity worldwide is produced using three sets of inputs: fossil fuels, nuclear energy, and renewable resources. From 1971 to 2021, on average, 67% of electricity production was generated using fossil fuels, 21% with renewable resources, and 12% with nuclear energy. Over the 50-year span, electricity production followed the trend of the world's gross domestic product (GDP). However, it did not keep pace consistently, likely due to the contribution of other energy sources influenced by global market conditions.

When separately analyzing the relationship of each input with respect to global GDP, a direct relationship is observed over time, although this is weaker with respect to nuclear energy. Electricity obtained from nuclear energy peaked in the mid-1990s, contributing 20% to electricity generation, but has since reduced to levels close to 10%.

Electricity production using fossil fuels and renewable resources has experienced growth over the study period, unlike nuclear energy, which appears to exhibit a horizontal trend since the mid-1990s. The contribution of renewable resources has moderately approached 30% by the end of the research term, whereas that from fossil fuels shows years of decline and increase in the long term, maintaining a share above 60% at the end of the period.

Promoting the production of clean energies must consider that doing so also stimulates the use of fossil fuels, given the dependency on them in electricity generation. The pollutant components of electricity amount to 79% of the total when considering only the input phase, meaning that only 21% is produced using renewable resources.

Regardless of how electricity is produced, the growth of the inputs supporting it does not respond to the annualized movement of GDP in the same manner.

It is essential to confirm that to evaluate the cleanliness of electricity in terms of its environmental impact, its production process must be considered.

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