Time-Varying Causal Relationship between Different Uncertainties and Renewable Energy Consumption in the USA

Hicham Ayad[1] and Alina Cristina Nuta[2]

[1]University Centre of Maghnia, LEPPESE laboratory, Algeria; h.ayad@cu-maghnia.dz; ORCID: 0000-0003-1624-3456

[2]Danubius International University, Romania; Women Researchers Council, Azerbaijan State University of Economics (UNEC), Istiqlaliyyat Str. 6, Baku 1001, Azerbaijan; alinanuta@univ-danubius.ro; ORCID: 0000-0003-3248-644X

Abstract: *The modern world is experiencing recurring states of uncertainty, in all economic and political fields, which increases the production costs that also have a significant impact on achieving Sustainable Development Goals (SDGs). Therefore, the main motivation of this paper is to investigate the causal association from six policy uncertainty indexes, such as economic, monetary, taxes, government spending, healthcare, and trade policy uncertainty, to renewable energy consumption in the USA. The empirical evidence is based on monthly variables spanning the period January 1985 to July 2022. Hence, the paper used unit root tests to determine the higher-order integration of the variables, and time-varying causal relationships to detect both traditional causation and hidden causality, using positive and negative cumulative components for the uncertainty variables. The results revealed a causal relationship running from all uncertainties except trade uncertainty to renewable energy, especially in the new millennium and with the positive changes. Accordingly, based on the results, it is clear that any policy and strategy for energy transition in the United States must consider the economic uncertainty, given its sensitive role in shaping energy consumption and, consequently, environmental deterioration.*

Keywords: economic uncertainty; renewable energy; time-varying causality; hidden causality

1 Introduction

The years since the beginning of the millennium, have been marked, beyond any doubt, by a great and growing interest in climate change, which threatens the stability and the economy of humankind. In this vein, the National Oceanic and Atmospheric Administration's measurements revealed that, on average, carbon dioxide levels rose by 2.6 parts per million in 2020, reaching 412.5 parts per million.

Additionally, a separate analysis from the Scripps Institution of Oceanography at the University of California in the United States showed that carbon dioxide levels have increased by 50% since before the Industrial Revolution. Measuring results also revealed that the amount of methane in the atmosphere increased dramatically in 2020, reaching its highest level since the National Oceanic and Atmospheric Administration started keeping track of it in 1983. The rate of increase seen was 14.7 parts per billion [1]. Nevertheless, the International Energy Agency (IEA) recently announced in London that the expansion of renewables and electric vehicles exceeded the need for coal, and it is predicted that this year's worldwide carbon dioxide emissions from burning fossil fuels will rise by just under 1%. Additionally, the same report also forecasts that CO2 emissions will climb by 300 million tons this year to reach 33.8 billion tons, a much smaller increase than 2021's approximately 2 billion extra tons.

According to the 2017 IEA report, only five nations—China, the US, India, Russia, and Japan—consume more than 60% of the world's energy, accounting for 65% of the planet's carbon emissions. Indeed, even though it has only 4.3% of the world's population, the United States consumes 16% of all energy, compared to China and India, which together have 36% of the world's population but only consume 28% of all energy. Therefore, this contrast highlights the significant role that the United States plays in energy consumption and, consequently, its sensitive role in driving up emissions. This is why the United States' adoption of renewable energies, benefits the entire world, by significantly and successfully reducing atmospheric emissions. Therefore, it is crucial to understand how economic factors affect the consumption of renewable energy sources to identify the factors most likely to increase or decrease their use.

It is important to note that [2] made a distinction between six different sorts of variables that could influence how much renewable energy (RENE) is consumed. Which are the political (institutional quality and government ideology), regulatory (renewable energy support policies and Kyoto protocol), economic (GDP, energy prices, international flows, and local financial sector), energy (energy security, fossil fuel production, and electricity consumption), environmental (CO2 emissions), and demographic (population) factors. However, on the economic side, the author largely ignored the economic uncertainty that would play a significant role in energy consumption, both renewable and non-renewable.

In this context, recently, there has been an increase in interest of the issue of uncertainty, especially after the 2008 global financial crisis, the trade war between the United States and China under the policies of Donald Trump, the COVID-19 pandemic at the end of 2019, and, recently, the Russian-Ukrainian war at the beginning of 2022. From this point of view, we can define economic uncertainty as a state of ambiguity and uncertainty that fills the economic environment due to government regulatory, fiscal, and monetary decisions, as well as external factors such as wars, economic, security, and health crises. Therefore, this state of uncertainty influences how economic agents make decisions in order to prevent any unforeseen market responses that could affect their production and market shares, raise production costs, and lower profits. According to [3-5], economic policy uncertainty (EPU) could have both positive and negative associations with energy consumption (both renewable and non-renewable). On the one hand, EPU can have a negative impact on energy consumption in a nation with high levels of energy-intensive product consumption and energy investment as institutions and companies may reduce production levels in response to high levels of uncertainty, which would increase costs and lower profits. As a result, due to the instability that EPU could cause in energy prices, particularly for fossil fuels (oil and natural gas prices), many firms turn to renewable energy sources, which means a higher proportion of renewable energy in total energy use. Whereas, this effect is called the consumption effect. On the other hand, higher levels of uncertainty may disrupt the trend towards renewable energies due to their high costs compared to cheap fossil fuels, and this effect has been called the substitution effect.

Consequently, renewable energy is considered one of the most important ways to achieve environmental SGDs that seek to curb climate change [6-15]. As many studies have indicated, the energy transition is still in its early stages and faces many difficulties, such as the high costs compared to non-renewable sources and the inefficiency of available technologies. Therefore, the importance of this study lies in shedding light on an area that can either stimulate or inhibit energy transfer, as noted above. This study seeks to determine the role of various types of uncertainty in influencing the energy transition plan in the United States in order to develop policies and strategies aimed primarily at taking advantage of uncertainty to enhance the use of renewable energies. Moreover, choosing six types of uncertainty, as explained above, allows for a more complete picture of the relationship between uncertainty and the energy transition, as economic uncertainty is not the same as commercial uncertainty, for example. Therefore, the study constitutes a serious attempt to clarify the possibility of energy transition in the United States in light of the increasing global uncertainty.

This paper aims to contribute to the existing literature in different ways. First, in contrast to previous studies that focused on the impact of uncertainty on RENE, this study sheds light on the causal relationship, enabling us to identify the possibility of using EPU to influence and predict RENE in the long run. Second, through this study, we will address multiple types of uncertainty, as we find that most previous studies focused only on EPU, neglecting the other types. Hence, we will try to fill this gap by addressing six different types of uncertainty represented in economic (EPU), monetary (MPU), government spending (GPU), taxes (TPU), healthcare (HPU), and trade (TRPU) in order to get a more accurate idea of the nature of the causal relationship between the two variables under study. Third, as is well known, traditional tests for causality, such as Granger, TYDL (Toda-Yamamoto-Dolado-Lutkepohl), Breitung-Candelon, and several other methods, assume the stability of causal association throughout the study period. However, this assumption cannot be accurate, especially over long periods characterized by frequent fluctuations and changes that affect the causal relationship, during which the relationship may disappear in some periods and then reappear. Therefore, this paper will adopt the modern methodology of time-varying causal relationships (TVC) proposed by [16], [17], which allows us to trace the causal relationship between the two variables across different inter-periods within the entire period. Fourth, to obtain more robust results, we will incorporate the concept of hidden causality into time-varying causation by including positive and negative changes, following the [18] procedure, for each uncertainty variable to examine its causal relationship with RENE. This will make it possible to create policy implications and recommendations that are more precise and obvious.

The remainder of the paper is organized as follows. Section 1 is represented by the previously stated introduction. The second section will review the literature on the relationship between policy uncertainty and renewable energy. The third section will be devoted to the study's data and methodology. The fourth section will highlight the most important findings from the econometric analysis. This is followed by a fifth section devoted solely to discussing the findings and comparing them with past research. Finally, the sixth section, will summarize the findings and discuss various policy implications.

2 Literature Review

In recent years, there has been an increasing interest in the impact and relationship of economic uncertainty with RENE, as it is a key determinant factor that has shown important and significant effects in the policies of countries, enterprises, and individuals to adopt renewable energies. Notably, various papers concluded that EPU plays a vital role in decreasing RENE in numerous countries. In 23 developed and developing countries, [19] examined the effect of EPU, GDP, trade openness, CO2 emissions, and financial development of RENE using parametric panel estimations. The findings indicated that these countries' high levels of uncertainty would impede the adoption of renewable energies. The study tested these findings using time-varying estimation techniques, and it became evident that the majority of the study period was filled with this negative effect. Moreover, [20] used the wavelet quantile-on-quantile method to investigate the impact of EPU on RENE across G7 countries. The results showed undoubtedly that the effect of EPU on RENE is significant and negative in all quartiles, which means that uncertainty with its various changes greatly impedes the use of renewable energy. Additionally, it was discovered that the higher quartiles had a stronger impact than the lower and middle quartiles, indicating that RENE is severely and quickly impacted by high uncertainty rates. In the context of the USA, [21] using the NARDL model, depending on monthly data from 1986 to 2019, confirmed a negative association between EPU and RENE, implying that higher EPU lowers RENE. In addition, [22] examined the association between non-renewable and renewable electricity consumption with EPU and CO2 emissions in the USA over the period January 1985 to December 2020, using a bootstrap rolling procedure. The results concerning the relationship between EPU and RENE showed the existence of a unidirectional causal link running from EPU to RENE only during the period 2008 - 2012.

[23] investigated the impact of foreign direct investment (FDI) and government debt, in addition to EPU, on renewable energy integration in 13 oil-importing countries over the period 1995-2018. For this reason, the authors used both panel ARDL and panel NARDL approaches to explore the symmetric and asymmetric association between the variables. Accordingly, the ARDL findings revealed a negative association between EPU and RENE. The same result was also found using NARDL, showing that both positive and negative changes in EPU reduce RENE in the long and short run. Moreover, the causality analysis explored the existence of a unidirectional causal relationship from EPU to RENE. Similarly, [24] examined the asymmetric effect of EPU on RENE using the world uncertainty index (WUI) across G7 countries over the period 1997-2019. The outcomes revealed clearly that both positive and negative changes in WUI lead to a reduction in RENE. Notably, the author concluded that it is impossible to ignore uncertainty in future projects to increase RENE in G7 countries. In the same vein, [25] studied the effects of informal economy, environmental governance, financial development, and EPU on RENE in BRICST countries. Depending on several estimators and tests, the authors showed that EPU is a fundamental impediment to energy transition in these economies. Likewise, this result confirmed the findings of [26][27]. The first study examined the effect of EPU on RENE with the control of FDI and financial development in BRIC nations (excluding South Africa and Turkey) over the period 1997Q01 to 2018Q04. The findings confirmed that both positive and negative shocks of EPU lessen RENE in all countries. Furthermore, using TYDL causality, the authors found a unidirectional causal relationship running from EPU to RENE in all nations. The second study evaluated the asymmetric impact of EPU and conventional energy on RENE in BRICS countries (without Turkey). Hence, the results inspired by panel NARDL-PMG estimation concluded that positive variation in EPU decreases RENE; conversely, negative changes in EPU were shown to play a reinforcing and contributing role in increasing RENE. Finally, [28] focused on China to examine the effects of EPU and financial development on RENE for the period 1990 to 2019, depending on NARDL estimation. Remarkably, the results showed that positive changes in EPU improved RENE by 3.2% and negative changes diminished RENE by 1.4% in the long run.

At the other extreme, we find a very limited number of studies that have studied the effects of other types of economic uncertainty on RENE. Recently, [29] focused on the effect of pandemic uncertainty on RENE, using the Wilder Hill Clean Energy Index over the period 3rd January 2005 to 30th June 2020, with quantile regression. The results showed that Pandemic uncertainty positively affects RENE, which means that an increase in Pandemic uncertainty will push towards the consumption of renewable energy. However, as in previous studies, the effect of EPU on RENE is negative, especially in lower quartiles, and it reverses in higher quartiles. Besides, [30] brought their attention to the MPU and its impact on RENE and non-renewable energy use in the USA. Hence, on one hand, the ARDL estimation results indicated that MPU has a short and long-run negative impact on RENE. On the other hand, NARDL estimation pointed out that negative changes in MPU decrease RENE in the long run. More recently, [31] treated the effect of three types of uncertainty represented by Fiscal policy uncertainty (FPU), MPU, and TRPU on RENE in the USA using the AARDL (Augmented ARDL model) methodology. The outcomes reached different conclusions for each type of uncertainty, as it was found that MPU plunges RENE, whereas FPU increases it, and there was no significant effect for TRPU.

Recently, [32] showed, using quantile-quantile regression, that RENE was negatively correlated with geopolitical oil price uncertainty (OPU) over the period 2004Q1 to 2019Q4. Notably, the authors discovered that RENE expansion could diminish the geopolitical oil price uncertainty in the long run. Similarly, [33] explored the causal association among, on the one hand, geopolitical risks, EPU, and CPU, and on the other hand, RENE. Using quantile VAR spillover models, the outcomes revealed 82.87% connectedness between RENE and the uncertainty indices. Accordingly, this finding confirmed the importance of the uncertainty in promoting the RENE on a global scale. Moreover, [34] used rolling-window causality with time-varying bootstrapping to detect causation among CPU, EPU, and RENE. The outcomes showed that the connection between RENE and CPU is positive when the administration is positive towards climate change; otherwise, it is negative. Conversely, EPU showed a negative association with RENE in most periods and cases.

Alternatively, using monthly data for the USA, [35] showed that climate policy uncertainty (CPU) drops the RENE in both the short and long run. In this paper, the authors proposed the necessity to reduce CPU in order to raise RENE. In the same context, [36] explored the effect of CPU on RENE in the presence of oil prices over the period January 2005 to April 2021. To achieve this, the authors used five types of RENE: hydro, solar, wind, geothermal, and biomass energies. Hence, the outcomes revealed that the association between CPU and these energies is time-varying and heterogeneous. For example, CPU positively affected both hydro and wind energy; however, CPU negatively correlates with solar and geothermal energies. In the context of Sub-Saharan African nations, [37] showed that EPU does not affect RENE in the long run despite the negative effect in the short run. Nevertheless, the causality analysis revealed a bidirectional causation between EPU and RENE.

In this brief review of prior studies, we can provide some findings. First, Previous studies focused largely on EPU and CPU, although there were very few studies that used FPU, MPU, TRPU and OPU. Hence, this is a major deficiency in previous studies, which neglected many other types of uncertainty, such as HPU, TPU and

GPU. Therefore, this study attempts to fill this gap by examining the causal relationship between RENE and several types of uncertainty. Second, uncertainty indicators have varying effects on environmental sustainability, as indicated by many studies (see [4][5][38]). Additionally, the positive impact of RENE on environmental sustainability is largely confirmed (see [39-41]). Therefore, it is necessary to track the relationship between uncertainty indicators and RENE to develop clear policies that ensure an energy transition that contributes to environmental sustainability. Third, previous studies largely focused on the symmetrical effects of uncertainty indicators on RENE while neglecting the asymmetrical effects. To this end, this paper seeks to fill this gap by exploring asymmetric causality from uncertainty indices towards RENE, including positive and negative cumulative components calculated according to the methodology of [42] in the TVC analysis.

3 Data and Methodology

Sequel to the objective of the paper, on one hand, we use the renewable energy consumption (RENE) as the target variable measured by Trillion Btu, including Hydroelectric Power consumption, geothermal energy consumption, solar energy consumption, Wind energy consumption, and Biomass energy consumption, and the data are obtained from the Federal Reserve Economic Database. On the other hand, we depend on economic policy uncertainty (EPU), monetary policy uncertainty (MPU), tax policy uncertainty (TPU), government spending policy uncertainty (GPU), healthcare policy uncertainty (HPU), and trade policy uncertainty (TRPU). Noticeably, all the data are in the logarithmic form.

Notably, the causal relationship is one of the most important concepts in econometrics since [42]. In this context, we say that a variable X causes another variable Y if the past values of the first variable affect the current values of the second. In other words, if the present values of variable X affect the future values of variable Y, then this means that there is a causal relationship running from variable X to variable Y. Remarkably, the previous literature on causation association is characterized by the presence of several tests in addition to [42] such as [43-49]. However, what distinguishes all of these tests is that they assume the causal link does not vary over time, so either there is a causal relationship throughout the entire period, or there is not.

Hence, based on the work of [50-53] on bubbles unit root tests and explosive behaviors in the series, [16][17] developed a new procedure of time varying causality analysis, where the main advantage of this methodology is the possibility of tracking the causal relationship through internal periods depending on supremum (sup) Wald test using three different algorithms. First, the recursive expanding algorithm (REW) presented by [51] uses a Wald test statistic over the range $[f_1, f_2]$ where the $f_w=f_2-f_1\geq f_0$ is the sample size fraction and is represented by $Wf_2(f_1)$.

Second, returning to [54] and [55], two other algorithms were presented in this area: Forward expanding (FEW) and rolling windows (RW), which are special cases of REW.

4 Empirical Results

4.1 Unit Root Tests

Before studying the causal linkages, the stationarity of the series must be assessed to determine the integration order of each variable. Particularly given this, the time-varying causal relationship technique requires detecting the highest level of integration among the variables under study, as does the TYDL methodology. Hence, we use two unit root tests to get a clear idea about the integration order. First, we use the bootstrap Augmented Dickey-Fuller (ADF) test which provides critical values for each series, unlike the previous tests, which use the same critical value for all the series. Second, we rely on the NG-Perron (2001) test, which consists of 4 partial tests that allow us to determine the degree of integration than conventional tests do. Thus, the results presented in Table 1 revealed that all series are stationary in first differences. Subsequently, all variables are I(1), and the highest integration order is d_max = 1 for all dualities.

Table 1: Unit root tests results

VAR	Bootstrap ADF test			NG-Perron test				Decision
	Statistic	5% CV	Prob.	MZa	MZt	MSB	MPT	
RENE	0.927	-2.255	0.964	-2.570	-0.963	0.375	29.644	I(1)
D(RENE)	-7.423	-2.959	0.000	-20.325	-3.235	0.142	3.932	
EPU	-1.981	-2.952	0.882	-11.012	-2.343	0.212	8.291	I(1)
D(EPU)	-10.781	-2.997	0.000	-44.723	-4.700	0.105	2.186	
MPU	-0.315	-3.034	0.912	-7.326	-2.012	0.182	7.325	I(1)
D(MPU)	-11.767	-2.983	0.000	-70.614	-5.893	0.083	1.504	
TPU	-2.272	-2.919	0.116	0.808	-0.558	0.690	90.105	I(1)
D(TPU)	-11.702	-2.945	0.000	-23.250	-3.391	0.145	4.030	
GPU	-2.279	-3.055	0.222	-6.048	-1.733	0.286	15.060	I(1)
D(GPU)	-9.802	-2.985	0.000	-34.421	-4.141	0.120	2.690	
HPU	-2.446	-2.947	0.146	-2.596	-1.138	0.438	35.040	I(1)
D(HPU)	-11.081	-2.948	0.000	-57.989	-5.380	0.092	1.589	
TRPU	-1.415	-2.990	0.310	-37.336	-4.319	0.115	2.448	I(1)
D(TRPU)	-10.667	-3.053	0.000	-1.883	-0.902	0.479	43.781	

D denotes first differences. 5% CV critical value at 5% significance level.

4.2 Causal Relationship Results

The next step in our study is to apply the time-varying causal relationship test presented by [16-17] to examine the causal relationship over time. It is worth noting that optimal lags are chosen according to the Akaike criterion, and the d max operator is 1 in all cases according to the unit root tests.

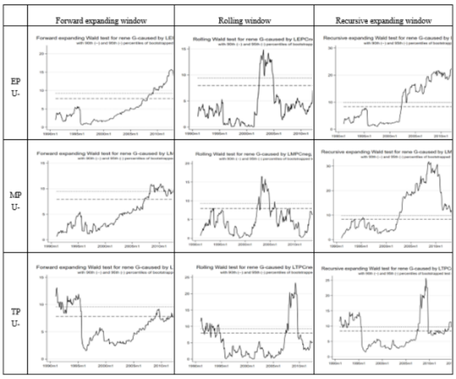

Figure 1: Causal relationship from policy uncertainty to RENE:

The outcomes obtained from Figure 1 show several results that can be summarized as follows. First, for the EPU, the figures show a causal relationship from EPU to RENE from 1998 to the present, especially with FEW and REW procedures, but using the RW, this causality disappears from 2016 to the end of the period. Similarly, the same results hold for MPU, GPU, and HPU, since the causal relationship is established after 1999 (2001 for HPU) and persists through the end of the study period, using both FEW and REW procedures. Besides, the causal relationship from TPU to RENE held throughout the entire period, suggesting that tax uncertainty is a primary driver of renewable energy consumption. Conversely, the results show that the causal relationship is not held from TRPU to RENE in the majority of the study period, except between 2011 and 2014 using RW and REW procedures.

4.3 Robustness Check

The final step is to run a Robustness check of the results using the positive and negative cumulative components instead of the original series for all our uncertainty variables. Through this procedure, we will be able to reveal hidden causal relationships and better understand the nature of the causal relationships between the variables, so that the RENE response to positive and negative changes in uncertainty can be determined separately. However, we should determine the integration order of cumulative components to detect d_max in this case. Similarly, the results from Table 2 confirmed that d_max = 1, since all the series are I(1).

Table 2: Unit root test results :

VAR	Bootstrap ADF test			NG-Perron test				Decision
	Statistic	5% CV	Prob.	MZa	MZt	MSB	MPT	
EPUps	0.455	-1.676	0.703	-15.026	-2.705	0.180	6.282	I(1)
D(EPUps)	-16.682	-3.060	0.000	-223.940	-10.574	0.047	0.412	
EPUng	0.184	-1.751	0.626	-16.456	-2.267	0.187	5.510	I(1)
D(EPUng)	-13.426	-3.089	0.000	-18.482	-3.038	0.145	4.936	
MPUps	-0.466	-1.743	0.335	-10.235	-2.233	0.218	9.043	I(1)
D(MPUps)	-14.157	-2.999	0.000	-222.747	-10.553	0.047	0.412	
MPUng	-1.149	-1.621	0.141	-8.203	-1.873	0.228	11.591	I(1)
D(MPUng)	-11.658	-2.965	0.000	-23.404	-4.304	0.083	2.764	
TPUps	-2.282	-1.756	0.017	-5.800	-1.556	0.268	15.506	I(1)
D(TPUps)	-6.271	-2.966	0.000	-223.373	-10.562	0.047	0.422	
TPUng	-2.439	-1.709	0.013	-3.190	-1.089	0.341	24.959	I(1)
D(TPUng)	-11.690	-3.013	0.000	-220.560	-10.501	0.047	0.413	
GPUps	-0.546	-1.680	0.330	-6.840	-1.807	0.264	13.372	I(1)
D(GPUps)	-12.006	-3.093	0.000	-223.656	-10.570	0.047	0.420	
GPUng	-0.556	-1.683	0.326	-5.531	-1.598	0.288	16.318	I(1)
D(GPUng)	-17.735	-3.096	0.000	-24.222	-4.452	0.043	2.576	
HPUps	-3.437	-1.820	0.000	-0.502	-0.282	0.563	67.666	I(1)
D(HPUps)	-24.007	-2.978	0.000	-223.963	-10.580	0.047	0.411	
HPUng	-4.006	-1.776	0.000	-0.042	-0.027	0.655	92.226	I(1)
D(HPUng)	-10.425	-2.960	0.000	-217.619	-10.428	0.047	0.425	
TRPUps	1.078	-1.728	0.882	-5.927	-1.655	0.279	15.305	I(1)
D(TRPUps)	-18.829	-3.147	0.000	-19.323	-3.032	0.158	5.288	
TRPUng	1.153	-1.745	0.884	-5.694	-1.601	0.281	15.849	I(1)
D(TRPUng)	-12.590	-2.965	0.000	-216.464	-10.403	0.048	0.422	

Where ps and ng are positive and negative changes; the critical values for NG-Perron test at 10, 5 and 1% significance level for MZa are -14.200; -17.300 and -23.800, for MZt are -2.620; -2.910 and -3.420, for MSB are 0.185; 0.168 and 0.143 and for MPT are 6.670; 5.480 and 4.030 respectively.

First, we focus only on positive changes.

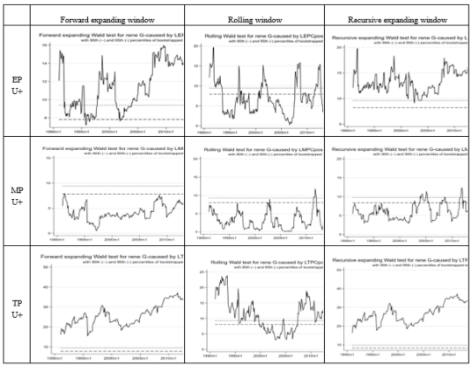

Figure 2: Causal relationship from positive changes in policy uncertainty to RENE

In Figure 2, the outcomes revealed clearly that positive changes in EPU, TPU, GPU, and HPU are very important to stimulate RENE over the study period, especially when using FEW and REW procedures. Moreover, it was found that positive changes in MPU did not cause RENE in most periods, indicating that this type of uncertainty does not significantly stimulate renewable energy consumption. Conversely, positive changes in TRPU are not causally related to RENE across the study period, as assessed using the three windows. This result shows that the consumption of renewable energies in the USA is almost independent of trade uncertainty.

Second, the causal relationships from negative changes in all uncertainties to RENE are presented in Figure 3.

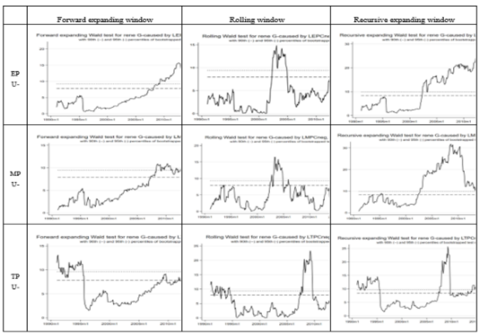

Figure 3: Causal relationship from negative changes in policy uncertainty to RENE

Clearly, all the uncertainties except TRPU showed a weak causal relationship to RENE in only some sub-periods (EPU and MPU from mid-2003 using REW; TPU from 2014 using both FEW and REW; GPU and HPU from 2005 using REW). Consequently, negative changes in uncertainty are also important in stimulating the consumption of renewable energies, but not as significant as the positive ones, which were previously shown to cause RENE over long periods and at low probability levels, as the curves moved further away from the 5% critical value. At the other extreme, the negative changes in TRPU showed effects that were relatively different from the positive ones, and it became clear that there was a causal relationship with RENE, especially between 2011 and 2014, a period characterized by a strong causal relationship. However, this relationship declined after that, remaining volatile until the end of the period.

5 Discussion

Without a doubt, previous oil price crises, such as the one that hit the world in 1973, are regarded as the most significant global conditions that demonstrated the pivotal and fundamental role of energy in the modern economy, as global oil prices have become a basic and major engine for economies, whether in developing or developed countries. However, with the start of the new millennium, humanity was confronted with a real challenge, the main hero of which was energy, particularly fossil fuels, which greatly disrupted the environmental system on the planet by increasing greenhouse gas emissions in the atmosphere, which means warming of the earth and changes in the ecosystem. Therefore, in recent years, global efforts have begun to identify alternatives that minimize the consumption of this form of energy and replace it with ecologically friendly energies. Notably, many of these technologies have been developed but are still far from replacing fossil fuels, owing to their high costs and, in many cases, their lack of profitability. Nonetheless, this energy transition has become an imperative requirement that necessitates sacrifices from all actors on this planet.

Accordingly, the purpose of this work was to analyze the causal association between various economic uncertainties and this transition using time-varying causality analysis to identify which form of uncertainty is most essential to any hypothetical energy transition in the United States. Hence, the focus was on six types of uncertainty represented in economic, monetary, government spending, healthcare, taxation, and trade uncertainty during the period between January 1985 and July 2022.

Firstly, the findings revealed a causal relationship running from EPU to RENE, particularly with positive changes. Conspicuously, this result is in line with [22][23][26]. These findings could be explained by the fact that EPU causes institutions and individuals to be uncertain about the state of the economy, causing them to engage in precautionary activities to reduce their losses and costs, such as reducing consumption and desisting from investment. Thus, since the prices of renewable energies are higher than those of non-renewable energies, economic agents shift toward non-renewable energies due to their lower prices. Furthermore, EPU causes organizations and institutions that are research-oriented toward renewable energies to halt R&D spending and automatically lower expenditures as an initial, fundamental reaction to the uncertainty caused by government policies. In the same regard, previous studies' outcomes concluded that EPU has a negative effect on renewable energy consumption while having a positive influence on non-renewable energy consumption, similar to [21][24][25][30][31]. This explains that, especially with its positive effects, uncertainty reduces consumption of renewable energy, so it may represent a real obstacle to the energy transition.

Besides, the outcomes in the case of MPU showed a causal relationship with RENE in the three cases (original series, positive and negative changes), especially in negative changes, which show a causal relationship with RENE throughout most of the study period. Hence, as declared by [56], the measures taken by central banks, similar to the US Federal Reserve, would create a great state of uncertainty among investors, institutions, and even households in light of the continuous movements of interest rates, much like when the Fed prepared in 2015 to withdraw from the zero interest rate policy [57]. Therefore, unstable and constantly changing interest rates and continuous monetary measures make the energy transition, with its additional costs, a difficult procedure to deal with, and this explains the fact that both positive and negative shocks to MPU cause RENE, as instability in monetary policy represents a real obstacle in the way of the energy transition.

On the other extreme, the results clearly showed a causal relationship over the entire study period from TPU to RENE, especially for positive changes, in contrast to negative changes that did not cause RENE at all. In this vein, according to [58], since 2006, the US government has provided subsidies and tax exemptions totaling more than $18 billion to families with an orientation toward alternative energy, which later turned out to have benefited high-income families. This indicates that the government has pursued tax policies that facilitate the energy transition, and the latter helped in increasing the percentage of renewable energy consumption in total energy consumption. Therefore, fluctuations in tax uncertainty, particularly increases, will automatically dampen the trend toward alternative energies among families and institutions. Rather, the issue may extend beyond lowering R&D investments in this setting and then attempting to cope with this uncertainty by relying on fossil energies because they are readily available. Low tax uncertainty, on the other hand, would incentivize investors to maximize profits by shifting toward non-renewable energy sources to capitalize on the potential for reduced taxes. That is why, to support the energy transition, taxes must be highly stable, with no increases or decreases.

By accessing the GPU, it is clear that the uncertainty in government spending causes RENE, especially at the end of the previous millennium (1998) to the present day, especially in the case of positive changes, where the causal relationship was achieved in most periods, while the causation of negative changes was only from the beginning of the year 2007. Economically, Government spending is among the most important means of protecting the environment by directing resources toward renewable energy through support, research, and development. It is noticeable, especially in the new millennium and after the Kyoto Protocol of 1997, that the US government's interest in the energy transition is reflected in significant government support to facilitate it, as many families and institutions depend on these expenses to rely on renewable energies. As a result, this is what makes any case of ambiguity and uncertainty, whether by increase or decrease, regarding government spending and subsidies, stimulate or impede the consumption of renewable energies, and this explains the importance of government spending in ensuring a smooth energy transition. Apparently, it is necessary to ensure a stable state of government spending, to avoid shocks and uncertainties that may destabilize this causation, through clear and consistent spending policies by the US government.

Moreover, the outcomes revealed that HPU causes RENE with positive changes in the full period. This means that an increase in uncertainty in health care would affect RENE, and the effect is likely negative. The healthcare system is one of the most powerful catalysts for various industries, particularly chemical ones, which emit several toxic gases from factories. The healthcare sector's supply chains, on the other hand, are among the most significant sources of these emissions through transportation. Further, the sector consumes significant energy across all its facilities. Furthermore, the healthcare sector plays an important role in carbon emissions and energy consumption, accounting for 4.5% of total emissions, particularly in the United States, the largest emitter through the healthcare sector.

Finally, it was clear that there is no causal relationship from TRPU to RENE, whether through the original series or positive and negative changes, except for causation at the end of the period, especially after 2016, through negative changes in addition to the period 2010-2014. This result shows the lack of importance of trade uncertainty for the consumption of renewable energy, and it agrees with the findings of [31]. Consequently, trade uncertainty is particularly evident in the volatility of oil and gas prices in international markets, making non-renewable energies a haven, even if temporarily, in light of the high prices, similar to the period between 2010 and 2014, marked by a significant increase in oil prices. Therefore, the lack of effect and causality from TRPU to RENE could be explained by the nonexistence of a response of American institutions to trade uncertainty and oil price volatility. In this sense, unlike renewable energies, non-renewable energies generated from fossil fuels continue to be the best option for energy production at the lowest cost, regardless of price fluctuations. In addition, the USA is an important oil producer, ensuring constant access to petroleum products regardless of conditions in global markets.

6 Conclusions

The main motivation of this study is to investigate the causal relationship between several uncertainty variables (economic, monetary, taxes, government spending, healthcare, and trade) and renewable energy consumption in the USA between January 1985 and July 2022. In light of this, we applied the contemporary time-varying causality test created by [16][17]. The results of the test showed that, with the exception of TRPU, all uncertainty variables cause RENE in the majority of periods, especially when there are positive changes. This finding indicates that the United States' transition to a clean-energy economy would be hampered by rising uncertainty across the economy, including monetary policy, taxes, government spending and the healthcare system.

In light of the results, we can propose the following policy implications. First, the need to ensure stable economic conditions by providing coherent, stable policies that encourage economic actors to access the renewable energy market and facilitate a smooth energy transition. Second, monetary policy managers, especially the US Federal Reserve, must ensure stable interest rates by adopting more transparent strategies that encourage investors to enter the renewable energy sector and pump more money into research and development. Third, based on the findings of a causal relationship between TPU and RENE, we advocate transparent tax policies that encourage families and investors to switch to renewable energy sources through tax exemptions. Furthermore, we strongly recommend maintaining a balanced, stable tax policy to avoid any doubt or ambiguity that would hinder the energy transition. Fourth, there is a need for government intervention to promote the use of renewable energy sources and their expansion through sustained, dedicated government spending that makes renewable energy technologies available to individuals and companies. Additionally, the government should increase its expenditure on research and development in this field, primarily to reduce the cost of this type of energy and make it accessible at prices competitive with those of non-renewable energy sources. Fifth, after the failure of the short-lived Clean Energy Plan, which was abandoned four years after it was initiated, and then, former President Donald Trump's withdrawal from environmental agreements and subsequent re-entry into the Paris Agreement, it is strongly recommended that successive US administrations maintain the continuity of past environmental policies. As these instabilities do not provide guarantees for companies and institutions that use renewable energy, they will seriously harm the energy transition. Therefore, to accommodate the use of renewable energy, policymakers should not only emphasize the design of appropriate green policies but also ensure their consistency and continuity.

The study's limitations and further directions relate to several aspects: expanding the analysis to include additional non-economic or social factors influencing US energy consumption, expanding the methodological section to address regional disparities, and incorporating additional countries or energy types.

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