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The mutual effects of residential energy demand and climate change in the United States: A wavelet analysis

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A R T I C L E I N F O

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A B S T R A C T

This study examines the complex and time-varying relationship between residential energy demand (including electricity, geothermal, and solar energy) and climate change using wavelet analyses with monthly USA data from January 1990 to March 2023. The results show that residential energy demand and climate change indicators exhibit a time-varying interrelationship with cyclical and lag effects. Specifically, before 2021, a positive correlation between residential electricity demand and carbon dioxide (CO_2) emissions in short-term frequencies was found, but the relationship reversed thereafter, with an increase in CO_2 levels influencing and decreasing residential electricity demand. In the long run frequencies, the link between residential power consumption and CO_2 emissions shifted over time, exhibiting inconsistent co-movement. The co-movements between residential geothermal and CO_2 show predominantly positive correlations, with CO_2 leading the relationship in the short run, while geothermal leads the co-movements in the long run. In both short and long-term frequencies, the dependency and co-movement between residential solar and CO_2 are mixed, with residential solar leading to positive correlations and CO_2 leading to negative correlations. Therefore, improved insulation, energy-efficient windows, and high-efficiency heating systems can all assist in reducing heat loss and the total energy demand for domestic heating and subsequently low CO_2 emissions.

1. Introduction

Climate change and global warming are presently the most significant issues that are commanding global public attention with their political, social, cultural, and demographic ramifications (Bilgili and Magazzino, 2022). It has been widely emphasized that greenhouse emissions (GHG) are the leading cause of climate change and global warming (Awan et al., 2022). According to Alnour et al. (2024), CO_2 emissions constitute over 64% of GHG emissions that mostly stem from fossil fuels' combustion. Therefore, without limiting the over-dependence on fossil fuels, the temperature rise will continue aggravating the heat challenge, which may lead to unpredictable environmental catastrophes. In that vein, scholars have been continuously exploring the relationship between energy consumption and climate change.

The residential sector is responsible for a significant share of global energy consumption and carbon emissions (Imran et al., 2022). Globally, residential sectors consume around 21.2% of the final energy supply (IEA, 2022) and contribute to 80% of global CO_2 emissions (Shi and Yin, 2021). Theoretically, residential energy consumption can deteriorate the natural environment through different activities including transportation, construction, power generation, cooking, heating, and other appliances (Yousaf et al., 2021). In addition to the

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Abbreviations

BIEN	Biomass Energy Consumed by the Residential Sector
CO_2	Carbon Dioxide
CLA	Consumer Lifestyle Approach
CWC	Complex Wavelet Coherency
CWT	Continuous Wavelet Transform
ELES	Electricity Sales to Ultimate Customers in the Residential Sector
FOSF	Total Fossil Fuels Consumed by the Residential Sector
GCC	Gulf Cooperation Council
GEEN	Geothermal Energy Consumed by the Residential Sector
GHG	Greenhouse Gas
IEA	International Energy Agency
INPI	Industrial Production Index
kWh	Kilowatt Hour
NGAS	Natural Gas Consumed by the Residential Sector
OECD	Organization for Economic Co-operation and Development
R&D	Research and Development
SDA	Structural Decomposition Analysis
SOLE	Solar Energy Consumed by the Residential Sector
TWh	Terawatt Hour
USA	United States of America
WLMC	Wavelet Local Multiple Correlation
WTC	Wavelet-Transform Coherence

channel of releasing GHG, the lack of access to some primary fuels like kerosene, coal, and solid biomass forces energy-poor households to use cheaper wood fuels, which leads to the cutting of trees, plants, and bushes to wipe out forests and deteriorate the ecological conservation (Oryani et al., 2022).

Empirically, utilizing national and city-level data, scientists have extensively analyzed the relationship between residential energy demand and environmental sustainability within the theoretical framework of ecological modernization, urban environmental transition, and compact city theories. While one strand of literature is centered on the factors affecting households' energy consumption (Liddle and Lung, 2010; Wang, 2014; Romero-Jordán et al., 2016; Guo et al., 2018; Ahmad et al., 2023; Li et al., 2023), the second strand of research has focused directly on the environmental consequences of residential energy demand (Feng et al., 2011; Yao et al., 2012; Lima Azevedo et al., 2013; Yang et al., 2016; Hu et al., 2020). Even though these studies have significantly contributed to energy economics literature, however, apart from the indecisive conclusions, several limitations can be reported. First, the existing studies on the relationship between household energy consumption and environmental quality have relied solely on the households' total energy consumption indicators. However, as discussed by Rosas et al. (2010), the overall residential energy consumption is a complex indicator consisting of several fuel types including fuel wood, electricity, natural gas, liquefied petroleum gas (LPG), solar, and kerosene. Each type affects the natural environment in a different way (cooking, heating, electrification/lighting, and appliances). Given their variety in the degree of importance to the households, it is plausible to assume that climate change responds differently to the impulse/innovation in each fuel. In light of this, disentangling the environmental consequences of residential energy consumption from disaggregated perspectives could effectively generate more practical outcomes and, subsequently, policy measures.

Second, previous studies have considerably centered on a unidirectional analysis and ignored the existence of a mutual interconnection between residential energy consumption and climate change. Evidently, higher CO_2 levels induce more electricity demand. An increase in global temperatures results in hotter climates and prolonged periods of heat waves (Schaeffer et al., 2012), leading to more demand for air conditioning in residential buildings to maintain comfortable indoor temperatures. Since air conditioning systems typically rely on electricity, the greater the need for cooling the higher the electricity demand, and hence pollution. Therefore, examining the mutual effect between residential energy consumption and CO_2 emissions would greatly improve the effectiveness of climate policies.

Third, the seminal studies on the environmental impact of residential energy demand have largely utilized conventional estimation techniques in which parameters' estimations are rigid over time or considering a maximum of three potential structural breaks of the series, with little potential in detecting the seasonal effect: PCC method (Q. L. Chen et al., 2022), spatial-temporal analysis (L. Q. Chen et al., 2022) input–output structural decomposition analysis (I–O SDA) (Hosseinzadeh, 2023), cost-effectiveness and trade-off (Lima Azevedo et al., 2013), CLA method (Feng et al., 2011), and surveys (Yang et al., 2016). The residential energy demand behavior in response to climate and temperature shocks is significantly related to the seasonal effect. The regions that experience milder winters due to higher temperatures may lead to a decrease in residential heating requirements. Conversely, warmer summers may lead to increased electricity consumption for cooling purposes. Thus, to cope with such temperature shifts, households can consume more electricity for fans, dehumidifiers, or other cooling devices. In addition, increased discomfort from heat may lead to a higher reliance on refrigeration and cold storage for food and beverages leading to higher electricity consumption. Thus, taking into consideration the seasonal effect can provide more realistic outcomes on the relationship between residential energy consumption and climate change.

Therefore, for a unique attempt, the primary objective of this study is to mutually examine the dynamic impacts of residential demand for electricity, geothermal, and solar energy on CO_2 emissions utilizing the partial wavelet approach with monthly data covering the period between January 1990 and March 2023 for the US. Exploring the threat that residential energy consumption poses on the natural environment of the US is of great interest for several reasons. First, the US is the second biggest carbon emitter on a global scale, right behind China. This air pollution is primarily driven by the burning of fossil fuels within the country (Kocak and Alnour, 2022). Second, the national residential sector is the leading cause of CO_2 emissions. Over 39% of the total energy in the USA is consumed by the household sector (Li et al., 2023), releasing nearly 38% of the total CO_2 emissions (Zhou and Yang, 2016). Comparatively, in various states like California, the residential sector's electricity consumption alone equals that of Argentina or Finland and half of Mexico's. The most significant contributors to CO_2 emissions in the residential sector include heating (~360 Mt), hot water (~140 Mt), lighting (~140 Mt), and cooling (~135 Mt) (Lima Azevedo et al., 2013). Given these immense potentials, decarbonizing the US residential sector could play a key role in the fight against global climate change. Therefore, this study aims to extend the discussion by addressing the above literature shortcomings and answering the following research questions.

- **RQ1**: What is the relationship between residential energy consumption (electricity, geothermal, solar energy) and climate change in the US?
- **RQ2**: What are the lead-lag patterns between residential energy demand and CO_2 emissions in the US?
- **RQ3**: Is there any cyclical dependency between residential energy demand and CO_2 emissions in the US?
- **RQ4**: To what extent do renewable energies have the potential to reverse the CO_2 emissions trajectories in the US?

The contributions of this study can be summarized as follows: (i) this study is the first attempt to examine the dynamics and mutual effect between residential energy consumption and climate change from a disaggregated data perspective utilizing the demand for electricity, geothermal, biomass, and solar energy; (ii) this study employs the partial wavelet technique, which is expected to reveal the impact of the leading variable (household energy demand) on the lagged variable (CO_2 emissions) in the estimated models that change over time or might change from high frequencies to low frequencies; (iii) this study considered the dynamic impacts of residential energy demand on CO_2 emissions for the world's largest economy (USA). The significant impact of the US economy on climate change means adjustments to US climate policies will have ripple effects across the globe. Therefore, the outcomes of the study might be important in developing common policies and collaborative sustainability efforts.

The rest of the paper is organized as follows: Section 2 examines relevant research on the subject. Section 3 describes the data used and the methods employed in the empirical analysis. Section 4 presents the key results, while Section 5 summarizes the main findings. Section 6 discusses potential policy implications.

2. Literature review

As of 2019, the breakdown of global electricity usage by sector showed industrial activities leading with 9566 TWh, followed by residential use at 6072 TWh, commercial and public services at 4849 TWh, other sectors consuming 1940 TWh, and transportation at 420 TWh. Notably, residential energy demands, and consumption accounted for 26.57% of total energy use, as reported by the International Energy Agency (IEA, 2022). Temperature fluctuations and population growth stand out as primary factors driving energy consumption changes, which in turn are pivotal in driving climate change, significantly impacting both demand and supply in electricity markets, as identified by Lam et al. (2022). There exists a dynamic and reciprocal relationship between residential energy demand and climate change, incorporating various interactions between residential energy use and climate variations (Qian et al., 2004; Li et al., 2019).

Recent findings highlight a continuous and significant rise in global temperatures and climate shifts, primarily attributed to CO_2 emissions from fossil fuel combustion (Kuşkaya and Bilgili, 2020; Ohms et al., 2022; Wang et al., 2023). This trend impacts heating and cooling requirements in residential buildings (Malik et al., 2022), potentially leading to fluctuations in residential energy demand across different seasons and regions (Eshraghi et al., 2021). As residential energy demands escalate, largely due to increased fossil fuel-based energy production, CO_2 emissions surge correspondingly. Rising temperatures may intensify cooling needs, while possibly reducing heating demands (Xiong et al., 2023). The increased need for cooling, prompted by higher temperatures, leads to broader and more intensive use of cooling systems, thus elevating energy consumption. This forms a self-perpetuating cycle that contributes to further global warming.

Isaac and van Vuuren (2009) demonstrated that global warming would reduce heating demand by more than 30% while increasing cooling demand by about 70%. However, the net effect of these changes is relatively small and largely dependent on the assumptions made in scenario development. Global energy-related CO_2 emissions saw a record increase of 6% over the previous year to 36.3 billion tonnes in 2021. This increase in emissions is largely attributed to the strong economic recovery from the COVID-19 crisis, which primarily used coal to support and sustain growth (IEA, 2021). In the European Union, the conflict in Ukraine has enabled policymakers to use high-emission energy sources, such as coal or fossil fuels, to mitigate the energy crisis, particularly expecting an increase in heating demand in the residential sector.

Based on the latest census figures, the total number of residential units in the USA is 143,786,655. An American household's average daily electricity consumption is 29 kWh, monthly consumption is 868 kWh, and annual consumption is 10,417 kWh. An average American's per capita electricity consumption is about six times the global average or five times the average of those with access to electricity (Shrink That Footprint, 2023).

An approach that can be used to compare energy choices of two households in different climate zones but appears similar aims to determine whether observed differences can be attributed to climate changes. However, a fundamental concern with this approach is the potential for unobserved household differences to be climate-related, thereby introducing the potential for omitted variable bias. Residential energy demand primarily contributes to GHG emissions through the combustion of fossil fuels (coal, natural gas, oil), leading to increased GHG concentrations in the atmosphere and subsequently global warming. The current literature supports that short-term (1–2 frequency periods) and long-term (2–4 years frequency band) analyses increase pollution emission in the residential sector (Qian et al., 2004; Raza and Lin, 2022; Guan et al., 2023; Yang et al., 2023).

Measuring household energy inequality and ensuring a fair energy consumption environment is important. However, previous researchers have not analyzed the effects of residential energy demand on different energy sources (e.g., renewable sources like solar and geothermal) in detail (Auffhammer and Mansur, 2014). The residential sector is the second largest energy-consuming sector in the USA and China, accounting for about one-tenth of total final energy consumption, with a significant portion comprising urban residents (Jiang et al., 2019). Even without climate change, the average household electricity consumption in China is expected to double by 2040 (Li et al., 2019). Therefore, analyzing the same factors affecting energy consumption in the residential sector in terms of heating, electricity, and carbon dioxide emissions is important, as the trends and significance of these factors may differ and lead to different effects (Jakučionytė-Skodienė and Liobikienė, 2023).

The heterogeneity in energy consumption among households has long been overlooked, leading to the low effectiveness of energy policies aimed at uniform demand. Based on these findings, authorities emphasize the design of common but differentiated residential energy conservation policies and highlight that income increase will promote patterns of energy consumption toward lower carbon intensity and more modernization (Lei et al., 2022). Projections for India's 28 states indicate that due to climate change, electricity demand is expected to rise by 6.7% under a scenario of 4% annual GDP growth, and by 8.5% under a scenario of 6% annual GDP growth by 2030 (Gupta, 2016). Residential energy consumption stems from energy-intensive activities such as heating, cooling, lighting, electronic devices, and household appliances and is one of the main sources of GHG emissions. Increased energy demand leads to higher energy production and, consequently, increased GHG emissions. This process accelerates climate change and intensifies its adverse effects (González-Torres et al., 2022; Hiruta et al., 2022; Wang et al., 2023).

A study across 48 states in the USA examined the sensitivity of residential electricity demand to seasonal climate changes and state-level structural changes. Researchers used state-level monthly demographic, energy, and climate data from 2005 to 2017 and employed linear regression models. They found that annual climate variability explained most of the demand variation during the summer and winter months. In 42 states, more than 70% of summer demand variation and more than 50% of winter demand variation were influenced by climate (Eshraghi et al., 2021).

Climate change is also associated with natural disasters and environmental events affecting energy consumption. Intense rainfalls, floods, droughts, and forest fires can damage energy infrastructure and cause sudden changes in energy demand (Randazzo et al., 2020; Lu et al., 2022; Kartal et al., 2022). A study assessing the energy resilience performance of the residential sector in China's hot and humid regions found that energy demand could increase by 102.2% in this region (Zou et al., 2023). Another study projected how climate change and building technology evolution would affect heating and cooling demands and forecasted demand changes for different regions (Z. Z. Li et al., 2023; Xiong et al., 2023). Climate and environmental policies will significantly impact the production and consumption of non-renewable energy sources, as the transition to renewable energy sources is considered a sustainable solution to combat global warming and reduce CO_2 emissions (Z. Z. Li et al., 2023).

Geothermal energy is highlighted as an underutilized potential to mitigate the threat of climate change, being a carbon-neutral, renewable, and sustainable energy source. Studies have shown the short and long-term CO_2 emission-reducing effects of geothermal energy, used for electricity generation, area heating, and industrial processes (Manzella et al., 2018; Soltani et al., 2021). In Iceland, approximately 53% of consumed energy is sourced from geothermal resources, with associated GHG emissions accounting for only 5% (Kristmannsdóttir and Ármannsson, 2003).

Research has shown that electricity generation based on solar energy was associated with CO_2 emissions during certain periods: 1992–2000, 2005–2007, 2009–2012, and 2014–2023. This is attributed to the use of hazardous materials in the production process of photovoltaic (PV) solar panels, leading to CO_2 emissions. However, periods such as 2008–2010 and post-2021 saw an increase in CO_2 emissions coinciding with a decrease in solar energy usage. Yet, the use of solar energy was found to reduce CO_2 emissions during the 1995–1999 and 2011–2016 periods (Yu et al., 2022).

A study covering the period from 1990:1 to 2022:6 analyzed the impact of solar energy usage on CO_2 emissions in the USA. The research revealed that solar energy consumption had a mitigating effect on CO_2 emissions at low frequencies (long-term cycles) and specific time frames (2014:1–2022:1) (Kuşkaya et al., 2023). Other studies examining the nexus between solar energy usage and CO_2 emissions in the USA also support the contribution of solar energy usage to reducing environmental pollution, ecological footprint, and CO_2 emissions (Destek and Aslan, 2020; Rahman et al., 2022; Yu et al., 2022). A focus on addressing energy consumption in households includes a study recommending increasing energy efficiency and insulation values of residential buildings. A study focusing on Germany's building stock emission targets for 2050 indicates that transforming German residential buildings will significantly reduce future heating energy demand (Olonscheck et al., 2011).

The literature contains many studies addressing the linkage between income inequality and household energy demand. It is frequently reported that high-income households generally consume more energy compared to low-income households. However, some studies contradict this finding, arguing that wealthy households might have lower energy demands due to the use of energy-efficient systems, better home insulation practices, and the ability to produce renewable and clean energy on-site. Lei et al. (2022) emphasized that changes in household size across different income levels could lead to completely different and even opposite effects on energy consumption. Moreover, the study suggested that the incentivizing effect of income increase on energy consumption could be moderated by considering various household appliance preferences and incorporating demand-side energy policies (Zhang et al., 2020). This research investigates how household consumption patterns and carbon emissions change over time, considering income inequality and its link to climate change. The study supports the view that lifestyle changes over time play a significant role in the observed increase in household carbon emissions.

Residential energy usage encompasses both direct and indirect emissions. Munksgaard et al. (2000) specifically examined CO_2 emissions related to private consumption, highlighting the significant challenges posed by consumers' demand for environmentally harmful goods and the change in consumption habits within households to achieve CO_2 emission reduction targets. The consumption of non-energy products, contributing almost equally to CO_2 emissions as the consumption of energy products, was noted. Direct emissions arise from the consumption of energy products used in households (electricity, central heating, gas), while indirect emissions stem from emissions associated with the production of all other goods consumed by households. Therefore, it is important to consider the energy demand and consumption estimates of all commercial assets when evaluating overall energy demand and consumption.

Several past studies explored the effects of residential energy consumption on overall CO_2 emissions, converging on a common understanding of the robust link between increasing residential energy usage and elevated CO_2 emissions. This current study's findings harmonize with and reinforce the existing literature. Kuşkaya (2022) investigated the effect of solar energy usage in USA households on climate change and employed the Morlet wavelet analysis to demonstrate a periodic decrease in pollution emissions over 1–2 year intervals within the monthly period from 1989 to 2020, with a notable reduction observed between the periods of 1990–2009 and 2010–2019. Magazzino (2012) assessed the relationship between disaggregated energy production and real aggregate income in Italy using annual data from 1883 to 2009. Causality tests confirm a bi-directional flow in the long run so that energy production and economic growth complement each other.

Guan et al. (2023) delved into energy-related CO_2 emissions across urban and rural residential areas in China, consistently noting that urban households emit more CO_2 than their rural counterparts. This pattern of rising emissions is largely linked to heating needs, particularly prevalent in China's northern regions. In Lithuania, Jakučionytė-Skodienė and Liobikienė (2023) revealed that households with a higher awareness of environmental issues tend to produce lower CO_2 emissions compared to those lacking such awareness. Magazzino et al. (2021) conducted an empirical analysis using yearly data for real GDP and primary energy consumption from 1926 to 2008 in Italy. Wavelet analysis results show that a causal flow from economic growth to energy consumption becomes dominant at lower scales. Matar et al. (2023) investigated the association among CO_2 emissions, electricity consumption, economic growth, urbanization, and trade openness for six Gulf Cooperation Council (GCC) countries using data covering the 1965–2019 period.

Miao et al. (2019) analyzed factors contributing to regional CO_2 emission differences in residential buildings in China from 2000 to 2016 using data from 28 Chinese provinces. Nationally, a positive correlation was observed between per capita GDP, population scale, cooling degree days, and CO_2 emissions for residential buildings. These findings confirm significant regional differences in residential CO_2 emissions. Galvin (2023) examined the impact of energy efficiency standards in residential buildings in Germany on CO_2 emissions. An increase in energy efficiency standards was seen to translate into increased costs associated with CO_2 reduction. Magazzino and Giolli (2024) analyzed the evolution of oil prices and renewable energy production in Italy during the first wave of the COVID-19 pandemic crisis. Wavelet findings show that oil prices and renewable energy sources were highly correlated during the pandemic shock. Kartal et al. (2023) investigated the influence of daily electricity generation from nuclear power and renewables on the achievement of carbon neutrality targets in the U.S., China, France, and Russia. Table 1 summarizes some selected papers published in recent years.

Kartal et al. (2022) investigated energy consumption's impact on environmental degradation at both aggregate and disaggregated levels, emphasizing the significant impact of energy consumption on CO_2 emissions in the short, medium, and long term in the USA. The findings underscore the importance of renewable energy consumption in reducing CO_2 emissions and improving environmental quality, urging policymakers to focus on reducing fossil sources and increasing renewable sources.

The relationship between residential energy demand and climate change is complex and interactive. Implementing energy efficiency measures, transitioning to renewable energy sources, and enhancing

Table 1
Summary of the literature using the wavelet analysis.

Author (Year)	Research Topic	Data Period	Methods Used	Main Findings
Kuşkaya and Bilgili (2020)	The effect of fossil fuel use on CO_2 emissions	1990–2020	Wavelet Analysis	Fossil fuel use is the main source of CO_2 emissions.
Kuşkaya (2022)	The impact of residential solar energy use on CO_2 emissions in the USA	1989:1–2020:1	Morlet wavelet analyses	The use of residential solar energy has a strong effect on reducing CO_2 emissions in the USA in the 1–2 year frequency range.
Magazzino et al. (2021)	The relationship between energy consumption and economic growth over 80 years in Italy. It aims to analyze the dynamics of this relationship using wavelet analysis and frequency domain techniques	1926–2008	The combination of wavelet analysis and frequency domain techniques	The relationship between energy consumption and economic growth in Italy across different time scales. The results indicate that this relationship is stronger at lower time scales.
Adebayo and Kartal (2023)	The impact of green bonds, oil prices, and COVID-19 on industrial CO_2 emissions in the USA	March 2020–September 2022	WLMC	Highlights complex long-term correlations between variables with the dominant effect of oil prices, offering significant insights for policymakers.
Ben-Salha et al. (2018)	The impact of energy consumption on CO_2 emissions in the USA	2005Q1 - 2015Q3	Wavelet power spectrum, the cross wavelet, and the wavelet coherence	Shows that research indicates the importance of considering diverse energy sources and economic sectors when shaping economic policies and evaluating the output-energy relationship.
Dogan et al. (2022)	Behaviors on domestic energy consumption and domestic energy expenditures, triggered by ethnic diversity, income disparity, and climate characteristics in the USA	1984Q1 - 2020Q4	Multiple wavelet coherency analyses	strong connection between residential energy consumption and socio-economic factors, showing that energy poverty precedes ethnic conflicts, and the condition of buildings significantly influences energy expenses.
Liu et al. (2023)	The interactions between CO_2 emissions and coal usage efficiency, uncertainties in climate policy, green energy, and energy savings	1990Q1 - 2020Q4	Wavelet transform and wavelet coherence	Importance of green energy and innovation in reducing CO_2 emissions in the US, recommending support for these approaches.
G. F. Fan et al. (2023)	New hybrid model to improve electricity consumption forecasts using American residential electricity data	December 6–28, 2014, and December 5–27, 2015	EWT-MOLSTM-SVR	The EWT-MOLSTM-SVR model has shown superior performance by improving forecast accuracy compared to other models.

environmental sustainability are crucial steps in mitigating climate change effects. Increasing the capacity to adapt to and build resilience against climate change effects and fluctuations in energy demand is equally important for sustainable energy consumption management and effective climate change mitigation.

The methodology involves estimating a series of functions with control variables (NGAS, BIEN, FOSF, and INPI) to analyze the impact of different energy consumption types on CO_2 emissions comprehensively. This approach is crucial for understanding the relationship between energy consumption and CO_2 emissions, with the effects of specific energy types considering control variables.

The selection of the estimated equations and the methodology draws from literature to understand the environmental impacts of various energy consumption forms accurately. The use of control variables improves the analysis's accuracy, offering a broader perspective on the relationships between energy consumption and CO_2 emissions.

This comprehensive analysis highlights the need for researchers and policymakers to focus on understanding and mitigating the relationships between energy consumption and CO_2 emissions, providing a basis for informed policy decisions.

3. Methods

3.1. Data description

The paper investigates the co-movements between electricity consumption by the residential sector (ELES) and CO_2 emissions (CO_2), geothermal energy consumption by the residential sector (GEEN) and CO_2 emissions, and solar energy consumption by the residential sector (SOLE) and CO_2 emissions, by utilizing the Morlet's wavelet analyses. The study employed monthly data for the US economy over the period January 1990–March 2023. Detailed information on the variables is presented in Table 2.

To observe the co-movements between electricity and CO_2 with control variables (NGAS, BIEN, FOSF, and INPI), functions 1a, 1b, and 1c are estimated as follows:

Table 2
Overview of the data.

Abbreviation	Definition	Unit	Data Source
NGAS	Natural gas consumed by the residential sector (excluding Supplemental Gaseous Fuels)	Trillion Btu	EIA (2023)
FOSF	Total fossil fuels consumed by the residential sector	Trillion Btu	
GEEN	Geothermal energy consumed by the residential sector	Trillion Btu	
SOLE	Solar energy consumed by the residential sector	Trillion Btu	
BIEN	Biomass energy consumed by the residential sector	Trillion Btu	
ELES	Electricity sales to ultimate customers in the residential sector	Trillion Btu	
CO_2	Total energy CO_2 emissions	Million Metric Tons of Carbon Dioxide	
INPI	Industrial production: total index	Index	FRED (2023)

$$CO_2 = f\ (ELES, NGAS, BIEN, INPI) \tag{1a}$$

$$ELES = f\ (CO_2, FOSF, BIEN, INPI) \tag{1b}$$

$$CO_2 = f\ (ELES, FOSF, BIEN, INPI) \tag{1c}$$

To analyze the co-movements between GEEN and CO_2 with control variables (NGAS, BIEN, and INPI) the following equations represent the estimated forms of functions 2a and 2b:

$$GEEN = f\ (CO_2, NGAS, BIEN, INPI) \tag{2a}$$

$$CO_2 = f\ (GEEN, NGAS, BIEN, INPI) \tag{2b}$$

To analyze the co-movements between SOLE and CO_2 with control variables (NGAS, BIEN, and INPI) functions 3a and 3b are defined by the following estimated expressions:

$SOLE = f (CO_2, NGAS, BIEN, INPI)$ 3a

$CO_2 = f (SOLE, NGAS, BIEN, INPI)$ 3b

Descriptive statistics showing the basic characteristics of the data set used in the analysis (NGAS, FOSF, GEEN, SOLE, BIEN, ELES, CO_2, and INPI) are given in Table 3.

In the analysis, 399 observations of each variable for the period January 1990–March 2023 were used. According to Table 3, the three variables with the highest mean values are FOSF, CO_2, and NGAS, while the three variables with the lowest mean values are GEEN, SOLE, and INPI. Also, the high standard deviation of FOSF indicates significant fluctuations or variability in its values. Table 4 presents the correlation matrix of the variables.

The correlation matrix is given in Table 4. For instance, a strong correlation coefficient between NGAS and FOSF is found. Also, a strong correlation coefficient (0.7473) between GEEN and INPI with a significant *t*-value of 2.241 is found. In addition, positive correlations are observed between GEEN and SOLE, GEEN and ELES, as well as SOLE and ELES. Additionally, INPI exhibits moderate positive correlations with both GEEN and SOLE. Conversely, moderate negative correlations exist between NGAS and SOLE, but also INPI and BIEN. Fig. 1 presents a visual representation of the changes in these variables over the observed time span.

3.2. Methodology

Wavelet analysis decomposes a time series into a time-frequency representation, allowing the capture of localized information in both the time and frequency domains. This process is effective in identifying localized intermittent periodic behavior in the data (Grinsted et al., 2004; Roueff and von Sachs, 2011; Wu et al., 2023).

Wavelet transforms can be applied in a continuous form, offering a more nuanced analysis. The Continuous Wavelet Transform (CWT) allows obtaining an expression of the entire frequency range as a function of time (Issartel et al., 2014). CWT decomposes a signal into wavelet components by scaling and shifting the Morlet wavelet function across the signal (MathWorks, 2024). The scaled and shifted wavelet function is then correlated with the signal, resulting in a coefficient that reflects the similarity between the signal and the wavelet at that particular scale and time (Torrence and Compo, 1998). By performing this for various scales and time positions, a CWT coefficient matrix is obtained, representing the signal's time-frequency decomposition. The CWT is a function of the two variables ($W_{(s,\tau)}$) defined as:

$$W_{(s,\tau)}(t) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-\tau}{s}\right)d_t \begin{cases} s \neq 0 \\ s, \tau \in \mathbb{R} \end{cases} \tag{1}$$

The wavelet coefficients, denoted by ($W_{(s,\tau)}$) quantify how the scales (represented by the s values) contribute to the signal at various time positions τ. The τ and the s terms are the transformation parameters representing the time domain location of the wavelets, and the scaling parameter shows the frequency domain position of the wavelets, respectively; * represents the complex conjugate form.

Wavelet analysis is based on different types of wavelet transforms, and among them, the Morlet wavelet stands out as a significant tool for signal analysis, particularly in monitoring and predicting features in wideband signals with time-varying frequency and scale characteristics (Najmi and Sadowsky, 1997). The Morlet wavelet was originally introduced by Morlet and Grossmann (1984), and its mathematical representation can be expressed by Eq. (2) as follows:

$$\psi(t) = \pi^{-\frac{1}{4}} e^{i\omega_0 t} e^{-\left(t^2/2\right)} \tag{2}$$

In Eq. (2), i is equal to $\sqrt{-1}$, and e shows the non-dimensional frequency. The term ω represents the central frequency parameter of the Morlet wavelet $\psi(t)$.

Cross-wavelet transform is a mathematical technique used to analyze the relationship between two-time series in the time-frequency domain. It extends the concept of CWT by examining the coherence and phase relationship between two signals at different scales and time positions (Grinsted et al., 2004). Cross-wavelet transform first performs separate CWTs on both signals, resulting in two CWT coefficient matrices. These matrices represent the time-frequency decomposition of each signal (Wachowiak et al., 2018). For each scale and time position, the cross-spectrum between the two CWT coefficients is calculated. The cross-spectrum captures the coherence (strength of the relationship) between the signals at those specific time and frequency components (Percival and Walden, 2000). Additionally, the phase angle between the CWT coefficients is computed (Chinarro et al., 2015). This reveals the lead-lag relationship between the signals. A zero-phase angle indicates in-phase behavior, while a non-zero-phase angle indicates a lead or lag relationship. To analyze the interaction between two-time series, Torrence and Compo (1998) introduced the concept of the cross wavelet transform for $\{X\}$ and $\{Y\}$. Eq. (3) defines the CWT functions W_x and W_y, which are used to analyze the behavior of each time series.

$$W_{x,y}(s,\tau) = W_x(s,\tau)W_y^*(s,\tau) \tag{3}$$

where the asterisk (*) stands for complex conjugation. While the term τ symbolizes the space, the term s allows for compression or expansion of the wavelet to capture trends at diverse frequency bands.

Complex Wavelet Coherency (CWC) uses both the magnitude and phase information of the CWT coefficients from both signals. This captures not only the strength of the correlation (coherence) but also the relative timing (phase) between the signals at different frequencies and time points. CWC analysis often involves examining both the real and imaginary parts of the complex coherence values. The real part reflects the co-variation between the signals, similar to standard coherence (Sharott et al., 2005). The imaginary part is sensitive to phase-locked relationships between the signals, not influenced by volume conduction. CWC values are often normalized between −1 and 1. A value of 1 indicates perfect coherence, 0 indicates no coherence, and values in between represent varying degrees of coherence (Percival and Walden, 2000; Grinsted et al., 2004). One can describe the complex wavelet coherency for $\{X\}$ and $\{Y\}$ as follows as explained in Aguiar-Conraria et al. (2013):

Table 3
Descriptive statistics of the variables.

Statistics	NGAS	FOSF	GEEN	SOLE	BIEN	ELES	CO_2	INPI
Mean	410.34	514.31	1.90	9.09	40.13	361.99	452.68	89.46
Median	289.63	381.22	1.55	5.64	39.80	351.76	454.02	92,99
Std. Dev.	285.39	325.06	1.22	8.13	6.29	77.42	42.17	13.08
Minimum	103.27	134.47	0.42	2.71	28.38	214.63	305.22	60.30
Maximum	1069.71	1224.39	3.36	41.39	54.20	570.17	560.77	104.11
Skewness	0.544	0.529	0.099	2.025	0.225	0.390	0.111	−0.973
Kurtosis	1.845	1.845	1.194	6.469	1.958	2.529	3.011	2.643
Count	399	399	399	399	399	399	399	399

Table 4
Correlation matrix.

	NGAS	FOFS	GEEN	SOLE	BIEN	ELES	CO_2	INPI
NGAS	1.000							
FOFS	0.998 (3.016)	1.000						
GEEN	−0.0041 (−0.082)	−0.0598 (−1.194)	1.000					
SOLE	−0.1813 (−3.674)	−0.2200 (−4.495)	0.6065 (1.520)	1.000				
BIEN	−0.0094 (−0.188)	−0.0202 (−0.404)	0.1349 (2.713)	0.1204 (2.418)	1.000			
ELES	−0.0420 (−0.838)	−0.0729 (−1.456)	0.5847 (1.436)	0.3818 (8.233)	−0.1186 (−2.380)	1.000		
CO_2	0.4299 (9.489)	0.4534 (1.013)	−0.2687 (−5.558)	−0.5210 (−1.216)	−0.3620 (−7.738)	0.3239 (6.821)	1.000	
INPI	0.0055 (0.111)	−0.0307 (−0.613)	0.7473 (2.241)	0.4282 (9.441)	−0.3941 (−8.544)	0.6147 (1.553)	0.1530 (3.085)	1.000

Notes: *t* statistics are given parentheses.

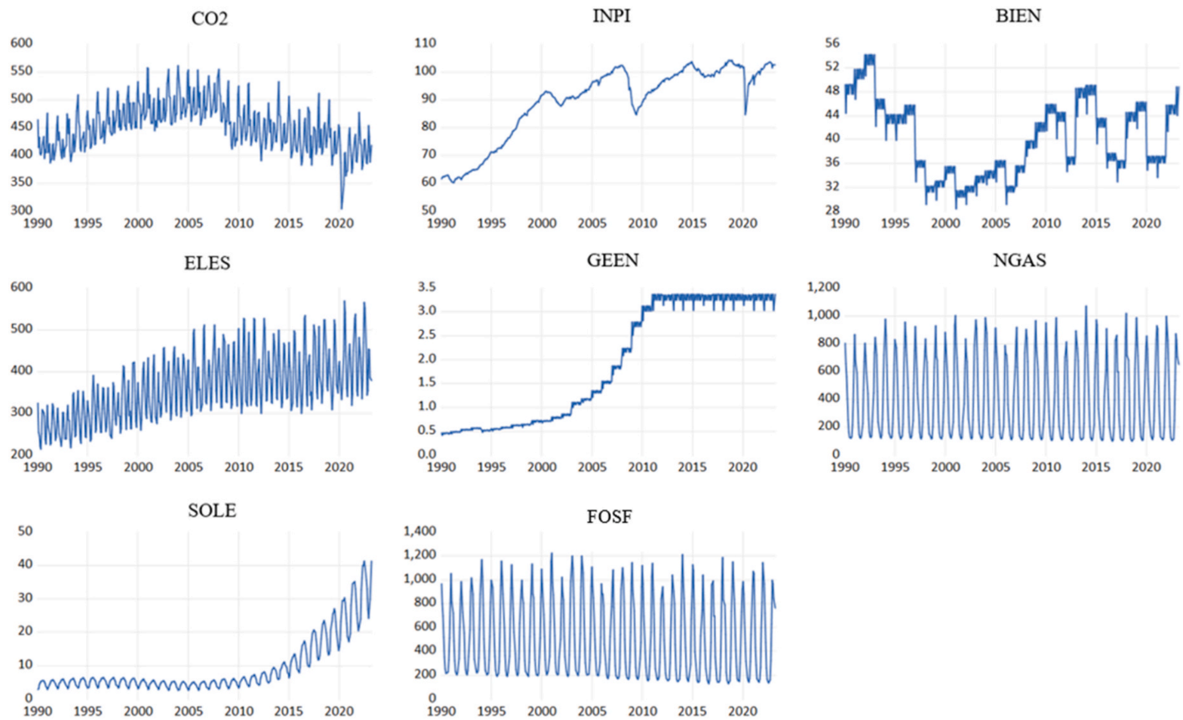

Fig. 1. Variables' trends.
Source: authors' elaborations in Matlab.

$$\varphi_{xy} = \frac{S(W_{xy})}{\sqrt{S\left(|W_x|^2 S\left(|W_y|^2\right)\right)}} \tag{4}$$

In Eq (4), the term φ_{xy} represents the complex wavelet coherency, W_x and W_y are the wavelet transforms of the time series x and y, respectively. Additionally, W_{xy} denotes the cross wavelet transform of x and y. The parameter S corresponds to a smoothing operator applied to both time and scale domains. The inclusion of S is essential because, without it, the coherency would be consistently equal to one across all scales and times.

The phase difference between the two chronicles serves as a complementary indicator that enables us to determine the direction of the relationship, as well as the mutual influences between the variables, with the concept of a Leader (Awada and Mestre, 2023). The phase difference between $\{X\}$ and $\{Y\}$ is depicted in Eq. (5):

$$\Theta_{x,y} = arctan\left(\frac{\Im m\,(W_{xy}(s,\tau))}{\Re e(W_{xy}(s,\tau))}\right) \tag{5}$$

In Eq (5), the terms $\Im m\,(W_{xy})$ and $\Re e(W_{xy})$ show imaginary and real parts of the smooth power spectrum, respectively. The phase difference undergoes cyclic variations ranging from -π to π throughout the component waveforms. Positive values indicate that *x(t)* leads *y(t)*, whereas negative values suggest the opposite scenario, with *y(t)* leading *x(t)*. Values near zero signify a symmetric relationship between the two series, if any relationship exists (Morlini et al., 2023).

4. Empirical results and discussion

The present study examines the co-movements between; i) electricity consumption by the residential sector (ELES) and CO_2 emissions (CO_2), ii) geothermal energy consumption by the residential sector (GEEN) and CO_2 emissions, and iii) solar energy consumption by the residential sector (SOLE) and CO_2 emissions by utilizing Morlet wavelet analyses. The study has employed the monthly data for the USA economy over the period 1990:01–2023:03. The estimated outcomes of the study are yielded in three main coherency figures ranging from 2–4. Before moving to the discussions, it is worth mentioning that the thick black lines signify the influence cone; demonstrating the regions influenced by edge effects in all coherency figures. The color bar code changing from blue to red depicts the coherency power; the red color reflects strong association (power) whereas the blue color is synonymous with weak association (Shehzad et al., 2021; Kuşkaya et al., 2023). Furthermore, the 1–2 year frequency band indicates short and medium-term cycles while the 2–4 year frequency band reflects long-term cycles For better comprehension, three separate wavelet coherency models have been developed that are given below.

4.1. Residential electricity consumption and CO_2 emissions

Wavelet model-I (Fig. 2a) observes the co-movements between electricity consumption by the residential sector (ELES) and CO_2 emissions (CO_2) with control variables of residential natural gas consumption (NGAS), residential biomass energy consumption (BIEN), and industrial production index (INPI) as a proxy for GDP. Figs. 2a and 2b indicate the outcomes from phase difference analyses at the 1–2 year frequency band (short run), while Figs. 2a and 2c depict the output from phase difference analyses at the 2–4 year frequency band (long run). When the co-movements between ELES and CO_2 emissions are spotted (Figs. 2a and 2b), the following outcome is within the shorter cycle (1–2 year frequency band). (a) ELES and CO_2 emissions are in phase and move together until 2021. They reflect a positive coherence that an increase in ELES (CO_2) is associated with rising CO_2 (ELES) as well. This outcome has twofold highlights; (a_1) Within the significant positive co-movements period (1994–2021), an increase in ELES causes CO_2 to increase (an increase in ELES is accompanied by an increase in CO_2). (a_2) Within the significant positive co-movements period (1994–2021), an increase in CO_2 emissions causes ELES to increase (an increase in ELES is associated with an increase in CO_2). However, (a_3) after 2021, a negative correlation is observed as CO_2 is the leading variable and ELES is the lagging variable. CO_2 causes ELES to decline (a decline in ELES is accompanied by an increase in CO_2). In the long run (at a 2–4 year frequency band), the wavelet coherence outcomes (Figs. 2a and 2b) reveal that; (b_1) an increase in ELES causes CO_2 emissions to increase reflecting that an increase in ELES is accompanied by an increase in CO_2 during the periods 2013–2015 and 2017–2020. (b_2) For the period 2015–2017 and 2020 onwards until the end of the sample period that is March 2023, an increase in CO_2 causes ELES to decline (a decrease in ELES is accompanied by an increase in CO_2).

Wavelet coherence analyses of ELES and CO_2 have unfolded many dimensions/implications. Firstly, outputs (a_1) and (b_1) disclosed that an increase in electricity consumption by the residential sector caused environmental deterioration by enhancing CO_2 emissions in SR as well as in two longer periods (2013–2015 and 2017–2020), respectively. Various empirical findings and theoretical reasoning in the existing literature such as (Zhu et al., 2013; Miao, 2017; Khanna et al., 2021) are in support of these outcomes. Miao (2017) states that house-based residential energy consumption triggers CO_2 emissions. The argument might be valid for electricity usage being an essential part of residential energy consumption as indicated by (Papachristos, 2015). Khanna et al. (2021) claimed that electricity demand from buildings accounted for 28% of carbon dioxide emissions at the global level in 2013 and reached

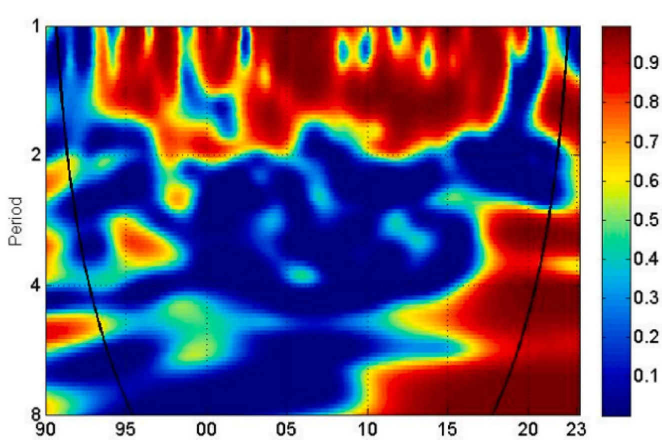

Fig. 2a. Partial wavelet coherency (ELES).

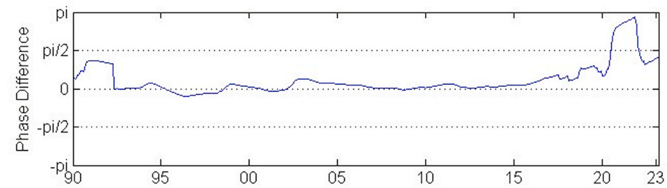

Fig. 2b. 1–2 frequency band.

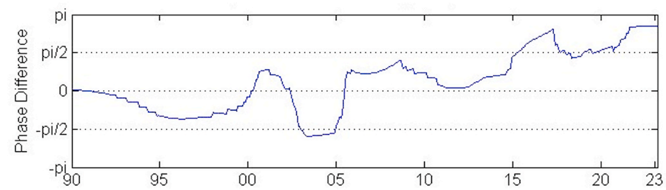

Fig. 2c. 2–4 frequency band.
Source: authors' elaborations in Matlab.

10 Gt CO_2 (60% of total carbon emissions) in 2019. The possible reason behind this positive linkage between CO_2 emissions and residential electricity consumption is the dependence on fossil fuels-led electricity generation as well as the carbon-intensive nature of electricity-generating power plants. The electricity consumed by residential households is predominantly produced from fossil fuels, such as coal, petroleum, and natural gas which is why an increase in residential electricity consumption indirectly contributes to higher CO_2 emissions. Because the electricity suppliers (power plant operators) burn more fossils at their power plants to economize as well as to make easy profits. It is relatively time-consuming and relatively expensive to replace the existing power plants with environment-friendly ones in competitive environments. Above all, in the short run, it is a bit hard for entrepreneurs to switch towards alternative solutions by risking their market share without significant incentives. Hence, they carry on burning fossil fuels to cope with excessive energy demand and it is indisputable that fossil fuels are the major source of carbon dioxide emissions (Mahalik et al., 2021; Bilgili et al., 2023).

Another possible reason behind the excessive carbon dioxide emissions might be the persistence of inefficient and carbon-intensive fossil fuel-based power plants; such power plants produce the same amount of electricity by consuming much more fossil fuels as compared to efficient ones. During the seasons of higher electricity demand as a consequence of climate change and extreme weather, such as peak load periods, such types of power plants may be activated to meet the unexpected upsurge in electricity demand by the residential sector (Zhu et al., 2013; Yuan et al., 2014).

These power plants often rely on fossil fuels and emit more CO_2 per unit of electricity generated as compared to cleaner alternatives (Khanna et al., 2021). Therefore, an increase in residential electricity consumption can lead to the activation of inefficient carbon-intensive power plants, resulting in elevated CO_2 emissions. It seems logical when looking at data for the USA energy production sources. For instance, electricity-generating power plants in the USA are predominantly fossil fuels-based and carbon-intensive. The USA generated 4.24 trillion kWh of electricity in 2022; out of which only 22% of electricity generation was from renewable sources; which is far higher than in past years. While 60 percent of electricity generation came from fossil fuels such as coal, petroleum, natural gas, and other non-renewables. The rest 18 percent has been generated through nuclear sources (EIA, 2023).

Following (a_2) wherein the significant positive co-movements period (1994–2021) specified that an increase in CO_2 emissions has caused ELES to increase. This outcome is in line with the empirical findings of Papachristos (2015), Fan et al. (2019), Zhang et al. (2020), and Khanna et al. (2021). Moreover, it is registered that higher levels of CO_2 emissions induce climate change (Pizarro-Irizar et al., 2020). In the extreme winter season, households might increase electricity usage to keep their houses warm and livable. During summer, households use fans, air conditioning, and dehumidifiers excessively which raises electricity consumption. For instance, in EU-27 the housing sector has consumed 29.4% of total electricity production to facilitate heating, lighting, and cooking (Papachristos, 2015). Zhang et al. (2020) observed a surge in electricity demand for cooling and heating amidst extremely hot summers and cold winters, respectively. Rising global temperatures, influenced by increased CO_2 levels result in extreme climates and prolonged periods of heat waves (ECMWF, 2023). The logic behind this is longer summers and frequent heat waves lead to an increase in demand for air conditioning in residential buildings to maintain comfortable indoor temperatures. Air conditioning systems typically rely on electricity, so the greater the need for cooling the higher the residential electricity consumption (Zhang et al., 2020). Climate change also has an impact on seasonal energy demand patterns. Warmer summers may lead to increased electricity consumption for cooling purposes (Dirks et al., 2015; Fan et al., 2019). Consequently, households can consume more electricity for fans, dehumidifiers, or other cooling devices to cope with higher temperatures. Additionally, increased discomfort from heat leads to a higher reliance on refrigeration and cold storage for food and beverages, resulting in increased electricity consumption (Li et al., 2012; Papachristos, 2015; Emodi et al., 2018). While rising CO_2 emissions have reduced residential electricity consumption from 2021 onwards, as indicated in (a_3). The argument is residential heating requirements subsequently energy consumption has fallen in predominantly colder regions, where winters are relatively mild and the overall climate is getting warmer due to rising global temperature (Emodi et al., 2018; Fan et al., 2019). It seems logical, as the world has witnessed an unprecedented rise in temperature even in relatively colder regions, especially after the 2019 recent year (ECMWF, 2023).

Following (b_2), an increase in CO_2 causes ELES to decline during 2015–2017 and from 2020 onwards until the end of the sample period, which is March 2023. That is an increase in carbon emissions is associated with a decline in electricity consumption by the residential sector. This result is in line with Emodi et al. (2018) and Fan et al. (2019). The argument is that increased levels of CO_2 emissions have reduced residential energy consumption by limiting the demand for heating in winter. Rising CO_2 emissions have caused global climate change and unprecedented shifts in weather patterns such as mild winters and overall warmer climates (Franco and Sanstad, 2007; Emodi et al., 2018; UNEP, 2022; ECMBF, 2023). Consequently, overall residential electricity consumption for heating purposes has declined in regions where heating dominates energy consumption (Clarke et al., 2018; Emodi et al., 2018). Recently, the USA Energy Information Administration witnessed a decline in energy consumption during winters in the USA due to mild temperatures (EIA, 2023). Besides, increased awareness of climate change and recent emphasis on the reduction of CO_2 emissions led to improved building standards and energy-efficient designs (Papachristos, 2015). Better insulation, energy-efficient windows, and high-efficiency heating systems helped to minimize heat loss and reduced the overall energy demand for residential heating (Emodi et al., 2018; Khanna et al., 2021) and hence electricity consumption. The theoretical reasoning and outcomes are in line with the predictions of Zhu et al. (2013). Lastly, it is important to note that the outcomes remained the same when conducting wavelet analyses using variables of total fossil fuels consumed by the residential sector (FOSF), biomass energy consumed by the residential sector (BIEN), and industrial production index (INPI) (see Figs. 3a, 3b, 3c) (see Fig. 4a, 4b, 4c).

4.2. Residential geothermal energy consumption and CO_2 emissions

Fig. 5a (Wavelet model-II) demonstrates the partial wavelet coherency between geothermal energy consumed by the residential sector (GEEN) and CO_2 emissions (CO_2) by employing residential natural gas consumption (NGAS), residential biomass energy consumption (BIEN), and industrial production index (INPI) as control variables. Fig. 5a indicates the outcomes from phase difference analyses at the 1–2 year frequency band (short run) while Fig. 5a accompanied by Fig. 5c depicts the output from phase difference analyses at the 2–4 year frequency

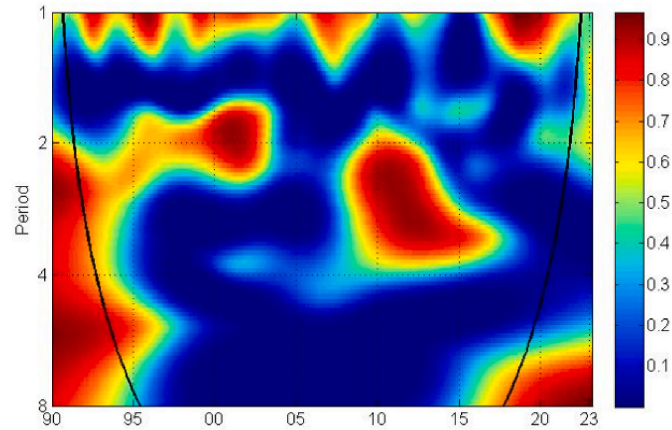

Fig. 3a. Wavelet coherency (ELES, CO_2).

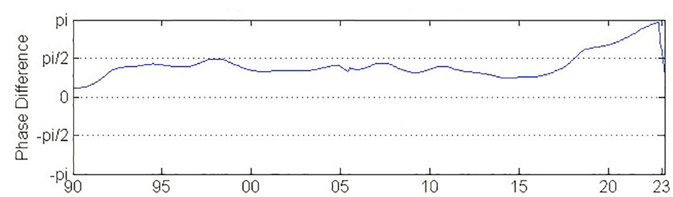

Fig. 3b. 1–2 frequency band.

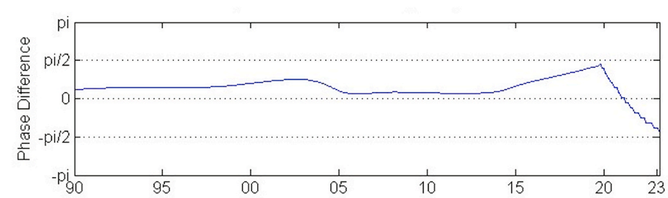

Fig. 3c. 2–4 frequency band.
Source: authors' elaborations in Matlab.

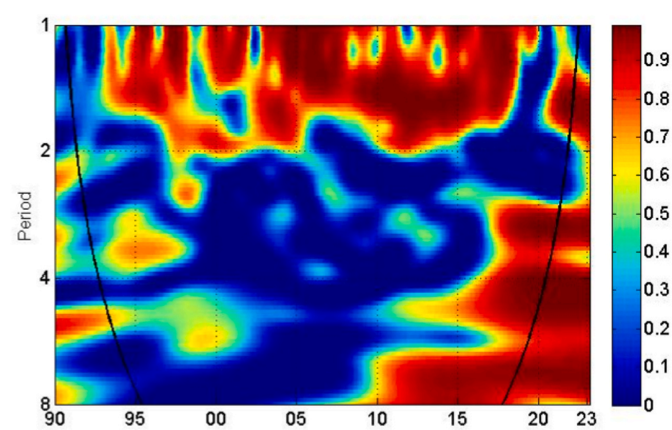

Fig. 4a. Partial wavelet coherency (ELES, CO_2//FOSF, BIEN, INPI).

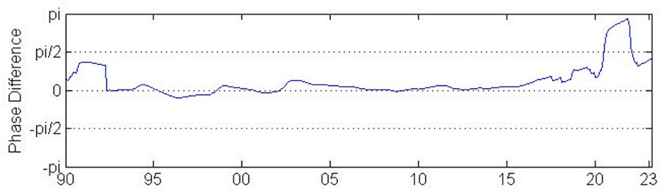

Fig. 4b. 1–2 frequency band.

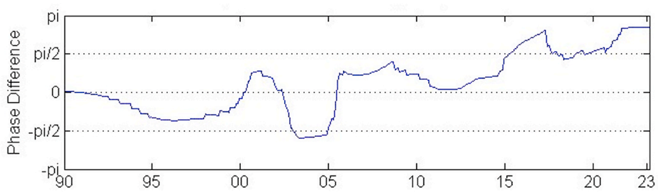

Fig. 4c. 2–4 frequency band.
Source: authors' elaborations in Matlab.

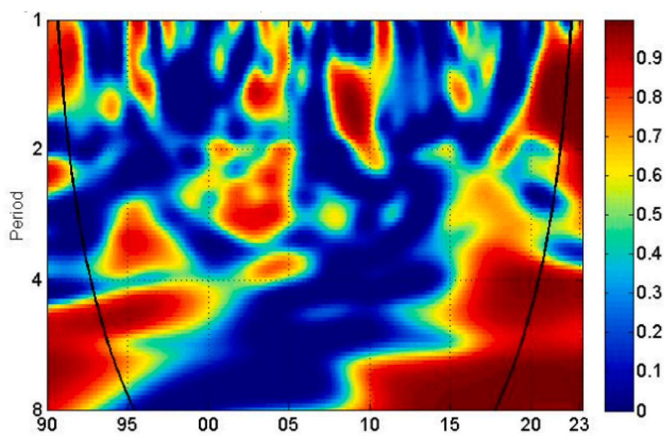

Fig. 5a. Partial wavelet coherency (GEEN, CO_2).

band (long run). In the short run (Figs. 5a and 5b), partial wavelet coherency outcome revealed that; a_1) an increase in CO_2 emissions has diminished GEEN usage for the periods 1995–1997; and 1920–1923. a_2) the rise in GEEN has boosted CO_2 during 2002–2004 and 2017–2018. a_3) Increase in CO_2 emissions enhanced GEEN during 2007–2010. The long-term partial wavelet analysis results (Figs. 5a and 5c) disclosed that; b_1) an increase in GEEN consumption diminished CO_2 emissions during 1995–1997 and 2015–2017. b_2) The upsurge in CO_2 emissions diminished GEEN usage during 2003–2005. b_3) Consumption of GEEN increased CO_2 emissions during 1997–2003 and from 2017 until the end of the sample (2023). b_4) From 1990 to 1995, 2016–2017, increases in CO_2 widened GEEN consumption.

The outcomes (a_1) and (b_2) specified that soaring CO_2 emissions have diminished geothermal energy consumption by the residential sector in the USA. The outcome has some similarities with the findings of (Clarke et al., 2018). The authors explored that carbon emissions have indirectly reduced residential energy demand for heating. In some regions including the USA, CO_2 emissions-led global warming has reduced the intensity of the winter season and consequently reduced heating-driven energy consumption. The logic is also applicable to residential geothermal energy consumption being part of the energy basket. However, this notion is not appropriate for the regions where demand for space cooling dominates energy consumption. The USA EIA (2023) report has confirmed a decline in energy demand for heating in the USA due to relatively mild winter temperatures (EIA, 2023). Energy efficiency might be another reason for lower geothermal energy usage as indicated by (Cadelano et al., 2019). Besides, implications to water resources (Kristmannsdóttir and Ármannsson, 2003; Shortall et al., 2015; Mott et al., 2022), the higher costs and localization of technology associated with geothermal energy (Vargas et al., 2022) might also be the reason for lower geothermal energy consumption despite rising carbon emissions (Soltani et al., 2021). Considering the theoretical reasoning and explanations of previous studies, it can be stated that residential geothermal energy consumption falls due to rising global average temperature, inefficiencies, higher costs, and environmental implications associated with geothermal energy plants, despite rising CO_2 emissions. Rising global average temperature has mitigated the intensity of winters and subsequently reduced the demand for energy for heating purposes that dominates residential energy consumption in colder regions. Energy inefficiency, higher installation costs in the short run (Cadelano et al., 2019), and environmental implications of geothermal energy plants, in some cases, might be the other reasons for declining geothermal energy usage. Contrary to (a_1) and (b_2), outcomes (a_3) and (b_4) observed a surge in geothermal energy consumption by the increase in CO_2 emissions. CO_2 emissions indirectly raise the global average temperature as well as the frequency of heat waves by inducing climate change (UNEP, 2022; Kuşkaya et al., 2023). Although the global temperature has been rising since the 1990s, the world observed another intense upsurge in average global temperature following heat waves especially in June and July 2023 amidst rising CO_2 emissions (WMO, 2024). Consequently, the demand for energy consumption has been consistently rising to facilitate space cooling and refrigeration, particularly in warmer regions (Clarke et al., 2018). This notion might be true for geothermal energy consumption by the residential sector being part of the residential energy mix to generate electricity as identified by (Shortall et al., 2015).

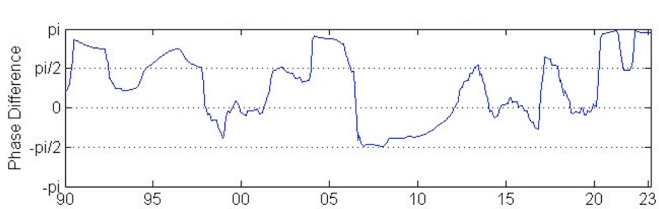

Fig. 5b. 1–2 frequency band.

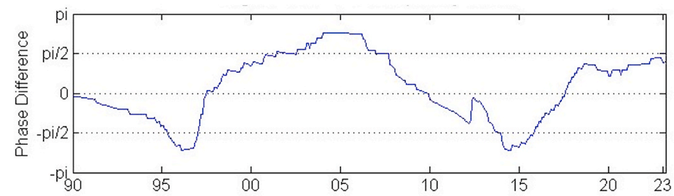

Fig. 5c. 2–4 frequency band.
Source: authors' elaborations in Matlab.

Following (b_1), wherein an upsurge in residential geothermal energy usage has diminished CO_2 emissions in the longer term. The outcome has confirmed the findings of Shortall et al. (2015) and Vargas et al. (2022), who noted that geothermal energy is a clean baseload resource that can cover residential electricity demand in megacities across the globe. Furthermore, it is a clean and environment-friendly energy source that posits many features such as; i) independent of weather conditions, ii) no storage cost, iii) covering lesser space, and iv) lesser impacts on the landscape compared to wind and solar. Meanwhile, the outcome is also in line with the findings of Fidorów-Kaprawy and Stefaniak (2022), who claimed that geothermal energy has enormous potential for passive cooling in the residential sector. Additionally, it can reduce 1186–1830 kg of CO_2 emissions per annum. Umar et al. (2021) stated that geothermal energy usage had reduced carbon emissions in Italy, Mexico, and New Zealand during 1990–2019. This shows that geothermal energy can be an alternative to fossil fuels to limit CO_2 emissions. Besides, it may be an important environment-friendly electricity-generating renewable source to facilitate heating and cooling in residential buildings during winters and summers, respectively. On the contrary, outcomes (a_2) and (b_3) revealed that residential geothermal has boosted carbon emissions in both the short and long run. The result is somehow similar to the findings of Chandarasekharam et al. (2014) and Umar et al. (2021) regarding geothermal energy and CO_2 nexus. Umar et al. (2021) disclosed that geothermal energy consumption induced carbon emissions in the USA and India during 1990–2019. Chandarasekharam et al. (2014) argued that geothermal energy consumption is associated with minimum emissions of carbon dioxide compared to fossil fuels. It can significantly reduce CO_2 emissions when used in larger quantities to generate electricity instead of conventional energy sources. Besides, another possible reason might be inefficiency and higher costs related to investments in geothermal-based electricity (Soltani et al., 2021).

4.3. Residential solar energy consumption and CO_2 emissions

Wavelet Model-III (Fig. 6a) illustrates co-movements between solar energy consumed by the residential sector (SOLE) and CO_2 emissions (CO_2) by utilizing residential natural gas consumption (NGAS), residential biomass energy consumption (BIEN), and industrial production index (INPI) are as control variables. Figs. 6a and 6b indicate the output from phase difference analyses at the 1–2 year frequency band (short run) while Figs. 6a and 6c depict the output from phase difference analyses at the 2–4 year frequency band (long run). In the shorter term; a_1) the increase in CO_2 emissions decreased SOLE usage during 2008–2010 and after 2021 until the end of the sample period. a_2) The increase in SOLE usage intensified the CO_2 emissions during 1992–2000; 2005–2007; 2009–2012; 2014–2023. In the longer term; b_1) SOLE usage decreased the CO_2 emissions during 1995–1999 and 20211-2016. b_2) Increase in CO_2 emissions diminished the usage of SOLE after 2020. b_3) SOLE usage increased the CO_2 emissions for the periods 2017–2020. b_4) rise in CO_2 emissions boosted SOLE consumption over the periods 1990–1995; 2011–2012 and 2016–2018.

Following (a_1) and (b_2) wherein an increase in CO_2 emissions has reduced residential solar energy usage. The outcome is similar to the findings of Clarke et al. (2018) and Zhang et al. (2020), who revealed that CO_2 emissions-led global warming leads to an increase in temperature and hence mild winters in many regions across the globe. Overall, warmer climates and mild winters lower electricity demand by households due to declining heating requirements in colder regions. It is noteworthy that demand for heating dominates residential energy usage. Thus, CO_2 emissions may indirectly diminish residential energy consumption in specific regions. The logic applies to residential solar

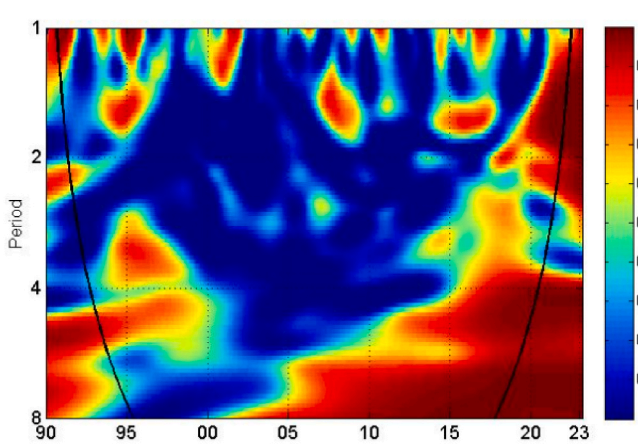

Fig. 6a. Partial wavelet coherency (SOLE, CO_2).

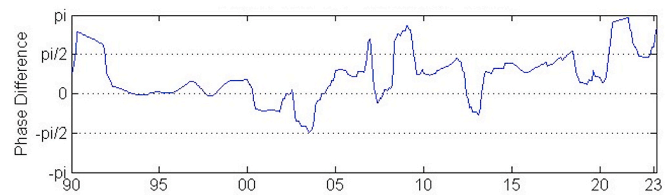

Fig. 6b. 1–2 frequency band.

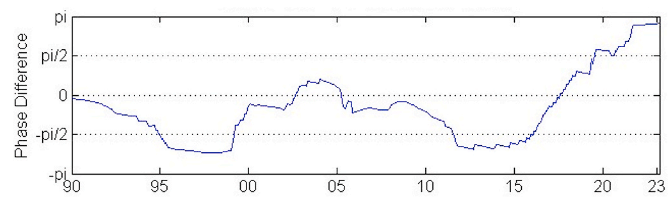

Fig. 6c. 2–4 frequency band.
Source: authors' elaborations in Matlab.

energy consumption which accounts for 43% of total solar and a major part of the residential energy mix (Kuşkaya, 2022). Besides energy efficiency, high-tech heaters and other heating devices, and climate awareness may be another reason for falling overall residential energy consumption (Papachristos, 2015; Emodi et al., 2018). While the output given in (b_4) observed a boost in residential solar energy usage following soaring CO_2 emissions. The outcome seems logical as CO_2 emissions-led global warming has been consistently raising the global average temperature and intensified the summer season with rising warmth and frequent heatwaves as confirmed by UNEP (2022) and WMO (2024). Ultimately, total energy consumption including solar energy consumption by the residential sector has surged to cope with the soaring energy demand for cooling and refrigeration especially in warmer regions (Zhang et al., 2020; Mele et al., 2021). Besides, easy access and availability of a wide range of air conditions, dehumidifiers and refrigerators, and the use of low-cost inefficient cooling devices may be another reason for excessive use energy consumption amid CO_2 emissions-led rising temperatures.

Coming to the outcome (b_2) where an upsurge in residential solar energy consumption has reduced CO_2 emissions in the long run. The result is consistent with the empirical findings of Kuşkaya (2022) who revealed a negative linkage between SOLE and CO_2 in the USA. The argument is that solar energy is amongst the cleaner and environment-friendly renewables strongly associated with reducing carbon emissions. Above all, the installation of solar panels on roofs and in nearby vicinities is an easy and viable option for households. This reflects an enormous potential for emissions reduction by utilizing solar panels in the residential sector (Hamed Banirazi Motlagh et al., 2023). Other studies (Yang et al., 2014; An et al., 2023) concluded that solar energy has significantly reduced carbon emissions in many countries and emerged as an efficient alternative to conventional emissions-led energy sources. On the contrary, (a_2) and (b_3) have depicted a positive coherency between SOLE and CO_2; that is an increase in solar energy consumption boosts carbon emissions. The outcome is in line with Yu et al. (2022). However, the phenomenon existed for a limited period. The potential reason might be the deployment of inefficient solar-based technology. Being a cleaner alternative to fossil fuels, the installment and function of solar energy systems might induce carbon emissions in the short and medium run due to inefficiency in manufacturing and utilization, as highlighted by Chen et al. (2019). This calls for comprehensive and efficient strategy and management while deploying solar energy systems.

5. Conclusions

This study offers fresh insights into the interdependent and mutual dynamics between residential energy demands (specifically in the realms of electricity, geothermal, and solar energy) and climate change. Using the partial wavelet coherence approach with monthly data of the United States, encompassing the time period from January 1990 to March 2023, the empirical results reveal a complex, time-varying co-movement and interdependence between residential energy demand and climate change indicators, including cyclical patterns and lag effects. This study disclose that, in the pre-2021 period, there was a positive correlation between electricity demand and CO_2 emissions at shorter time intervals. This correlation indicates that increases in electricity demand were associated with elevated levels of CO_2 emissions, and conversely, decreases in electricity demand were linked to lower CO_2 emissions. However, after 2021, in the same interval, the relationship reversed, where the increase in CO_2 levels is influencing and lowering residential electricity demand. In long-run frequencies, the relationship between electricity demand and CO_2 has varied, showing inconsistent co-movement and time-varying. Interestingly, there have been two extended periods of positive correlation where both variables moved in the same direction and two extended periods of negative correlation where electricity demand and emissions moved in opposite directions. Moreover, the empirical findings indicate that the relationship and co-movement between GEEN and CO_2 are mixed in the short-term frequency, with predominantly positive correlations and CO_2 leading the relationship. However, after 2020, CO_2 appears to have a negative influence on GEEN usage. Additionally, in the long-term spectrum, the dependency and co-movement between GEEN and CO_2 are also mixed, but predominantly positive, with GEEN leading the co-movements and causing an increase in CO_2. Furthermore, in the short-term frequency, the dependency and co-movement between SOLE and CO_2 are mixed, with SOLE leading to positive correlations and CO_2 leading to negative correlations. Notably, the increase in CO_2 emissions decreased SOLE after 2021. In the long-term frequency, SOLE and CO_2 also exhibited cyclical dependency, with CO_2 mostly leading the relationship. However, after 2020, CO_2 emissions appeared to negatively impact the usage of SOLE.

Therefore, the empirical findings of this study have significant policy implications, emphasizing the need to improve energy efficiency and implement commercially feasible green energy technology as measures to reduce CO_2 emissions. Governments can successfully encourage the widespread adoption of energy-efficient technology and renewable energy sources through the implementation of incentives and the provision of funds for research and development activities. Potential ways to encourage the use of green energy technology include a range of tactics. These measures include the provision of tax breaks aimed at both firms and individuals, so encouraging them to engage in sustainable activities. Furthermore, the distribution of subsidies to encourage renewable energy generation is critical in motivating the shift to greener energy sources. Furthermore, the introduction of educational programs offers great potential in terms of encouraging energy-saving habits, therefore improving the overall sustainability of energy systems. Policymakers have the ability to effectively limit energy demand, cut carbon emissions, and alleviate the effects of climate change by implementing these policies. Besides, greater awareness of climate change and the need to reduce CO_2 emissions can lead to higher construction standards and more energy-efficient designs. Improved insulation, energy-efficient windows, and high-efficiency heating systems can all assist in reducing heat loss and the total energy demand for domestic heating. Lower energy demand can lead to lower power use and consequently CO_2 levels.

The current study has some limitations. Firstly, our findings are limited to the case study analyzed, which may restrict their generalizability to other nations. To conduct a thorough comparative analysis, future studies should use high-frequency data from developed and developing nations by focusing on the most populous countries like China and India. Secondly, this study utilizes US national-level data that gives an overall picture. Future research can use panel data for different states of the USA to investigate the nexus between residential energy demand and CO_2 emissions by utilizing contemporary estimation techniques. Nevertheless, new research can also explore the relationship between commercial energy demand and carbon emissions. This sector is responsible for a significant share of global energy consumption and carbon emissions. Additionally, there is a need for data with a high frequency, particularly on a daily and weekly basis.

6. Policy implications

Keeping in view the empirical findings, the present study offers several policy recommendations to limit fossil fuels-led CO_2 emissions. Sustained, economical, and clean energy generation is inevitable for sustainable economic growth and development. The outcomes of the current study have identified that residential electricity consumption induces CO_2 emissions reflecting predominantly fossil fuels-based electricity generation. Furthermore, existing global efforts to restrict carbon emissions are insufficient. Therefore, it is highly recommended to discourage fossil fuels-based power plants. For that, governments should; (i) regressively tax the conventional power-generating units, (ii) permanently ban the inefficient power plants without significantly compromising the electricity supply, (iii) regressively tax the conventional power-generating technology, equipment and fossil fuels, and (iv) impose massive restrictions on easy access to credit to the conventional energy sector. Thus, the government can introduce a carbon emissions tax on producers and consumers simultaneously without compromising economic growth and development. It will also provide governments with an opportunity to generate additional funds to finance green energy projects. On the contrary, governments should encourage the use of clean and renewable electricity generation and consumption by providing; (i) tax exemptions to the renewable sector at least for a specific period, (ii) easy access to credit, (iii) significant finances to R&D in renewable sector, and (iv) incentives on installation of solar panels by households. Solar energy is a viable and fast-evolving sector. To capitalize on the enormous potential of this sector, governments can set up regional solar grids. Because establishment of regional solar grids will enable them to avoid energy shortfalls arising from changing weather conditions; as sunny weather in one country will compensate for cloudy weather in another country. Secondly, it will also allow regional countries to utilize the barren land and deserts by installing mega solar parks. Geothermal energy is another relatively clean energy source. However, the installation of geothermal plants is often costly and sometimes pollution-oriented. Thus, the government should pay significant attention to this sector by providing; (i) subsidies on installations of plants, and (ii) technological assistance to avoid environmental implications and inefficiency.

On the demand side, various steps should be taken to limit electricity consumption. Firstly, governments should encourage the production of highly efficient air conditioners, refrigerators, heaters, stoves, and other home appliances to optimize electricity usage by scaling up; (i) subsidies and tax exemptions (ii) investment in R&D. Secondly, the government should financially encourage temperature-resistant building structures to minimize energy consumption inside buildings and impose restrictions on conventional construction practices. Finally, climate change is a global challenge that can be tackled effectively through a framework that allows coordinated actions and cooperation at international, regional, national, and local levels. For that, the international community has to devise comprehensive mechanisms and institutions. Above all, understanding and realization of the dire environmental situation at the mass level is inevitable. This is the only effective and sustainable way to conserve nature by ensuring environmental awareness and environmental ethics.

CRediT authorship contribution statement

Faik Bilgili: Conceptualization, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **Sevda Kuskaya:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Cosimo Magazzino:** Conceptualization, Investigation, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Kamran Khan:** Data curation, Formal analysis, Methodology, Writing – original draft. **Mohammad Enamul Hoque:** Methodology, Software, Validation, Writing – original draft. **Mohammed Alnour:** Resources, Software, Validation, Writing – original draft. **Seyit Onderol:** Investigation, Software, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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