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Global energy consumption trends

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Review Paper

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Abstract:

Energy consumption is becoming a pressing concern in today's digital era, driven by the rapid pace of innovation and the increasing demand for faster computational devices. Over the decades, global energy consumption trends have undergone significant changes, with far-reaching implications for the environment, economy, and society. This paper is aimed at conducting a comprehensive analysis of the trend in global energy consumption focusing on the interplay between economic growth, technological advancements, and environmental sustainability and assessing whether consumption increased or decreased as well as examining the factors driving these changes. The study covers a time span from 1900 historical data with a projection of up to 2050 to contemporary energy scenarios and examines energy consumption patterns across various countries like China, USA, India, South Korea, South Africa and Australia with particular emphasis on both developed and emerging markets. Utilizing an empirical methodology that includes data collection from reputable sources such as the Energy Institute and the U.S Department of Energy and analytical techniques, the study employs quantitative analysis to assess shifts in energy consumption and the transition towards renewable energy sources. The main findings indicate a significant increase in global energy demand driven by population growth and urbanization, alongside a notable shift towards renewable energy adoption. The study highlights the critical role of technological innovations in enhancing energy efficiency and reducing reliance on fossil fuels. Furthermore, it identifies the need for comprehensive policy frameworks that promote sustainable energy practices and investment in renewable technologies. The relevant policy implications from the study suggest that governments and stakeholders must prioritize the development of policies that facilitate the transition to renewable energy, enhance energy efficiency, and support technological advancements. By addressing these areas, the study contributes to the discourse on achieving a sustainable energy future and mitigating the environmental impacts of energy consumption.

Keywords: Energy consumption; Renewable; Efficiency; Fossil fuels; Climate changes; Innovation

Abbreviations/Nomenclature:

CO_2; Carbon dioxide
FITs: Feed in Tariffs
RPS: Renewable Portfolio Standards
CPM: Carbon Pricing Mechanisms
Twh: Tera-watt - hour
Kwh: Kilowatt - hour
CSP: Concentrated Solar Power
CIS: Common wealth of Independent States
OECD: Organization for Economic Cooperation and Development
IEA: International Energy Agency
UNIDO: United Nations Industrial Development Organization
EU: European Union
GDP: Gross Domestic Product
NZE: Net Zero Emission

1. Introduction

Energy has been a vital component of human civilization since ancient times, with its significance only continuing to grow as the world's population and economies expand. Understanding energy consumption trends is crucial for addressing challenges like climate change and resource depletion, as it significantly impacts economic development, environmental sustainability, and social well-being, as global energy demands continue to rise [1–3]. This study provides a fresh perspective on global energy consumption patterns, highlighting the increasing adoption of renewable energy sources and decreasing reliance on fossil fuels, which is crucial for understanding the 21st-century energy transition dynamics [2].By examining important variables like energy consumption, energy sources, economic development, population growth, technological advancements, energy efficiency, policy implications, and geopolitical and environmental factors, the study seeks to provide a thorough understanding of the complex relationships between energy consumption, economic growth, technological advancements, and sustainability efforts. Findings from the study will offer valuable insights for policymakers, highlighting trends and drivers of energy consumption, which can be used to develop effective energy policies that align with climate goals, and promoting sustainable energy practices. The study makes use of a wide variety of data sources, such as information from the U.S. Department of Energy, reports from the Energy Institute, and historical estimations by Vaclav Smil. This choice of samples ensures a comprehensive analysis that captures various aspects of global energy consumption. The methodology used in the research is appropriate; it standardizes measurements for consistency and uses the substitution method to account for energy conversion inefficiencies. The comparative analysis of energy consumption trends across different regions enhances the study's credibility. The reliability of the findings is increased by the study's use of credible and diverse data sources and also, for more insightful comparisons and a better grasp of trends in energy usage, terawatt-hours (TWh) and kilowatt-hours (kWh) are used as units of measurement. The present study adds to the extant body of literature by offering a thorough examination of worldwide patterns in energy consumption, with a particular focus on the impact of technical progress and the transition towards renewable energy sources. It closes knowledge gaps about the relationship between energy demand and economic growth. The study is limited to the difficulties associated with estimating traditional biomass consumption as well as challenges with data reliability in developing countries. This transparency enhances the study's credibility and sets acceptable standards for its findings. The study is structured so that it will analyze past trends, assess present consumption trends, discuss the implications of its findings, and suggest possible directions of research and policies.

This paper contributes to literature by providing a comprehensive and updated analysis of global energy consumption trends, focusing on the complex relationship between energy consumption, economic growth, and environmental sustainability. It addresses research gaps related to pollutants and external factors like global energy prices. This study represents an interesting research area due to its timely exploration of the intricate relationship between energy consumption, economic growth, and environmental sustainability in a rapidly changing global landscape. It highlights the importance of understanding how factors like technological advancements, urbanization, and policy frameworks shape energy consumption patterns. The research not only addresses global issues like climate change and resource depletion but also provides valuable insights for policymakers and stakeholders aiming for a sustainable energy future. The novelty of the research output lies in its comprehensive and contemporary approach to analysing global

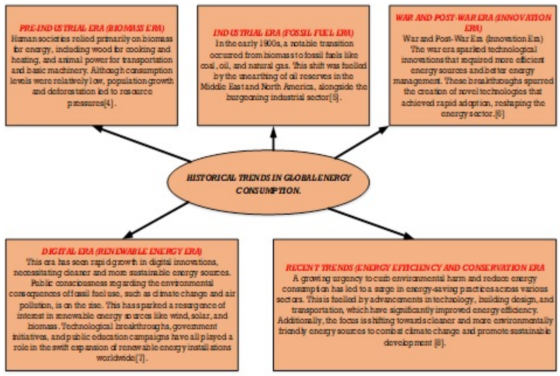

Figure 1. Historical trends in global energy consumption [4–8].

energy consumption trends by integrating up-to-date data and employing innovative methodologies that address the limitations of previous studies. Unlike earlier research that often relied on historical data and focused narrowly on fossil fuels, this study emphasizes the transition to renewable energy sources and the multifaceted influences of economic, environmental, and social factors on energy dynamics. It introduces a holistic perspective that considers a broader range of pollutants and external influences, such as global energy prices and geopolitical factors, thereby enriching the discourse on energy sustainability.

The originality of this paper is reflected in its innovative integration of contemporary data and a holistic framework that examines the relationship between energy consumption, economic growth, and environmental sustainability. It highlights the impact of technological advancements and renewable energy adoption on reducing fossil fuel reliance. The findings suggest policy recommendations for targeted investments in renewable energy technologies and comprehensive energy efficiency standards. The paper emphasizes the need for interdisciplinary collaboration among stakeholders and prioritizes long-term ecological health and social equity. This study contributes to the discourse on sustainable energy practices, guiding policymakers towards informed decisions for a resilient and sustainable energy future.

The rest part of the paper is structured as follows: the literature review is presented in section 2, the methodology employed in energy consumption trend analysis is contained in section 3, while the findings and discussion of findings is presented in section 4, followed by the conclusion in section 5.

2. Literature review

2.1 Historical trends in global energy consumption

Global energy consumption has changed significantly during the course of several evolutionary eras, including the pre-industrial, industrial, war and post-war, digital, and energy efficiency and conservation eras [4–8] as shown in figure 1.

2.2 Factors influencing global energy consumption

Global energy consumption has experienced a dramatic rise in recent decades. Several key factors, as identified

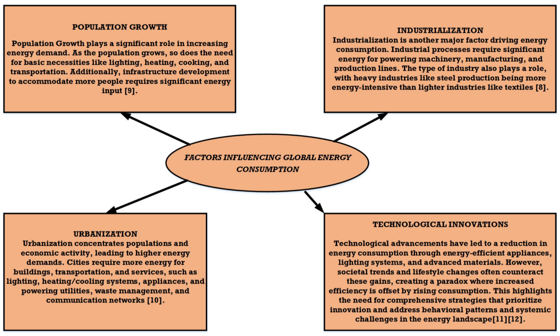

Figure 2. Factors influencing global energy vonsumption [8–12].

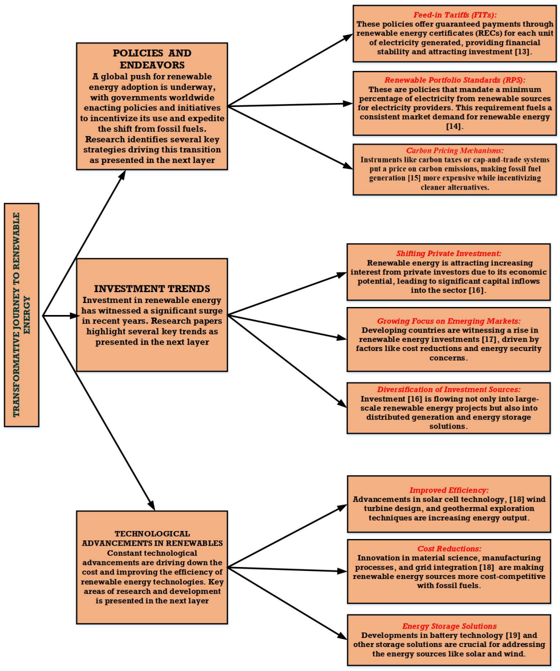

Figure 3. Transformative journey to renewable energy [13–20].

by research papers, contribute to this trend [9–12]. This includes population growth, urbanisation, industrialization, and technological innovation as shown in figure 2.

2.3 Transformative journey to renewable energies

Fuelled by rising anxieties about the environmental impact of fossil fuels, a significant global movement is embracing renewable energy sources. This shift marks a turning point for energy landscape, with far-reaching consequences for the future. To understand this transition, we must examine the multifaceted forces driving it. Technological advancements in solar and wind power, along with the development of sustainable infrastructure and policies that incentivize clean energy adoption, are all threads woven into the rich tapestry of this paradigm shift [13–17]. Furthermore, the complex interplay between government initiatives, private sector investments, and public advocacy underscores the multifaceted nature of this transition. As we navigate this transformative journey, it becomes increasingly clear that the shift to renewable energy is not just about technological innovation. It's a holistic endeavour encompassing economic, social, and environmental considerations [18–20]. A schematic shown this transformative journey is presented in figure 3.

2.4 Review of related works

In a study reported by [21], the study examines the impact of energy consumption, particularly renewable energy, and economic risks on ecological quality in BRICS (Brazil, Russia, India, China and South Africa) countries from 1990 – 2018 as measured by the load capacity factor. It aims to understand how these factors influence environmental sustainability and contribute to sustainable development and climate change mitigation in emerging economies. The study uses advanced methodologies to emphasize the importance of transitioning to renewable energy sources and addressing economic risks to improve ecological quality in these nations. The study's strength lies in its comprehensive analysis of the interrelationships between renewable energy consumption, economic risks, and ecological quality in BRICS nations, using advanced econometric methods and longitudinal data for practical policy recommendations. The study's limitations include its exclusive focus on BRICS countries, exclusion of political risk factors, and reliance on data from 1990 – 2018, potentially limiting its generalizability and applicability to recent developments.

A study reported by [22] examines the correlation between Swiss nuclear energy consumption and economic growth from 1970 to 2018, considering factors like capital, labor, and exports. It uses time-series econometric methods and Machine Learning techniques, specifically Artificial Neural Networks, to understand the impact of Switzerland's decision to phase out nuclear energy by 2034. The research emphasizes the need for careful policy planning to mitigate potential adverse effects on economic growth. The strength of the study lies in its innovative methodological approach, combining traditional econometric analysis with advanced Machine Learning techniques, specifically Artificial Neural Networks (ANNs), to examine the causal relationship between nuclear energy consumption and economic growth. The comprehensive dataset covering a significant historical period (1970 – 2018) and incorporating economic factors like capital, labor, and exports mitigate potential omitted variable bias. This research provides timely insights for policymakers and contributes to the discourse on energy policy and economic sustainability, particularly in Switzerland's impending nuclear phase-out. The study has several limitations, including the potential for model specification errors in econometric and Machine Learning approaches, the limitations of the findings being generalizable to other countries with different energy policies or economic structures, the reliance on historical data up to 2018, and the lack of extensive attention to qualitative aspects of energy policy changes, such as public perception and political factors, which could influence the implementation of phase-out strategies.

The study in [23] explores the relationship between economic growth, CO_2 emissions, and energy consumption in Russia from 1990 to 2020. It employs advanced econometric methodologies and Machine Learning techniques to analyze the bidirectional causality between energy consumption and CO_2 emissions and the unidirectional influence of CO_2 emissions on real GDP. The research aims to fill a gap in Russia's literature and inform effective energy conservation policies in the context of geopolitical developments. It offers practical policy implications, suggesting energy conservation measures can be pursued without hindering economic growth, especially in the face of geopolitical developments and rising energy prices. However, the study's limitations include its reliance on historical data, its complexity, its generalizability to other countries with different economic structures and energy profiles, and its inability to address external factors influencing the relationships among variables.

The study in [24] investigates the casual link between primary energy consumption and economic growth using a model that integrates capital and labour with Israel as a case study. A cointegration relationship is found among th variables. Causality test's results display both short-run and long-run relationship between economic growth and primary energy consumption. The study displays a competitive edge from other studies as it aims to realize two objectives. First, the research draws researcher's attention to current methodological issues as it presents an in- depth review of the literature review in this area. It provides a global state of the art review of past energy GDP nexus analysis whose conclusions are thought to enlarge the research field and suggest new research alternatives. However, a major limitation of the study is that the study dwelt on Israel which affects generalizability to other countries with different economic structures and energy profiles.

The study in [25] examines Japan's Environmental Kuznets Curve (EKC) after the Fukushima disaster and deteriorating income. It uses advanced econometric techniques to assess the relationship between economic growth, energy consumption, and CO_2 emissions. The findings show that the EKC exists even in challenging economic conditions, suggesting natural disasters can cause environmental degradation. The study emphasizes energy consumption's role in environmental degradation and proposes policy instruments for efficient energy management. Despite the benefits of the study on Japan's EKC, based on historical data from 1961 to 2012, it still has some limitations. The historical data may not accurately reflect the country's economic and environmental landscape, especially post-Fukushima. The analysis also overlooks regional variations and sectoral impacts, and does not consider external factors like global economic trends or technological advancements. This suggests that while the findings offer valuable insights, they may not fully address Japan's current and future environmental challenges.

The study reported in [26] examines the impact of globalization and energy consumption on environmental degradation in South Africa, using data from 1971 to 2014. It uses advanced econometric models to analyze the relationship between globalization, energy use, and economic growth. Results show an upward EKC dynamic, with excessive fossil fuel use contributing to environmental degradation. The study suggests conservative energy policies and a pollution-free energy mix to improve South Africa's environmental quality. The study's main limitation is its reliance on historical data from 1971 to 2014, which may not accurately reflect South Africa's economic and environmental changes, especially in light of evolving energy policies and globalization trends. It also focuses mainly on CO_2 emissions, overlooking other pollutants and environmental factors. The use of specific econometric models may introduce limitations due to structural stability and linearity assumptions.

Another study in [27] examines the relationship between economic growth, trade openness, and energy consumption in the UK from 1970 to 2013, finding that economic growth can alleviate energy consumption issues, but trade openness exacerbates them, impacting energy policy. A major limitation with the study is that the study rely's on historical data from 1970 to 2013, which may not accurately represent recent trends in energy consumption and economic dynamics, and the use of methodologies like Bayer-Hanck integration approach and ARDL bounds testing, which may be susceptible to biases. The study's focus on the UK may limit its generalizability to other contexts or countries with different economic structures. Reliance on historical data, method adopted may be susceptible to bias. The study focus on one location (UK) which limits its generalizability to other countries.

A study by Rafindadi and Ozturk's [28] explored the relationship between financial development, trade openness, economic growth, and energy consumption in South Africa from 1970 to 2011. They found that financial development significantly stimulates energy demand, while trade openness and economic growth also increase energy consumption. The study suggests that higher energy consumption is linked to improved economic growth. It emphasizes the need for developing financial infrastructure to improve energy efficiency and provides policy recommendations for sustainable energy use and economic development in South Africa and the African context. The major limitations of the study are its focus on South Africa, its time frame from 1970 to 2011, and its reliance on specific econometric methods. It also overlooks recent developments in energy consumption and economic dynamics. The study also fails to consider external factors like global energy prices or geopolitical influences on the relationship between financial development, trade openness, and energy consumption. Furthermore, it could benefit from a more detailed exploration of the mechanisms through which financial development influences energy consumption and its implications on environmental sustainability.

The study reported in [29] examines the impact of financial development, trade openness, capital use, and economic growth on energy consumption in Germany from 1970 to 2013. It found that a 1% increase in economic growth leads to a 2.1053% increase in energy consumption, while financial development and trade openness negatively affect energy demand. The study highlights the need for policy considerations to balance economic growth with sustainable energy consumption amidst environmental challenges. The study has several limitations, including relying on historical data from 1970 to 2013, which may not accurately reflect current energy and economic conditions, and using methodologies that may be affected by structural breaks and omitted variable bias. The study's focus on the United Kingdom limits its generalizability to other countries with different economic and energy contexts. Additionally, the analysis does not account for external influences like global economic fluctuations or technological advancements that could impact the relationship between economic growth, trade openness, and energy consumption.

The study in [30] examines the relationship between financial market development, energy consumption, and economic growth in the UK from 1970 to 2013. It uses data from 1970 to 2013 and employs econometric techniques to find an inverted U-shape. The research shows that financial market development initially increases energy demand, but this demand declines after reaching a certain threshold. Economic growth also negatively impacts energy consumption, suggesting that rising economic activity doesn't necessarily lead to increased energy use. The study emphasizes the bidirectional causality between sustainable energy consumption and financial market resilience, urging policymakers to consider these dynamics in the UK's energy and economic strategies. The study's limitations include its reliance on historical data from 1970 to 2013, which may not accurately reflect the changing dynamics of financial markets and energy consumption. A summary of the review is as presented in Table 1.

2.5 Research gaps from previous study

Many of the aforementioned studies in the review of related work often rely on historical data, which may not accurately reflect current economic and environmental conditions. For example, studies on South Africa, the UK, Germany, and Japan use data from 1970s to 2010s. In addition, some of the Studies often focus on CO_2 emissions, neglecting other environmental factors and pollutants, potentially leading to an incomplete understanding of the environmental implications of energy consumption. The study's focus on just a specific country like South Africa, the UK, and Japan limits its generalizability to other contexts with diverse economic structures and energy dynamics. The reliability of results can be affected by biases and assumptions introduced by specific econometric models and methodologies, such as ARDL bounds testing and VECM Granger causality analysis.

Many of these studies overlook external factors like global energy prices, geopolitical influences, and technological advancements that could significantly influence economic growth, trade openness, and energy consumption, limiting the comprehensiveness of the analyses. The call for comprehensive studies on alternative energy sources and the impact of financial development on energy consumption is of great emphasis, focusing on sector-specific data and its implications for environmental sustainability.

It is in view of this, that this study aims to address the limitations of existing studies on energy consumption by focusing on up-to-date data, incorporating multiple environmental factors and pollutants, and exploring diverse contexts and energy dynamics. Researchers should evaluate biases and assumptions in their econometric models and methodologies, and consider external factors like global energy prices, geopolitical influences, and technological advancements. This approach will provide more accurate insights into energy consumption's environmental implications, ultimately informing effective policy and decision-making.

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3. Methodology

The study examines global energy consumption trends, relying on data (1900 to 2050 projections) from reputable source such as the Energy Institute's global energy data report and historical estimates by Vaclav Smil [4]. To provide a comprehensive understanding of primary energy consumption and electricity generation, information from the U.S. Department of Energy's Energy Information Administration and Ember is also utilized [8–12]. To ensure consistency and accuracy, the study employs two methods: the substitution method to account for inefficiencies in fossil fuel and biomass conversion, and standardized units of measurement, with primary energy consumption reported in terawatt-hours (TWh) and per capita consumption in kilowatt-hours (kWh) per person [31], each selected for its ability to provide multifaceted insights into complex dynamics at play.

These methods were chosen for their robustness and relevance as they enable a comprehensive understanding of economic, environmental, and technological factors, enhancing the reliability of findings and addressing existing literature gaps. The study examines the relationship between energy consumption, economic growth, and environmental sustainability using an estimated equation. The dependent variable is energy consumption, while independent variables include GDP growth, population size, technological advancements, and energy efficiency metrics.

The study uses literature to highlight the impact of economic activity, demographic factors, and technology on energy demand. It also includes environmental indicators like CO_2 emissions to assess the sustainability implications of energy consumption patterns. The analysis focuses on comparing global energy consumption trends over time and across countries, with an emphasis on total energy and electricity consumption, per capita energy consumption, and consumption patterns [32]. While this study provides a comprehensive overview, it acknowledges limitations, including potential data reliability issues for developing countries where traditional biomass consumption is significant, and the lack of analysis on specific energy sources powering consumption or decarbonization efforts. The study provides valuable insights for policymakers to navigate the transition to a more sustainable energy landscape, ensuring a

Table 1. Summary of review of related works.

Author	Objective	Merit	Limitations
[21]	The study examines the impact of energy consumption, particularly renewable energy, and economic risks on ecological quality in BRICS (Brazil, Russia, India, China and South Africa) countries from 1990-2018 as measured by the load capacity factor	The study's strength lies in its comprehensive analysis of the interrelationships between renewable energy consumption, economic risks, and ecological quality in BRICS nations, using advanced econometric methods and longitudinal data for practical policy recommendations	The study's limitations include its exclusive focus on BRICS countries, exclusion of political risk factors, and reliance on data from 1990-2018, potentially limiting its generalizability and applicability to recent developments
[22]	Examination of the correlation between Swiss nuclear energy consumption and economic growth from 1970 to 2018, considering factors like capital, labor, and exports It uses time-series econometric methods and Machine Learning techniques, specifically Artificial Neural Networks,	The strength of the study lies in its innovative methodological approach, combining traditional econometric analysis with advanced Machine Learning techniques, specifically Artificial Neural Networks (ANNs), to examine the causal relationship between nuclear energy consumption and economic growth. The comprehensive dataset covering a significant historical period (1970-2018) and incorporating economic factors like capital, labor, and exports mitigate potential omitted variable bias.	The limitations of the findings include lack of generalization to other countries with different energy policies or economic structures, the reliance on historical data up to 2018, and the lack of extensive attention to qualitative aspects of energy policy changes, such as public perception and political factors, which could influence the implementation of phase-out strategies.
[23]	Explores the relationship between economic growth, CO2 emissions, and energy consumption in Russia from 1990 to 2020. It employs advanced econometric methodologies and Machine Learning techniques	It offers practical policy implications, suggesting energy conservation measures can be pursued without hindering economic growth, especially in the face of geopolitical developments and rising energy prices	The study's limitations include its reliance on historical data, its complexity, its generalizability to other countries with different economic structures and energy profiles, and its inability to address external factors influencing the relationships among variables.
[24]	Investigating the casual link between primary energy consumption and economic growth using a model that integrates capital and labour with Israel as a case study	The study displays a competitive edge from other studies as it aims to realize two objectives. First, the research draws researcher's attention to current methodological issues as it presents an in- depth review of the literature review in this area. It provides a global state of the art review of past energy GDP nexus analysis whose conclusions are thought to enlarge the research field and suggest new research alternatives.	A major limitation of the study is that the study dwelt on Israel which affects generalizability to other countries with different economic structures and energy profiles.
[25]	Examining Japan's Environmental Kuznets Curve (EKC) after the Fukushima disaster and deteriorating income. It uses advanced econometric techniques to assess the relationship between economic growth, energy consumption, and CO2 emissions	The study emphasizes energy consumption's role in environmental degradation and proposes policy instruments for efficient energy management	The historical data may not accurately reflect the country's economic and environmental landscape, especially post-Fukushima. The analysis also overlooks regional variations and sectoral impacts, and does not consider external factors like global economic trends or technological advancements. This suggests that while the findings offer valuable insights, they may not fully address Japan's current and future environmental challenges.
[26]	Examining the impact of globalization and energy consumption on environmental degradation in South Africa, using data from 1971 to 2014	The study suggests conservative energy policies and a pollution-free energy mix to improve South Africa's environmental quality	The study's main limitation is its reliance on historical data from 1971 to 2014, which may not accurately reflect South Africa's economic and environmental changes, especially in light of evolving energy policies and globalization trends.
[27]	Examination of the relationship between economic growth, trade openness, and energy consumption in the UK from 1970 to 2013	Findings from the study shows that economic growth can alleviate energy consumption issues, but trade openness exacerbates them, impacting energy policy.	A major limitation with the study is that the study rely's on historical data from 1970 to 2013, which may not accurately represent recent trends in energy consumption and economic dynamics, and the use of methodologies like Bayer-Hanck integration approach and ARDL bounds testing, which may be susceptible to biases.
[28]	Exploring the relationship between financial development, trade openness, economic growth, and energy consumption in South Africa from 1970 to 2011	The study emphasizes the need for developing financial infrastructure to improve energy efficiency and provides policy recommendations for sustainable energy use and economic development in South Africa and the African context.	The study's limitations include its focus on South Africa from 1970 to 2011, its reliance on specific econometric methods, overlooking recent energy consumption and economic developments, and not considering external factors like global energy prices or geopolitical influences on the relationship between financial development, trade openness, and energy consumption.
[29]	The impact of financial development, trade openness, capital use, and economic growth on energy consumption in Germany from 1970 to 2013	The study highlights the need for policy considerations to balance economic growth with sustainable energy consumption amidst environmental challenges	The study has several limitations, including relying on historical data from 1970 to 2013, which may not accurately reflect current energy and economic conditions, and using methodologies that may be affected by structural breaks and omitted variable bias
[30]	Examining the relationship between financial market development, energy consumption, and economic growth in the UK from 1970 to 2013	The study emphasizes the bidirectional causality between sustainable energy consumption and financial market resilience, urging policymakers to consider these dynamics in the UK's energy and economic strategies	The study's limitations include its reliance on historical data from 1970 to 2013, which may not accurately reflect the changing dynamics of financial markets and energy consumption.

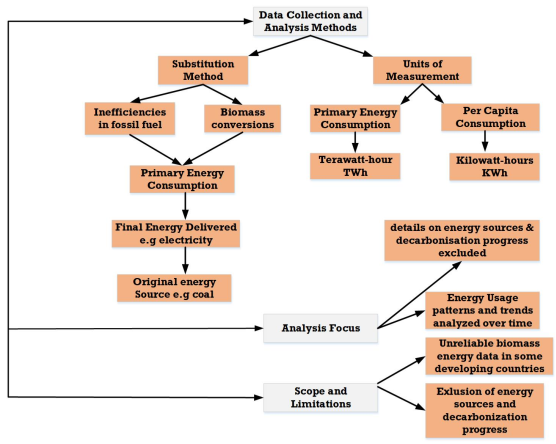

Figure 4. Overview of the methodology.

resilient and sustainable energy future. The overview of the methodology employed in the study is presented in figure 4.

4. Findings and discussion from global studies

4.1 Global energy consumption trends

Global energy consumption has increased significantly in the 21st century. Since 2000, there has been a staggering increase of about a third in global energy consumption, and projections suggest this trend will persist into the foreseeable future. In 2018 alone, global energy demand witnessed a robust growth of 2.9%. If we continue with business as usual, by 2040, global energy consumption is estimated to skyrocket to 2,054 TWh, [33] marking an additional 30% surge in demand. Looking ahead to the span from 2000 to 2040, this trajectory translates into a staggering 77% surge in global energy consumption. And when we widen our perspective from 1980 to 2050, the figures become even more daunting, with projections indicating that global energy use could triple from around 1,050 TWh to 3,150 TWh [34].
The sheer scale of global energy consumption can be difficult to comprehend. To put it into perspective, consider this: the energy consumed annually worldwide is equivalent to the energy released from the Hiroshima nuclear bomb detonating every four seconds. Moreover, a single TWh of energy is sufficient to power a large city for an entire year.
A recent research conducted using enerdata estimated the total energy consumption during the period of 2021 − 2022. It was seen that in 2022, global energy consumption growth slowed down notably, with a rate of 2.1% compared to 4.9% in 2021, although still higher than the average annual growth from 2010 to 2019 (1.4%). Both China and the United States, the largest energy consumers, saw reduced growth rates: China's consumption increased by 3%, down from 5.2% in the previous year, and the US experienced a growth of 1.8% compared to 4.9% in the previous year [33].
However, several countries displayed robust growth, including India, Indonesia, Saudi Arabia, Canada, and Latin American nations [33]. Energy consumption also rose in the Middle East and Africa, except for South Africa, which faced a decline due to coal supply issues where they experienced a serious decline in the coal supply. Europe and the Commonwealth of Independent States (CIS) experienced a decline in energy consumption due to fears of a potential recession triggered by the Ukraine war [35], surging energy prices, and milder weather conditions.
Europe, including the EU, UK, and Turkey, saw a decline of around 4%, while CIS consumption dipped by 3.2%, primarily due to the war in Ukraine and Western sanctions on Russia [35]. OECD-Asian countries, like South Korea and Australia, maintained stable or slightly decreased energy consumption in 2022. This data underscores the diverse factors influencing global energy consumption trends, including economic uncertainties, geopolitical tensions, and weather patterns.
Global energy consumption exhibits significant variations across regions, influenced by a complex interplay of factors. Key drivers of regional differences include economic development, climate, energy mix, and energy efficiency. Developed economies with established industrial sectors typically have higher energy consumption per capita, while regions with extreme temperatures require more energy for heating or cooling. The types of energy sources used also significantly impact consumption patterns, with regions reliant on fossil fuels for electricity generation typically consuming more energy.
Data-driven examples of regional variations include the clear disparity in energy consumption between developed and developing regions [2]. Rapidly developing economies like China and India provide examples of rapidly growing energy consumption driven by expanding industrial sectors. Efforts to transition to cleaner energy sources at the regional level, like the European Union's 2030 target for a 55% cut in greenhouse gas emissions, are also reshaping global energy consumption patterns, also impact energy consumption patterns [33].
The residential sector's energy consumption is on the rise due to population growth, improving living standards, and urbanization. However, advancements in technology [36] are leading to more efficient appliances and buildings, mitigating some of the demand growth. Stringent building codes and appliance standards can significantly reduce residential energy consumption.
Industrial activity and processes are major drivers of global energy demand, with high consumption levels persisting. While industrial energy efficiency and renewable energy integration are gaining traction, the transportation sector remains a significant energy consumer heavily reliant on fossil fuels. Vehicle ownership and fuel efficiency continue to be key factors shaping trends. However, a growing emphasis on public transportation, electric vehicles, and alternative modes presents a promising path towards reducing energy consumption in this sector. A global energy consumption trend is presented in figure 5.

4.2 Relationship between population growth and energy consumption

The intricate link between population growth and energy consumption is a critical consideration in shaping a sustainable future. Research suggests a positive correlation between these two factors, with a larger population translating to a greater demand for basic needs like lighting,

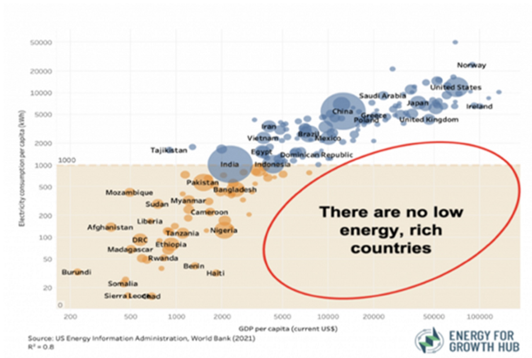

Figure 5. Global energy consumption trend [37].

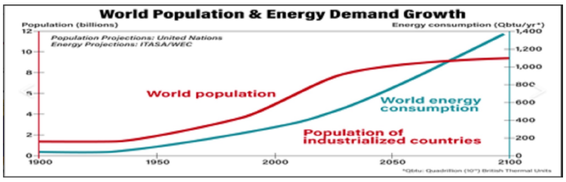

Figure 6. Demographic shifts and their impact on energy demand [43].

heating/cooling, cooking, and transportation [36–38]. This results in higher energy consumption across residential and commercial sectors. Additionally, population growth necessitates the construction of new housing, transportation networks, and industrial facilities, requiring significant energy input for materials, construction processes, and ongoing operations.

While population size plays a crucial role, the relationship with energy consumption is not always straightforward. Population growth often coincides with economic development, leading to rising living standards and increased consumption of energy-intensive goods and services [38] like electronics, personal vehicles, and leisure activities. However, technological advancements can offer more energy-efficient appliances, buildings, and industrial processes, helping to mitigate the impact of population growth on energy consumption [39, 40].

The graph in figure 6 shows a strong correlation between world population growth and energy consumption. Both have risen significantly since 1950 [41], with energy consumption growing at a faster rate. Population projections suggest this trend will continue until at least 2100. This highlights the challenge of balancing future energy demands with sustainable practices [42].

While population growth is a significant factor in energy consumption, demographic shifts within a population can also substantially alter energy demand patterns. Aging populations, for instance, can lead to a shift in energy demand from residential to healthcare facilities, [44] as individuals require more energy for healthcare services, which can offset the decrease in residential energy consumption due to smaller household sizes. On the other hand, a younger population with more families may lead to increased residential energy demand for larger homes and higher overall consumption [45]. Rapid urbanization concentrates people in cities, creating a higher energy demand across various sectors. This includes increased energy needs for buildings, such as high-rise buildings and dense residential areas, as well as transportation, including public transportation systems, personal vehicles, and traffic congestion. Urban lifestyles often involve higher living standards, increased reliance on technology, and greater consumption of energy-intensive goods and services [46].

Other demographic shifts, such as rising income levels, can also impact energy consumption. As income levels rise, people tend to consume more energy for appliances, electronics, personal vehicles, and leisure activities. It's important to recognize the complexities and interactions between demographic shifts, such as urbanization and ageing, and economic development and urbanization, which can further amplify energy demand across sectors [47].

4.3 Case studies of countries with significant population growth

Population growth presents unique energy challenges for different countries. Here, we explore three case studies with significant population growth and their distinct energy landscapes, drawing insights from research papers.

India, with its rapidly growing population, faces significant energy challenges. The country's population is projected to surpass China's in the coming years, creating a massive surge in energy demand. Economic development and urbanization are driving energy consumption, with a focus on fossil fuels, particularly coal, for power generation [47]. In response to concerns about air pollution and greenhouse gas emissions, India is taking a multi-pronged approach. This includes expanding renewable energy sources, improving energy efficiency, and enacting policies that promote sustainable development [47].

Rapid population growth in Nigeria, Africa's most populous nation, is straining the energy sector. Limited access to reliable and affordable electricity remains a key challenge. The country's dependence on fossil fuels further complicates the issue, raising environmental concerns. Research highlights the need for sustainable solutions, including diversifying energy sources and expanding electricity grid access [48]. Nigeria's energy strategy aims to address these challenges by investing in renewables, improving energy efficiency, and ensuring widespread electricity access [49].

Countries in tropical Africa [50] experiences some of the world's fastest population growth rates, with millions lacking access to good electricity. The region faces energy challenges, including limited access and dependence on fossil fuels. To address these challenges [51], the focus lies in expanding electricity access, ensuring sustainable solutions, and harnessing the region's vast potential for renewable energy sources like solar and wind power.

4.4 Industrialization and global energy consumption

Industrialization has fuelled a significant increase in global energy demand. Data from the International Energy Agency (IEA) reveals that the industrial sector consumed 27% of final energy consumption worldwide in 2021 [52], which is very massive. This dramatic rise stems from two primary factors. First, industrial activity necessitates vast amounts of energy to power machinery, production lines, and cli-

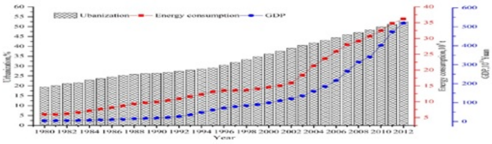

Figure 7. Relationship between urbanization and energy consumption GDP in China [56].

mate control systems within facilities. A study [53] by the World Bank found a strong correlation between industrial output and energy consumption, stating that the higher the industrial output in a region the higher the energy that has been consumed coherently, highlighting how economic growth fuelled by industrialization translates directly to increased demand for energy-intensive goods and services. For instance, China's industrial sector, a major driver of the nation's economic growth, witnessed a 5.7% increase in energy consumption in 2021 alone [52].
However, the narrative surrounding industrialization and energy consumption is not solely one of escalating demand. Technological breakthroughs are enabling a significant move towards energy-frugal industrial processes. According to the United Nations Industrial Development Organization (UNIDO), industries are embracing energy-saving technologies and practices at an increasing rate. This trend holds promise for decoupling industrial growth from its dependence on fossil fuels [54]. This trend is exemplified by the European Union, a global leader in industrial development. The EU has set ambitious goals for renewable energy integration, aiming for a 32% share of renewables powering its industrial sector by 2030 [55].
This multifaceted relationship between industrialization and energy consumption highlights the need for a nuanced approach. While industrial activity undeniably increases energy demand, technological advancements and policy initiatives offer a path towards a more sustainable future. Further research into specific case studies of leading industrialized nations [53]. Like Germany's focus on industrial energy efficiency through process optimization, can provide valuable insights into effective strategies for mitigating energy consumption within the industrial sector.

4.5 Urbanization and global energy consumption

Urbanization, characterized by the mass movement of people from rural areas to cities, is one of the defining trends of the 21st century. The relationship between urbanization and energy consumption GDP in China for example is presented in figure 7.
While urbanization offers economic and social opportunities, it also presents significant challenges, particularly in terms of energy consumption [57]. As people concentrate in cities, energy demand rises across various sectors. Buildings require more energy for lighting, heating, and cooling, while transportation systems contribute significantly to energy consumption. Additionally, urban lifestyles often involve higher living standards, a shift towards service industries, and increased consumption of energy-intensive goods and services.
Research has explored the link between urbanization and energy consumption, highlighting the complex relationships between these factors. Compact city design, improved public transportation systems, and energy-efficient building codes can mitigate the rise in energy demand associated with urbanization. While urbanization often leads to increased energy consumption, the relationship is not uniform. Factors such as population density, living standards, and the nature of economic activity all play a role in shaping this dynamic.
Urban planning can be a powerful tool for promoting energy efficiency in cities. Strategies like compact urban design, mixed-use development, and green building codes can significantly reduce energy use. Additionally, prioritizing public transportation and infrastructure for non-motorized options like cycling and walking can provide a sustainable alternative to car-dependent transportation.
Research has shown that these strategies can be effective in reducing energy consumption: - Studies indicate that compact urban design can have a dramatic impact on energy consumption, potentially leading to reductions of up to 50% [58]. Green building practices can also reduce energy consumption by up to 70%. Studies has also shows that investments in public transportation can yield significant environmental benefits. These systems can reduce energy consumption and greenhouse gas emissions by up to 80%, contributing to cleaner air and improved public health [59].
Emerging economies are experiencing rapid urbanization, unlocking economic opportunities but also presenting challenges in terms of energy consumption. The United Nations projects that by 2050, over 60% of the world's population will reside in urban areas, with much of this growth occurring in developing countries [60]. The rapid urbanization of emerging economies presents a unique opportunity to develop sustainable cities. While this growth fuels a rise in energy demand for infrastructure, residential needs, and various urban functions, it also necessitates innovative solutions. Promoting energy efficiency, investing in energy-saving technologies, and harnessing renewable energy sources like solar and wind power are crucial steps towards building a sustainable urban future.
Research in [56] has shown that urbanization leads to increased energy consumption in emerging economies, with urban residents having a higher energy demand compared to their rural counterparts. Scaling up investments in energy-efficient technologies and renewable energy offers a powerful solution for lowering energy consumption and lessening our environmental footprint.

4.6 Transition to renewable energy

The transition to renewable energy is driven by technological advancements, policy changes, and economic factors. Recent breakthroughs in renewable energy technologies are transforming the energy landscape. In the solar energy sector, [16] perovskite solar cells are emerging as a next-generation technology with higher efficiencies and lower production costs compared to traditional silicon-based solar panels. Concentrated Solar Power (CSP) technologies are also advancing, with improvements in molten salt heat storage systems enabling greater flexibility and dispatchability

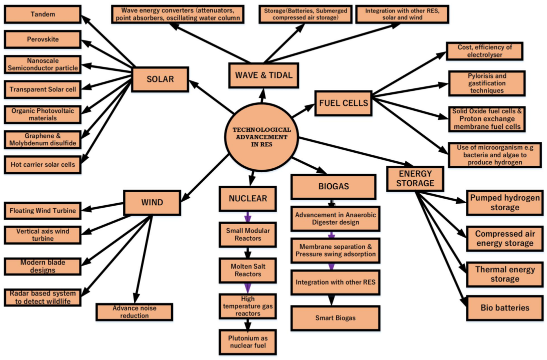

Figure 8. Technological advancement in RES.

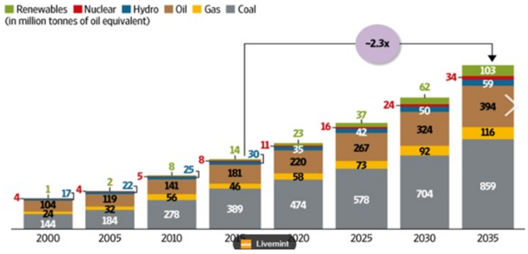

Figure 9. Future projection for use of renewable energy in meeting the growing energy demand [63].

[17].

In the wind energy sector, offshore wind turbines are becoming increasingly cost-competitive due to technological advancements in turbine size and efficiency. Floating offshore wind technology is also emerging, allowing wind turbines to be deployed in deep waters and expanding the potential for offshore wind energy. Additionally, advancements in onshore wind energy are leading to larger and more efficient turbines, reducing costs and increasing adoption.

In the energy storage sector, [16] the future of sustainable energy is brimming with promise. Advancements in battery technology are slashing costs and expanding storage capacity, while grid-scale solutions like pumped hydro and compressed air storage are becoming increasingly viable. Renewable energy sources beyond solar and wind, such as hydrokinetic, geothermal, and biomass, are also experiencing significant progress, solidifying their importance in the transition to a clean energy future.

Hydro-kinetic energy, which harnesses the power of moving water, is emerging as a promising technology for coastal and island communities. Geothermal energy, which leverages the Earth's natural heat, is also becoming more efficient and cost-effective. Biomass energy, which is derived from organic matter, is being advanced through new conversion technologies and feedstock development.

Overall, the transition to renewable energy is being driven by a range of technological advancements and innovations across various sectors. The continued evolution and improvement of these technologies promise demonstrably lower greenhouse gas emissions and a demonstrably more sustainable energy future. An overview of some of the technological advancements of the aforementioned renewables and many more renewables is presented in figure 8.

4.7 Future projections

Global energy consumption is poised for significant transformations in the coming decades. The International Energy Agency (IEA) in its World Energy Outlook 2023 [61] predicts that global energy demand will continue to rise, reaching 27% above 2021 levels by 2050 under its Stated Policies Scenario. This growth is primarily driven by population increase and economic development in emerging economies. However, the IEA also presents alternative scenarios, highlighting the potential impact of accelerated climate action. The Net Zero Emissions by 2050 (NZE) scenario paints a contrasting picture, with global energy demand peaking in 2025 and then declining by 17% by 2050. This significant reduction hinges on a rapid and widespread adoption of renewable energy sources [61].

Projections anticipate that renewable energy will be a central element in defining future energy use patterns. The International Energy Agency's (IEA) Net Zero Emissions (NZE) scenario predicts a substantial increase in renewables, reaching 80% of global electricity production by 2050, compared to just 28% in 2021. This significant shift towards renewables offers a dual benefit: mitigating greenhouse gas emissions and bolstering energy security by diversifying the global energy mix and lessening dependence on fossil fuels.

However, this transition is not without its own complexities. Incorporating large-scale renewable sources into existing grids necessitates substantial investments in infrastructure upgrades and grid modernization. Furthermore, ensuring consistent and dependable power requires solutions like energy storage and demand-side management strategies [62].

Figure 9 depicts rising primary energy demand with a projected increase of 2.3 times over the next 20 years. Renewables are expected to see the most significant growth, while fossil fuels like coal are expected to decline. This trend suggests a potential shift towards a more sustainable energy mix in the future.

Confronting these complexities is essential to unlocking the full potential of renewable energy sources. Governments worldwide are enacting policies that encourage the development of renewable energy and storage solutions. Technological progress is also expected to make significant contributions, with innovations in battery storage and smart grid technologies paving the way for a more adaptable and efficient energy system.

In conclusion, the future of global energy consumption is at a crossroads. While the stated policies scenario suggests a continuation of the current trends, the potential for a more sustainable future with a significant role for renewables exists. Overcoming the challenges associated with large-scale renewable energy integration will be central to achieving this vision and ensuring a secure and sustainable energy future for the planet.

5. Conclusion

This study examines the evolution of global energy consumption, highlighting the complex relationship between energy usage, economic growth, and environmental sustainability. It emphasizes the need for a paradigm shift in how we perceive energy consumption, recognizing the interdependence of ecological, economic, and social systems. The study advocates for a holistic approach to policy-making, promoting technological innovation in renewable energy, interdisciplinary collaboration, and public engagement. It emphasizes the importance of addressing energy consumption, economic growth, and environmental sustainability, recommending investments in renewable energy, comprehensive energy efficiency standards, and sector-specific energy consumption data analysis. Ultimately, the study encourages policymakers to prioritize long-term sustainability over short-term gains, ensuring a resilient energy system that protects future generations and addresses environmental concerns.

Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
The authors declare that the data supporting the findings of this study are available within the paper.

Conflict of interests
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.

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